The determination of wetland hydrologic characteristics using a bromide tracer
by Robert Boyd Morton

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
Sodium bromide was used in a natural gradient tracer test to determine acid mine drainage (AMD) flow velocity through a sedge peat fen in west-central Montana. A grid of auger holes and small diameter wells was installed at varying depths. Water samples taken from this grid network were analyzed in the field using a bromide specific ion electrode. Field hydraulic conductivity (K) was determined on auger holes and wells in the area of expected metal loading and tracer movement. The K ranged from 1.0 x 10-2 to 1.5 x 10-5 cm/s with a mean of 8.3 x 10-4 cm/s. Mean velocity determined from the K values was 7.1 x 10-5 cm/s. Water flow velocity considered the most representative of the AMD waters was then determined by the tracer experiment and ranged from 3.1 x 10-1 to 6.2 x 10-4 cm/s with a mean of 2.6 x 10-2 cm/s (73.7 ft/day). The wide range of velocities indicate a very heterogeneous wetland flow system. The large difference (three order of magnitude) between K determined velocity and tracer determined velocity indicates the measurement of two different flow systems. The tracer velocity represents preferential flow paths within the shallow (acrotelm) system and the K determined velocity represents that flow found at greater depth (catotelm). The distance the AMD water travels, before problem amelioration, was not determined from the tracer methods employed, but using a distance estimate of 200 m and the average tracer velocity, the average residence time of AMD water in contact with the wetland soils is approximately 9 days.

THE DETERMINATION OF WETLAND HYDROLOGIC CHARACTERISTICS USING A BROMIDE TRACER

by

Robert Boyd Morton

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Rehabilitation

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 1988

APPROVAL

of a thesis submitted by

Robert Boyd Morton

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

May 23, 1988
Date

D.J. Dollhopf
Chairperson, Graduate Committee

Approved for the Major Department

May 24, 1988
Date

Arthur C. Linder
Head, Major Department

Approved for the College of Graduate Studies

June 10, 1988
Date

Henry L Parsons
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his/her absence, by the Dean of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Robert B Morton

Date June 10, 1988

DEDICATION

This work is dedicated to those interested in natural environments and those who strive to wisely use, without abuse, our natural resources.

VITA

Robert Boyd Morton was born April 25, 1959 in Stuttgart, Germany, the son of Robert C. Morton and Susan B. (Dickinson) Morton. He grew up in Wisconsin where he became an Eagle Scout, Boy Scouts of America and joined the U.S. Coast Guard Reserves to become a Boatswains Mate Petty Officer. He moved to Montana in 1977 and graduated from Montana State University in 1982 with a Bachelor of Science in Earth Science, Geology option. He married Marcia J. (Davenport) Morton in 1983 and worked in the building construction trade in Montana. In the winter of 1986 he began graduate studies in Land Rehabilitation at Montana State University. To broaden his graduate program background in hydrology he attended the University of Montana during the 1986 - 1987 academic year.

ACKNOWLEDGEMENTS

There are many persons who helped in all aspects of this thesis. Some of the most deserving recognition include John Goering, Dan Rundell, Dr. Doug Dollhopf, Bob Rennick, Dr. Steve Custer, Dr. Dal Burkhalter, Charles Hardy, Mike Cormier, Martha Gitt, Dr. Frank Munshower, Dennis Neuman, Dr. Bill Woessner and Jeralynn Goheen. A special thanks to Michael Hiel and the Montana Department of State Lands, Abandoned Mine Reclamation Bureau for support through funding of this project. Thanks also to the many other persons who assisted but are unmentioned.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES--Continued

LIST OF CONVERSIONS

acres x 4.047×10^{-1} = hectares
centimeters x 3.281×10^{-2} = feet
centimeters x 3.937×10^{-1} = inches
centimeters/sec x 1.969 = feet/minute
centimeters/sec x 8.64×10^{-2} = meters/day
centimeters/sec x 2.835×10^{-3} = feet/day
hectares x 1.016×10^{-1} = acres
kilometers x 6.214×10^{-1} = miles
liters x 2.642×10^{-1} = gallons
meters x 3.281 = feet
milligrams/liter ~ parts per million

LIST OF ACRONYMS

AH = auger holes
AMD = acid mine drainage
Br^- = bromide
Cl^- = chloride
cm/s = centimeters per second
D = deep well
dh = change in head
dh/dl = hydraulic gradient
dl = change in length
EPA = Environmental Protection Agency
ft = feet
g/cc = grams per cubic centimeter
gal = gallons
gpm = gallons per minute
> = greater than
hrs = hours
in = inches
K = hydraulic conductivity
km = kilometers
< = less than
l = liters
m/m = meters per meter
MDI = MSI Detoxification Incorporated
mg/l = milligrams per liter
mi = miles
n_e = average effective porosity
NO^{3-} = nitrate
ppb = parts per billion
ppm = parts per million
S = shallow well
V = velocity

ABSTRACT

Sodium bromide was used in a natural gradient tracer test to determine acid mine drainage (AMD) flow velocity through a sedge peat fen in west-central Montana. A grid of auger holes and small diameter wells was installed at varying depths. Water samples taken from this grid network were analyzed in the field using a bromide specific ion electrode. Field hydraulic conductivity (K) was determined on auger holes and wells in the area of expected metal loading and tracer movement. The K ranged from 1.0×10^{-2} to 1.5×10^{-5} cm/s with a mean of 8.3×10^{-4} cm/s. Mean velocity determined from the K values was 7.1×10^{-5} cm/s. Water flow velocity considered the most representative of the AMD waters was then determined by the tracer experiment and ranged from 3.1×10^{-1} to 6.2×10^{-4} cm/s with a mean of 2.6×10^{-2} cm/s (73.7 ft/day). The wide range of velocities indicate a very heterogeneous wetland flow system. The large difference (three order of magnitude) between K determined velocity and tracer determined velocity indicates the measurement of two different flow systems. The tracer velocity represents preferential flow paths within the shallow (acrotelm) system and the K determined velocity represents that flow found at greater depth (catotelm). The distance the AMD water travels, before problem amelioration, was not determined from the tracer methods employed, but using a distance estimate of 200 m and the average tracer velocity, the average residence time of AMD water in contact with the wetland soils is approximately 9 days.

INTRODUCTION

Acid mine drainage (AMD) is a common problem which occurs when mining exposes sulfide ore to an oxidizing environment (Caruccio and Geidel 1978). Many water treatment and abatement techniques exist today to reduce the harmful effects of AMD (Subramonian and Sorg 1986). While traditional technology is effective in controlling AMD this technology is also expensive and labor intensive. Wetlands provide an economic alternative to conventional municipal wastewater treatment plants (Stanley 1987) and recent investigations (Kleinmann 1985, and Wieder and Lang 1984) show that wetlands can effectively reduce sulfate and heavy metal ion concentrations from AMD. The mechanisms by which wetlands reduce pollutants are not well understood but generally are agreed to include physical, chemical, and biological means. These mechanisms may include sedimentation, filtration, adsorption, precipitation, ion exchange, chelation, sulfate reduction, decomposition, microbial oxidation, plant metabolism and adsorption (Girts and Kleinmann 1986, and Brodie et al. 1986).

Wetlands are those areas of land where water is so abundant that it is the major factor which dictates the

nature of plant growth on the site. Natural wetlands commonly include bogs, marshes, swamps, fens, and wet meadows. The mining related industry is currently exploring optimum wetland design characteristics for amelioration of AMD problems. An understanding of wetland hydrologic characteristics is important in determining optimum water treatment design. More specifically, quantitative estimates of water flow rates and hydrologic residence times within wetlands are needed (Wieder et al. 1984). Tracer studies are one method of determining these hydrologic characteristics which has been recommended (Reed et al. 1980).

The purpose of this study is to determine if residence time of mine contaminated water in a natural wetland can be determined using a bromide tracer. This study involves the hydrologic aspects of a larger investigation (Reclamation Research Unit and MDI 1988) to determine the effects of AMD on a natural wetland near Lincoln, Montana. The wetland is being studied to facilitate the design of man-made wetlands to reduce acid mine drainage problems. The specific objectives of this study are as follows:

1) Investigate the ability of bromide as a tracer in the wetland.

2) Identify water flow velocity in the wetland.

3) Relate water flow velocity to wetland physical properties (hydraulic conductivity).

4) Determine residence time in the wetland area affected by AMD.

LITERATURE REVIEW

Hydraulic Principles of Tracer Use

In hydrology, a tracer is matter or energy carried by water which will give information concerning the direction and/or velocity of the water. When sufficient data are collected, tracers can assist with the determination of hydraulic conductivity, porosity, dispersivity and other hydrogeologic parameters (Davis et al. 1980). Introducing a tracer at one point in the flow field and observing its arrival at other points, is the most direct method of determining groundwater velocity (Freeze and Cherry, 1979).

One factor which controls velocity is hydraulic conductivity which represents the ease with which water moves through the soil or aquifer. Hydraulic conductivity, K, is often used to characterize an aquifer because it includes the properties of the fluid and the field of gravity as well as the properties of the porous medium such as permeability. Hydraulic conductivity has the dimensions of length/time (L/T) or velocity (Fetter 1980). Hydraulic conductivity, porosity and permeability values can vary widely in space and time. The relationship between velocity

and hydraulic conductivity is developed from Darcy's Law and is shown in the following equation:

$$V = (-K/n_e)(dh/dl) \qquad \text{(Eq. 1)}$$

Where:
V = average linear velocity
K = hydraulic conductivity
n_e = average effective porosity
dh/dl = average hydraulic gradient
dh = change in head
dl = change in length

Interpretation of ground water velocity from the results of tracer tests involves plotting the concentration of a tracer as a function of time or volume of water passing through the aquifer. In the resulting "breakthrough" curve the concentration is commonly given as a ratio of the measured concentration at the observation well, "C," to the initial tracer concentration injected, "Co." The average travel time of a non-reactive, "conservative," tracer can be determined from a breakthrough curve for transport from the injection point to the observation point. The first arrival time of a tracer as it moves through the system represents the maximum velocity of the groundwater. The peak concentration of the tracer represents the average transit time of groundwater through the system, if a conservative tracer is used. Retardation of the transit time of a tracer is related to the spread of the breakthrough curve. Figure 1 gives hypothetical examples of breakthrough curves for a mixture of tracers injected as a single slug into an

aquifer. Notice the change in the curve shape if the tracer is not conservative and interacts with the aquifer system.

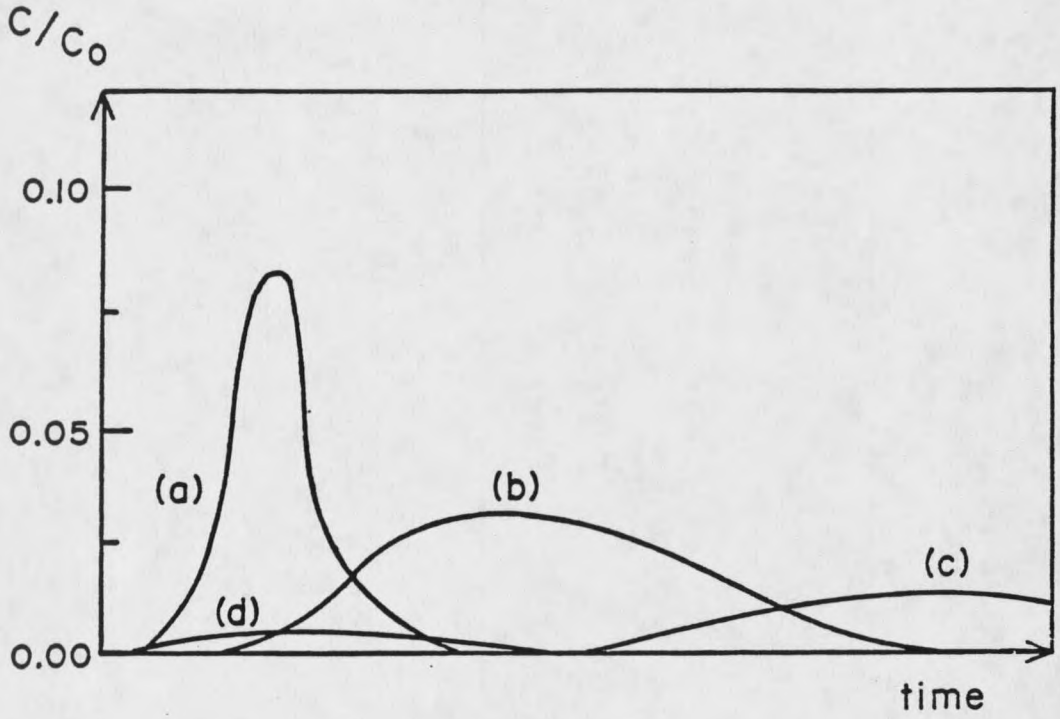

Figure 1. Breakthrough curves of four different tracer types: (a) is conservative, (b) some effect of sorption, (c) large effect of sorption, and (d) precipitated or destroyed (From Davis et al. 1985).

Tracer Flow Retardation and Tracer Dilution

Tracers are not perfectly conservative, the concentration distribution of a water soluble substance which is transported in a porous medium by groundwater is affected by sorption, molecular diffusion and hydrodynamic dispersion (Gustafsson and Klockars 1981). Sorption includes adsorption and absorption processes. The many chemical

processes which contribute to sorption result in retardation of tracer movement. Thus, velocity of the tracer is slower than that of the groundwater. Therefore to design a meaningful tracer experiment, the sorptive characteristics of the tracer must be known (Davis et al. 1985). Davis et al. (1985) and Gustafsson and Klockars (1981) provide equations to describe the effect of tracer sorption in relation to groundwater flow.

Hydrodynamic dispersion and molecular diffusion have the effect of diluting the concentrations of artificially induced tracers. Hydrodynamic dispersion generally affects short term tracer tests and molecular diffusion affects the concentration of slow moving tracers in heterogeneous materials (Davis et al. 1985). Freeze and Cherry (1979) also state that molecular diffusion is important only at low flow velocities. Figure 2 depicts movement by molecular diffusion in a dye and blotter experiment. Note that no water movement is required for the dye to spread out in a direction tending to equalize concentrations in the blotter.

Hydrodynamic dispersion is the spreading which occurs both perpendicular to and in the direction of groundwater flow, of a water-soluble substance that is transported with the groundwater. Some of the dissolved substances will be transported more slowly and some may be faster than the average groundwater velocity. Hydrodynamic dispersion is dependent on the velocity distribution in the medium and on

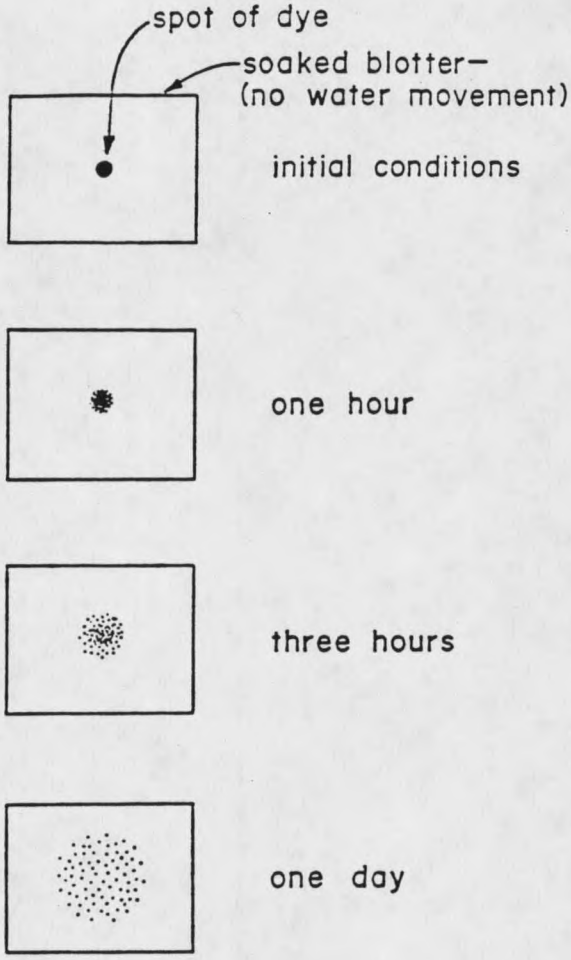

Figure 2. One dimensional example of movement by molecular diffusion (from Davis et al. 1985).

molecular diffusion. Bear (1972) gives a quite detailed evaluation of hydrodynamic dispersion. Dispersion of a solute requires groundwater flow in a medium with a system of pores or channels. An example of hydrodynamic dispersion which is caused by unequal velocities of the ground water is shown in Figure 3. Tracer particles released at the same time and carried by the groundwater have different flow

paths. This results in a more widespread distribution of tracer particles with time, a concentration decrease or "dilution." Not only tracer dilution and tracer flow retardation affect the shape of the tracer breakthrough curve, so does the tracer method employed.

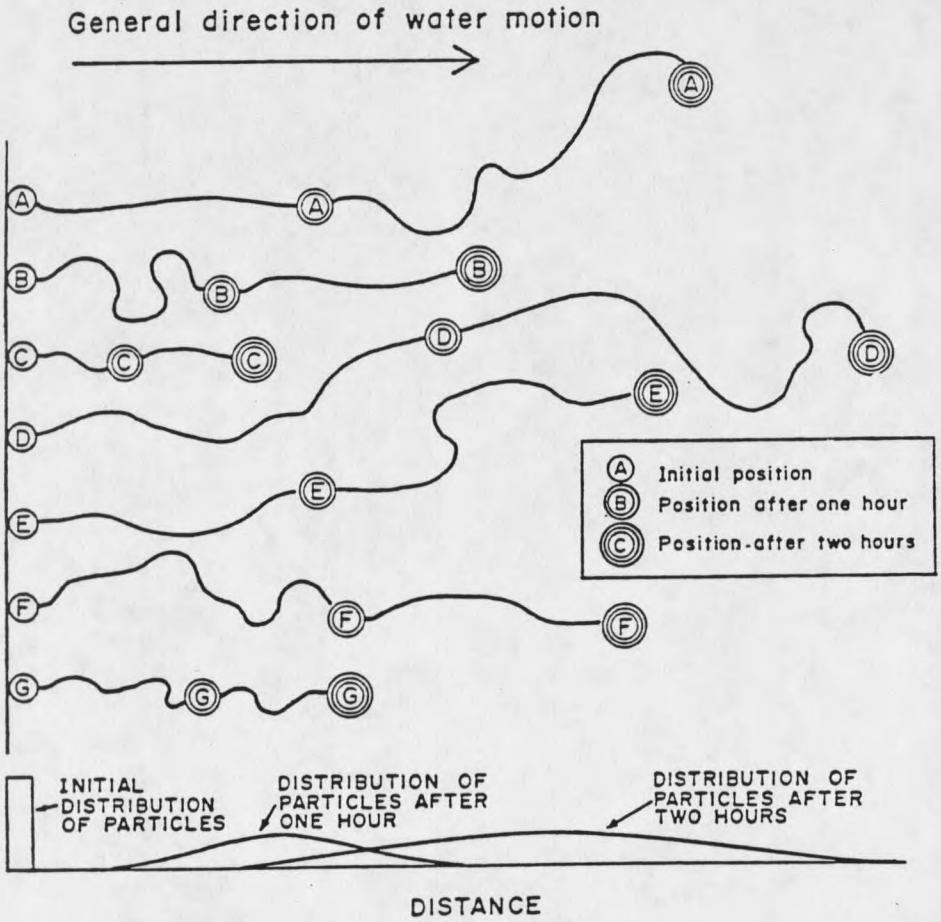

Figure 3. One dimensional example of hydrodynamic dispersion for tracer particles A - G (from Davis et al. 1985).

Tracer Methods

The initial step in conducting a tracer study is to collect as much hydrologic information as possible about the study site (Davis et al. 1985). This information should include homogeneity of the aquifer, layers present, fracture patterns, porosity, flow system boundaries, hydraulic gradient and hydraulic conductivity (Davis et al. 1985). This hydrologic information is used to assess the ground-water flow direction and velocity. Direction and velocity are usually estimated by the use of Darcy's law or running a preliminary tracer test (Davis et al. 1985). The second step is to determine the best tracer to use for the conditions and objectives at the site. The third step in conducting a tracer study is to determine the correct amount of tracer to be used. This amount is based on the dilution expected, the natural background concentration and the detection limit possible for the tracer. The next step is to determine the correct tracer method.

One possible method involves the use of an environmental tracer which is a substance that exists in the soil before the investigation begins. This tracer can be artificial (man induced), semi-artificial (tritium) or natural (natural radioisotope). A good environmental tracer must be free from chemical reactions, such as ion exchange and precipitation and must not react with the

medium (Fried 1975). Initial and boundary conditions must be known, chiefly by knowing the amount of tracer introduced and its history. The wetland system under investigation has the characteristic of a high organic matter content (large exchange capacity). Trace metal environmental tracers such as those found at the study site, commonly react with the organic material, making this environmental tracer method unacceptable.

Freeze and Cherry (1979) describe four main types of field dispersivity (tracer) tests. These are (1) single-well withdrawal-injection tests, (2) natural-gradient tracer tests, (3) two-well recirculating withdrawal-injection tests and (4) two-well pulse tests. In a natural-gradient tracer test, as employed in this study, the direction and velocity of the groundwater flow are very important (Davis et al. 1985). In the natural-gradient test, the tracer is introduced into the system and its migration is then monitored at one or more sampling points. Dispersivity values are obtained by fitting an analytical or numerical model to the experimental data. Davis et al. (1985) notes that:

> It is not at all uncommon to inject a tracer in a well and not be able to intercept that tracer in a well just a few meters away, particularly if the tracer flows under the natural hydraulic gradient which is not disturbed by pumping.

Part of the tracer method involves the type of injection technique. A tracer may be injected as a slug or

as a continuous source input. Mixing of the tracer during injection is important in most types of tests and can be as simple as pouring it in the water to be studied (Davis et al. 1985). For shallow wells a plunger can be surged up and down in the hole or the tracer can be released through a pipe with many perforations. The ideal condition is to inject the tracer into the water instantaneously as a slug.

Another part of the tracer method involves tracer analytical technique. Taking field measurements of electrical conductance within, ahead of, and behind a tracer slug can minimize the number of field samples kept for laboratory analysis (Lee et al. 1980). Electrical conductance is the simplest and most inexpensive detection and analysis technique for ionic tracers and can be used as a break-through indicator (Slichter 1902). In the wetland system being studied, the naturally high ionic content may make electrical conductance data difficult to interpret.

Tracer Problems

Many water tracing experiments are unsuccessful. Aley and Fletcher (1978) have found that the major causes of failure are: (a) insufficient hydrological field work before the tracer is injected, (b) tracing attempts during low flow conditions, and (c) failure to allocate sufficient time for tracing effort. Davis et al. (1980) found that tracer test failures are most commonly a result of incorrect choice of

tracers, insufficient concentrations of tracers and a lack of understanding of the hydrogeologic system being tested. For a given head drop, expected travel time is a function of the distance squared, and therefore increases very rapidly with the distance. Davis et al. (1985) note that this relationship causes one of the most common errors in tracer tests, which is to conduct tests between points which are separated by too great a distance. Freeze and Cherry (1979) describe four main disadvantages to the determination of groundwater velocity by the direct tracer method:

(1) because groundwater velocities are rarely large under natural conditions, undesirably long periods of time are normally required for tracers to move significant distances through the flow system;

(2) because geological materials are typically quite heterogeneous, numerous observation points (piezometers, wells, or other sampling devices) are usually required to adequately monitor the passage of the tracer through the portion of the flow field under investigation.

(3) because of (1), only a small and possibly nonrepresentative sample of the flow field is tested; and

(4) because of (2), the flow field may be significantly distorted by the measuring devices.

Another problem which needs to be addressed is how much tracer to add to the flow system. The concentration of ion to be injected should be well above the natural background concentration level found at the study site and high enough to ensure detectable levels in the observation wells (Davis

et al. 1985). The ion concentration to be injected must also be kept low enough so that density effects do not effect movement of the tracer. An insufficient quantity of tracer will result in an unsuccessful trace, because of non-detection: too much tracer wastes materials and can degrade water quality. Dilutions of a tracer in transit from injection to sampling wells are almost always at least tenfold for "slug" injections and dilutions of ten thousand-fold are common (Davis et al. 1980).

Lenda and Zuber (1970) describe a method to estimate the adequate amount of tracer and carrier to be injected. The effects of adsorption and the uncertainty from whether the observation well is exactly at the center of the tracer path should be accounted for by the use of a safety factor on the order of 10 (10 times the proposed injection amount). Skibitzke and Robinson (1963) used tracers to show that solid particles (sand grains) retard diffusion in a porous medium. Biggar and Nielsen (1962) concluded that the mere presence of a tracer downstream from the point of injection is a poor indicator of the velocity of the fluid. Pore geometry, water content changes and the magnitude of the interaction between the tracer and the porous medium are important in determining an accurate estimate of the fluid velocity.

Bromide as a Tracer

There is no such thing as the perfect tracer but Davis et al. (1980) note that the ideal ground-water tracer is nontoxic, inexpensive, moves with the water, is easy to detect in trace amounts, does not alter the natural direction of the flow of water, is chemically stable for a desired length of time, is not present in large amounts in the water being studied and is neither filtered nor sorbed by the solid medium through which the water moves. Tracer selection should be based on purpose of the study, type of aquifer system, aquifer characteristics, natural background concentration of the tracer in the groundwater, and analytical techniques available (Davis et al. 1985). Different types of tracers include: water temperature, solid particles, ionized substances (bromide), stable isotopes, radioactive tracers, organic dyes, gases, and fluorocarbons. Davis et al. (1980) report that some of the most useful general tracers are bromide, chloride, rhodamine WT, and various fluorocarbons. Most tracers have relatively limited or specialized uses. In most cases anions are not affected by the aquifer medium (Davis et al 1985), but the characteristics of some aquifers will cause retention or exclusion of anions moving through the system.

Anionic tracers such as bromide (Br^-) and chloride (Cl^-) are particularly useful because of their low

susceptibility to adsorption or ion exchange processes of natural aquifer materials (Davis et al. 1980). Bromide does not appear to be lost by precipitation, adsorption or absorption and is biologically stable (Schmotzer et al. 1973) and therefore can be considered a conservative tracer. Bromide offers one of the best possibilities as a general tracer for groundwater studies (Davis et al. 1980) and is considered a conservative tracer which may be effectively used in wetland systems (Bowmer 1987). Most bromide compounds also have relatively low toxicities. Davis et al. (1980) note that bromide samples, being nonvolatile can be stored indefinitely without concern for tracer loss to the atmosphere and sampling can be done using inexpensive air-lift pumps. Bromide as a tracer is commonly injected as NaBr, $CaBr_2$ or KBr. Davis et al. (1985) relate that bromide is perhaps the most frequently used ion tracer. These authors list advantageous characteristics of the tracer bromide as being inexpensive, stable, low limit of detection, low background concentrations, low toxicity and "no sorption". The concentration of bromide in natural ground waters is roughly 1/300 that of chloride and usually <1 mg/l (Davis et al. 1980; Vinogradov 1959). Detection of bromide is relatively simple with a specific ion electrode which has a lower limit of detection of about 0.4 mg/l. If natural water has 30 mg/l of chloride (suggesting the natural presence of 0.1 mg/l of bromide) and if the bromide

tracer is introduced with a concentration of 1000 mg/l, then a dilution factor of 10^4 is possible before it is masked by the natural background concentration (Davis et al. 1980). Concentrations of chloride in the introduced tracer should not exceed about 3000 mg/l because of increased density of the solution (Davis et al. 1980). Since the halides bromide and chloride behave similarly (Bohn et al. 1985) it is thought that bromide should not exceed the 3000 mg/l concentration.

Vinogradov (1959) found that bromide correlated well with iodine content and both bromide and iodine content were proportional to the amount of organic material in the soils studied. The concentration of bromide is greater in humic soils and there is practically no dependence of chlorine content on soil organic matter content. The studies by Vinogradov (1959) suggest that bromide is sorbed by peat and that the amount sorbed decreases somewhat with aging of the peat. Vinogradov (1959) found that as soil organic carbon content increased bromide and iodine content increases, whereas chloride content has no effect on organic carbon content.

Davis et al. (1985) stated that an advantage of anions used as tracers, such as bromide, is they do not decompose and are not lost from the system. This statement is generally true but under certain circumstances anions such as bromide may be affected by anion exclusion and/or anion

exchange. As anions move through soil they do not come in contact with all of the soil water. This is termed anion exclusion and occurs in response to the fluid flow rate and the fact that water near negatively charged soil surfaces is relatively immobile. The result of this exclusion is that anions can move through the soil faster than one would predict on the basis of uniform association with all the soil water (Smith and Davis 1974). The association between anion exclusion and cation exchange capacity is strong. Anion exclusion is a manifestation of the unequal ion distribution in the diffuse double layer surrounding charged colloid surfaces (Bohn et al. 1985). Factors affecting anion repulsion (exclusion) include: 1) anion charge and concentration, 2) species of exchangeable cation, 3) pH, 4) presence of other anions, and 5) nature and charge of the colloid surface (Bohn et al. 1985). Thomas and Swoboda (1970) suggested that in soils with high cation exchange capacities anion exclusion causes anions to move much faster than they would if no interaction with clays were to occur. This suggestion agrees with the theory that anion exclusion is a function of negative charge.

Grim (1968) mentioned two types of anion exchange in clay minerals. One is the replacement of hydroxide (OH) ions and the other factor is related to geometry of the anion. The geometry of the bromide anion does not fit that of silica tetrahedral sheets, thus it cannot be so absorbed.

Anion exchange would take place around the edges of the clay minerals, not on the basal plane surface. A factor which complicates anion exchange studies is that any free or exchangeable iron, aluminum or alkaline earth elements present in the clay may form insoluble salts with the anions (Grim 1968). Mattson (1929) has shown that the adsorption of anions was found to be negative in neutral and alkaline solutions and that as pH decreases the capacity of clay minerals for holding anions increases. The interaction of cations with clays is much more frequent than interaction of anions with clays. Berg and Thomas (1959) found that sulfate and chloride anions are adsorbed in soils high in kaolin clays and aluminum and iron oxides. Chloride will desorb readily at pH values found in most field conditions, but at low pH values chloride ions are not easily desorbed. They also found that sulfate is held much more tightly to these soil types than is chloride. Tennyson and Settergren (1980) found indication of bromide retention occurring because bromide concentrations above background levels were present in the soils studied three weeks after application of the tracer.

The study site is in the headwaters area of the Blackfoot River and bromide toxicity was a concern. Alexander et al. (1981) studied the effect of sodium bromide (NaBr) on Fathead minnows. Sodium bromide has a low toxicity to fathead minnows with the average 96 hour LC_{50}

(lethal concentration for 50% of the test population) being 16,479 mg/l. Tests by Barnes et al. (1981) show that the mean number of organisms (thirty-five species of algae and zooplankton were studied) increased with time due to the addition of 1000 ppb potassium bromide and nutrients to the system. Species diversity decreased slightly in this situation. Schmotzer et al. (1973) reported that bromide has a very low toxicity in humans at 50 to 100 mg of Br^-/100 ml of blood. To be toxic a human would have to drink 12 liters of 200 mg/l bromide. The LD_{50} (lethal dose) of bromide orally in rats is 3.5 g/kg (Merck Index 1983).

Martin et al. (1956) concluded that plant tolerance to bromide is quite variable. Carrot tops contained 2.5% (25,000 ppm) bromide with no reduction in growth but citrus trees containing 0.2% (2000 ppm) demonstrated reduced plant growth.

The desirable characteristics of using bromide as a soil water tracer were demonstrated by Onken et al. (1977) to be easy detection, unlikely contamination of the environment and lack of reaction with soil and soil constituents. Schmotzer et al. (1973) conducted a fairly extensive study of using bromide as a groundwater tracer and found bromide to successfully fulfill the requirements devised by Schmotzer to be as close as possible to being the ideal tracer. The favorable characteristics of bromide include low toxicity, high sensitivity of detection, little

loss through precipitation, little adsorption and absorption, high stability, low background concentrations, small sample size requirements (post sampling activation analysis), low cost, government approval is relatively easily available and bromide is biologically stable.

Smith and Davis (1974) found that bromide is a good tracer for mimicking the movement of nitrate (NO^{3-}) through subsoils. Merrill et al. (1985) used bromide as potassium bromide (KBr) to trace nitrate-nitrogen movement and indicate water flux in a study to develop an understanding of plant growth response to soil thickness over sodic minespoils. Onken et al. (1977) used sodium bromide (NaBr) and sodium nitrate ($NaNO^3$) to show that nitrate and bromide move together in the soil profile. They note that both nitrate and bromide are readily absorbed by plants but the rates of removal from soil are different.

Tennyson and Settergren (1980) used a sodium bromide tracer to evaluate percolating water and ion movement in an irrigation saturated surface soil. Background levels of bromide in soil water, groundwater, and precipitation were measured and bromide movement was quantified by soil water sampling and post-sampling neutron activation analysis. They suggested that laboratory measured hydraulic conductivity was not adequate in evaluation of the site because the bromide tracer moved through the soil much more rapidly than the hydraulic conductivity suggested. Tennyson and

Settergren (1980) found peak concentrations of the bromide tracer moved through 0.9 m of these soils within 3.75 hours after field application, therefore tracer studies do help to better define rates of water movement in natural systems.

Wetland Classification and Origin

This study used tracers in a wetland environment. There are many ways to classify wetlands. Classification criteria "may be the present surface flora (e.g., mangrove, sawgrass); chief botanical origin (e.g., sphagnum, sedges); nature of the water, its mineral and flow properties (e.g., high moor, low moor, salt marsh, bog, fen, mire); degree of decomposition (e.g., sapric, hemic, fibric, peat, muck); or intended use (e.g., horticultural, industrial, fuel) (Mathur and Farnham 1985)." Typically classification schemes for wetlands rely on hydrologic processes and vegetation type. An example of a fen is a wetland which receives moisture both from precipitation and from slow-moving streams and groundwater. Fen vegetation is dominated by mosses, shrubs and sedges (Thurman 1985). The U.S. Department of Agriculture (Soil Survey Staff 1975) classifies wetland organic soils (peat) primarily on degree of decomposition. Soil scientists call these organic soils Histosols, one of the 10 soil orders. Organic wetlands are also sometimes called peatlands.

World peatlands are estimated to cover about 500 million hectares and 90% of the peatlands occur in glaciated areas of the northern hemisphere (Mathur and Farnham 1985). Erosion and sediment deposition resulting from glacial action are largely responsible for the development of wetland areas. Lesica (1986) noted that "West of the Continental Divide in Montana, small mires (wetlands) are common in forested areas at low to mid-elevations where climate is relatively moist and there has been a history of glaciation." Reichmuth (1986) described additional processes which can form wetlands:

1) natural fluvial processes (oxbows, braided streams)
2) geologic accidents (landslide dams, tectonic uplift)
3) constructed landscapes (glacial activity, beaver activity)
4) climatic change (lake drying).

Wetland Hydrology

Wetland hydrologic systems can be considered quite heterogeneous (Figure 4). Not only are there seven orders of magnitude for hydraulic conductivity variation reported in the literature shown but there is often quite a large range of conductivity within a study site. Freeze and Cherry (1979) and Davis et al. (1985) noted that a problem which arises in determining the direction of water movement and travel time is that local differences in hydraulic

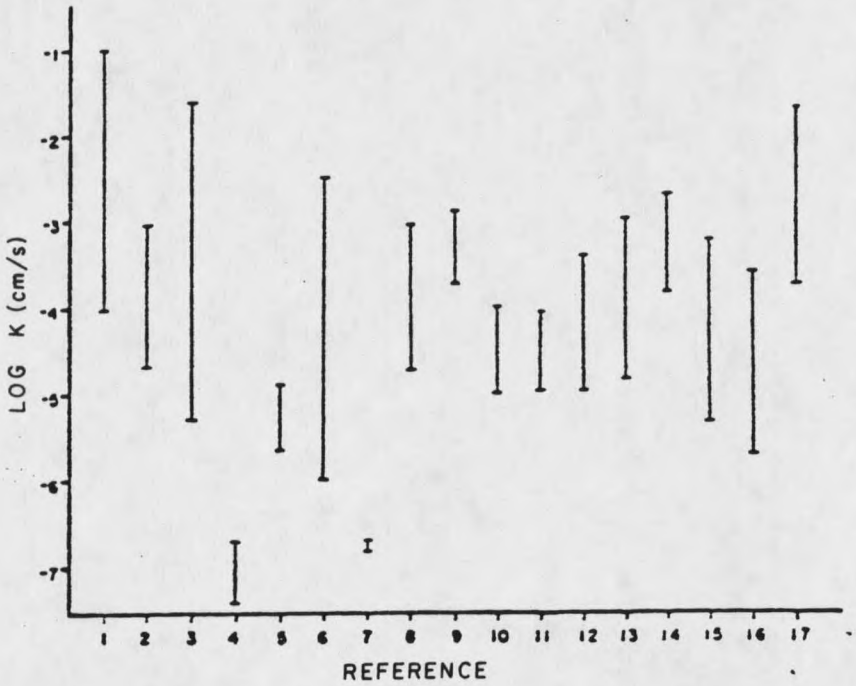

Figure 4. Ranges of published field data on K (hydraulic conductivity) of peat: 1. Baden and Eggelsman (1961, 1963, 1964); 2. Eggelsman and Makela (1964); 3. Boelter (1965); 4. Ingram (1967); 5. Galvin and Hanranahan (1968); 6. Romanov (1968); 7. Sturges (1968); 8. Dowling (1969); 9. Irwin (1970); 10. Yamamoto (1970); 11. Knight et al. (1974); 14. Paivanen (1973); 15. Galvin (1976); 16. Dasberg and Neuman (1977); 17. Chason and Siegel (1986). Adapted from Chason and Siegel (1986).

conductivity may amount to several orders of magnitude. Wetland Hydrologic characteristics have been investigated by a number of authors. Hydrogeologic factors (Winter and Carr 1980) that affect wetland ground water flow include:

1) geometry of the geologic framework through which ground water flows, including flow boundaries;

2) hydraulic conductivity of the geologic materials, including anisotropy -- the ratio of vertical to horizontal hydraulic conductivity;

3) recharge and discharge of the ground water system.

In particular, Winter and Carr (1980) found three major interrelationships between wetlands and ground water:

1) some wetlands appear to recharge ground water;

2) some wetlands are flow-through types where ground water enters one side and surface water seeps into the ground on the other side;

3) some wetlands are discharge areas for ground water.

These interrelationships are further complicated by changing throughout the year.

One of the more important physical properties that affect the hydrologic features of bog areas is the hydrologic conductivity of the peat soil horizons (Boelter 1965). Dai and Sparling (1973) suggested using the piezometer method to determine the velocity of flow from the hydraulic conductivity. Ingram et al. (1974) used field experiments to find that estimates of hydraulic conductivity in humified peat increased with head, which is not in accordance with Darcy's law. Boelter (1965) used field measurements of hydraulic conductivity (K) and found they covered a wide range of values. Chason and Siegel (1986) found that horizontal K was significantly greater than vertical K.

Sturges (1968) studied the hydrologic properties of a

mountain bog in Wyoming. Undecomposed surface peat had the lowest bulk density, 0.160 g/cc, and much of its volume consisted of large voids which emptied at low suctions of less than 0.10 bar. Greater suctions were required to drain the smaller pores of the higher bulk density, decomposed material found at depth. In this bog, surface peat hydraulic conductivity would be higher than that found at depth.

In 1969 Boelter found that the classification of peat materials based on degree of decomposition as measured by fiber content (>0.1 mm) and bulk density can relate significant information about the hydraulic conductivity, water retention, and water yield coefficient. Regression equations were employed to determine a range in hydraulic conductivity and other physical properties for fibric, hemic and sapric peat materials (Table 1). Chason and Siegel (1986) studied a Minnesota wetland complex and found that hydraulic conductivity, bulk density and humicity all vary widely through the peat profile and in most cases were not mutually dependent. There are two major hydrologic zones within a peat soil column (Ingram 1983):

1) the acrotelm, a thin upper aerated zone of fluctuating water conditions composed of undecomposed dead and live vegetation,

2) The catotelm, an underlying anaerobic zone in a constant waterlogged state composed of more humified peat.

Chason and Siegel (1986) found acrotelm thicknesses between 25 to 50 cm.

Table 1. Range of important physical characteristics of fibric, hemic, and sapric peat materials from northern Minnesota bogs (From Boelter 1969).

Organic material	Bulk density g/cc	Total porosity %	0.1 bar H_2O content %	Hydraulic conductivity 10^{-5} cm/sec
Fibric	<.075	>90	<48	>180
Hemic	.075-.195	85-90	48-70	2.1-180
Sapric	>.195	<85	>70	<2.1

The results of field and laboratory studies indicate that the properties of peat change drastically when it becomes partially desaturated (Dasberg and Neuman 1977). Two layers result from this change, a permanently saturated layer below the zone of water table fluctuation, and an overlying partially unsaturated layer with properties that vary with depth. The saturated peat layer studied had a high porosity (90%); organic matter content (60% by weight); specific yield (20 to 30%); and specific storage is very high (0.7×10^{-3}, to 1.7×10^{-3}). The unsaturated peat layer was found to have a high bulk density, up to 0.8 g/cc near the surface. The hydraulic conductivity of the unsaturated layer is generally higher than 1.0 mm/h (3.0×10^{-5} cm/s), but much more variable than the saturated peat layer. In summer the unsaturated surface layer can develop shallow cracks which may increase the hydraulic conductivity by several orders of magnitude.

Ingram (1967) described a "water track" as a mire surface feature having a higher rate of water movement due to more steeply inclined water tables and/or peat with higher hydraulic conductivity. These water tracks are associated with the presence of more eutrophic plant communities and are sites of greater ion supply. Some authors (Dasberg and Neuman 1977; Ingram 1967; Sturges 1968) noted erosion channels or fractures at depths within wetland systems. Erosion channels occur both on the surface and at depth in peat deposits with the associated vegetation often being unlike the surrounding vegetation. Subterranean erosion tunnels are frequently encountered in blanket bogs but little is known of these concealed free drainage systems (Ingram 1967). Wetland hydraulic conductivity measured in situ by the piezometer method (Sturges 1968) at depths of 46 and 91 cm was 23.9×10^{-3} and 16.1×10^{-3} cm/day respectively. Two of five piezometers at the 91 cm depth showed much higher hydraulic conductivity (greater than 10^{-2} cm/day), indicating the piezometers terminated in or near a fissure. The fissures running through the deeper peat are filled with water under positive pressure and there are no surface physical features to indicate fissure location. Overall wetland hydrologic characteristics are found to be complicated by the fact that they vary greatly between wetlands, within wetlands and with time.

Wetland hydrologic characteristics can be determined with tracer experiments. Tracers are seldom applied to wetland hydrology, "primarily because of the difficulty in choosing an appropriate tracer and the disturbance of the experimental area which results from frequent sampling (Girts 1986)." Knight et al. (1971) successfully used a tritium tracer to reveal variable patterns of movement in a wetland under different drainage conditions. The flow rate variation was found to be attributed to factors within the peat rather than to analytical procedure. Girts (1986) successfully used bromide and chloride tracers to yield flow rates within the range of published values (see Figure 4).

Bowmer (1987) used bromide and dye tracers to study a man made wetland used to treat sewage. In this study theoretical retention time of effluent was predicted using the pore volume of the system. Preferential flow paths and "dead zones" were found using the tracers and a substantial proportion of the effluent was found to travel through the system faster than predicted by the theoretical retention time. The hydrology of this man made system was further complicated by occasionally high evapotranspiration rates and diurnal changes in water consumption.

MATERIALS AND RESEARCH METHODS

Site Location

The study area is approximately 28 km (15 mi) northeast of Lincoln, Montana, along Montana Highway 200 (Figure 5). More specifically the study area is in Section 20, T15N, R6W, Lewis and Clark County, Montana. The wetland covers approximately 0.65 km^2 (0.25 mi^2) adjacent to the Blackfoot River. Acid mine waters from the abandoned Carbonate Mine seep into Swamp Gulch which drains into a wetland (Swamp Gulch wetland) via a highway culvert.

Site Characteristics

The study site elevation is between 1579 to 1572 m (5180 to 5160 ft) and is in the headwaters area of the Blackfoot River. The site is approximately three miles southwest of the continental divide at Rogers Pass. The elevation at Rogers Pass is 1710 m (5609 ft). Average annual precipitation, mostly in the form of snow (Coffin and Wilke 1971) is 71 to 76 cm (28 to 30 in) (SCS 1980). Precipitation for the water year, October 1986 to September 1987, was 60.3% of normal at the nearby Lincoln

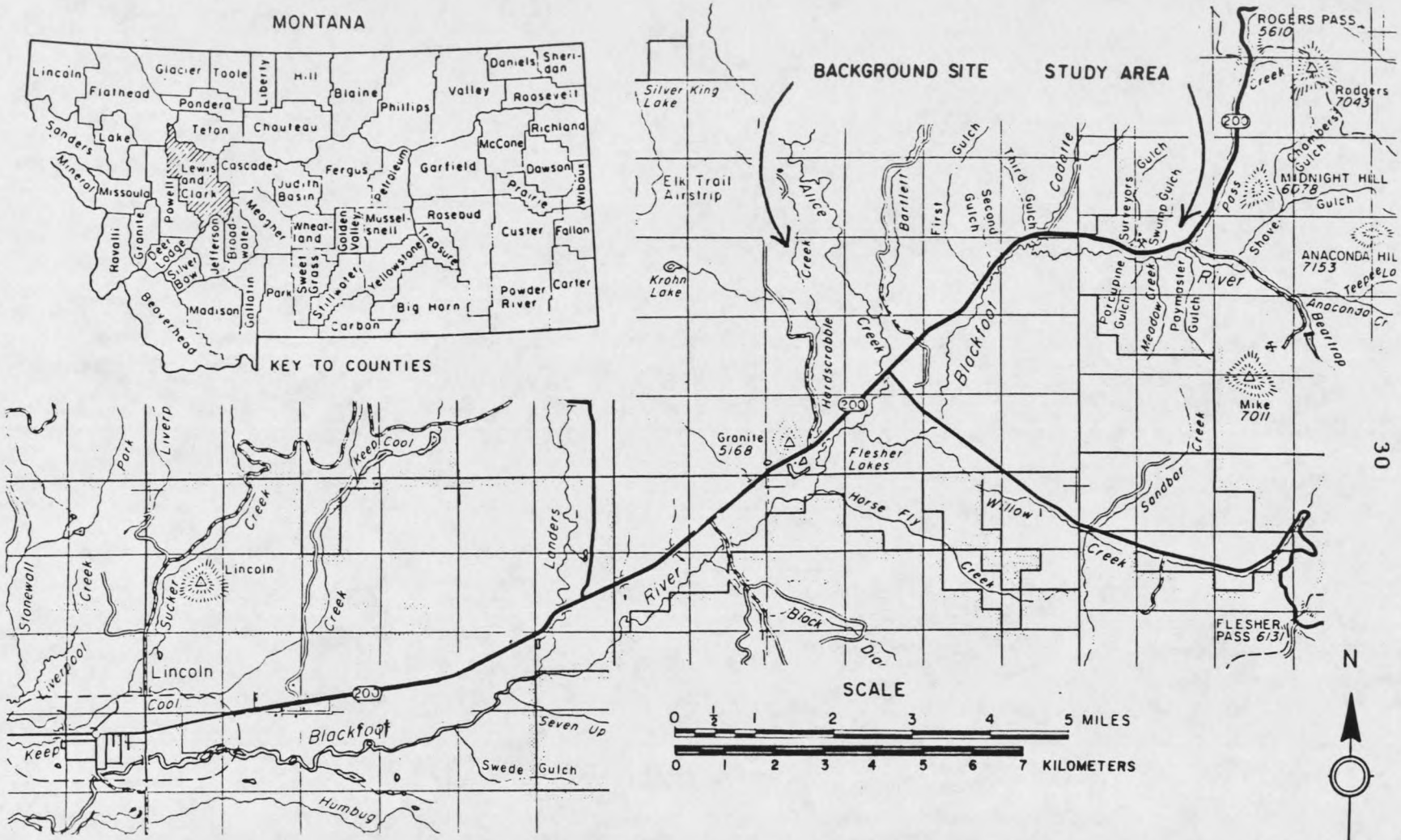

Figure 5. Area map of Swamp Gulch Wetland Study, Lewis and Clark County, Montana (From MT Dept. of Highways, 1975).

Ranger Station (NOAA 1987). Average winter temperature for the region is -5°C and mean summer temperature is 16°C.

Swamp Gulch and many other drainages of the region have been impacted by mining. The Carbonate Mine is within the Heddleston mining district. In 1933 the mine included an adit about 850 feet long and a shaft approximately 300 feet deep (Pardee and Schrader 1933). A 75 ton mill was erected in the summer of 1944 and reportedly 2500 tons of lead-zinc ore was removed in 1945 (Shea 1947).

The geology of the Carbonate Mine is similar to that of the Mike Horse Mine which is the largest mine in the district (Shea 1947). The mine workings are in a diorite sill that intruded argillite of the Spokane Formation in the Precambrian Belt Supergroup (McClernan 1983). The diorite sill and Belt rocks are further intruded by a decomposed rhyolite dike (Shea 1947). Pardee and Schrader (1933) describe the lode as consisting of a sheared and altered diorite partly replaced by sulphides. The mine lode contains abundant pyrite in several forms including fine grained, coarse grained and radial. Ore minerals are galena, sphalerite, silver and gold. Gangue minerals occur primarily as sericite, pyrite and quartz and also include "a carbonate containing calcium, iron and a little manganese" (Pardee and Schrader 1933).

Glaciation is the latest major landforming event in geologic history. The Rocky Mountains north of the Clark

Fork and the Blackfoot Rivers in Montana were heavily glaciated 15,000 to 130,000 years ago (Alden 1953). This glaciation has largely affected topography of the Blackfoot River valley. The wetland area being studied was most likely constructed by glaciers. Sediment deposited by a retreating valley glacier created a series of moraines and outwash plains in the Lincoln area. These moraines partially dam the river forming wetlands on the upstream sides (Alt and Hyndman 1986). A thin covering of glacial till over shallow bedrock and a narrowing canyon occur immediately downstream of the wetland being studied. This situation had a damming effect on the river, creating the wetland. Beaver activity has further modified the wetlands through creation of dams and ponds. The gravel deposits most often found at depth in the wetland are fluvial in origin resulting from glacial outwash and meandering of the river since glaciation.

The dominant wetland vegetation are sedges, mosses and shrubs. Water input is received from precipitation, slow-moving streams and ground water passing through the wetland. This description classifies the wetland as a fen (Thurman 1985). Using the US system (Soil Taxonomy 1975) surface wetland soils (approximately 0 to 0.9 m) are broadly classified as Fibric Histosols and more specifically as Hydric Borofibrists.

Site Instrumentation

Thirty-eight shallow small diameter wells (piezometers) were installed throughout the study area during the spring and summer of 1987. Twenty-eight of these wells are paired, with one well shallow and one deep, resulting in 24 well sites (Figure 6). These wells were positioned to facilitate water sampling and water level monitoring.

Well holes were constructed using 5.1 cm (2 in) diameter Giddings soil core barrels hand driven into the ground. A 7.6 cm (3 in) silage auger (Arts 1987) modified with a core cutter/holder was used to obtain soil samples in the 0 to 1.2 m (0 to 4 ft) depth at each well site. An additional 32 auger holes were excavated near the highway culvert outflow to a depth ranging between 0.5 and 0.9 m (1.6 and 3.0 ft). These additional auger holes were positioned (Figure 7) to facilitate tracer sampling.

The shallow wells are completed to a total depth between 1.2 to 1.5 m (4 to 5 ft) and deep wells to a total depth between 1.8 and 4.9 m (6 and 16 ft). Wells were constructed of 2.5 cm (1 in) diameter PVC pipe and Timco 0.025 cm (0.01 in) slotted (0.944 in^2/ft density), capped PVC screen. All wells were completed with a 20-30 grain (0.5 - 0.8 mm) sand pack and bentonite pellets. Surge blocking and overpumping were both used to develop the wells. Figure 8 depicts a typical paired well site construction.

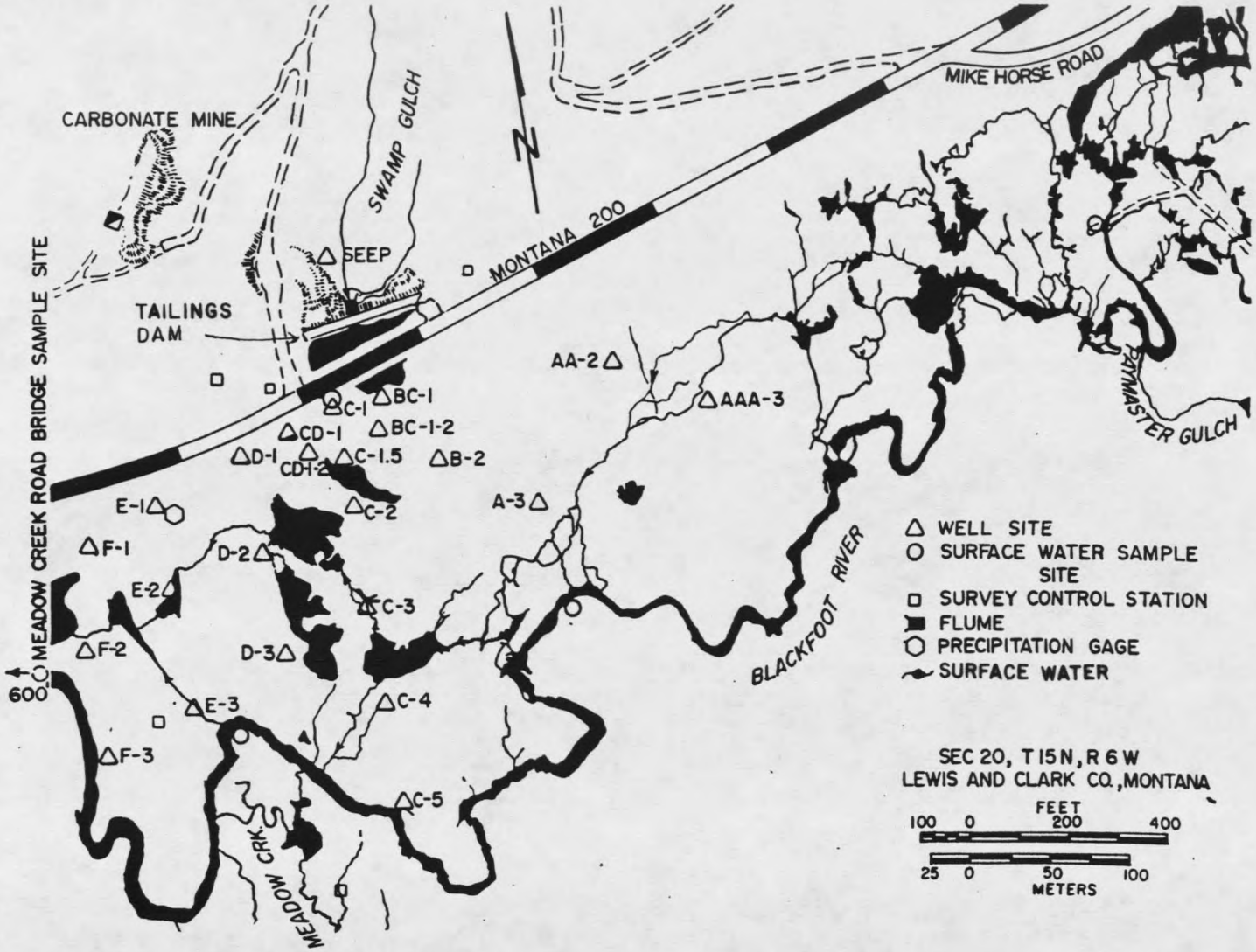

Figure 6. Swamp Gulch Wetland study area.

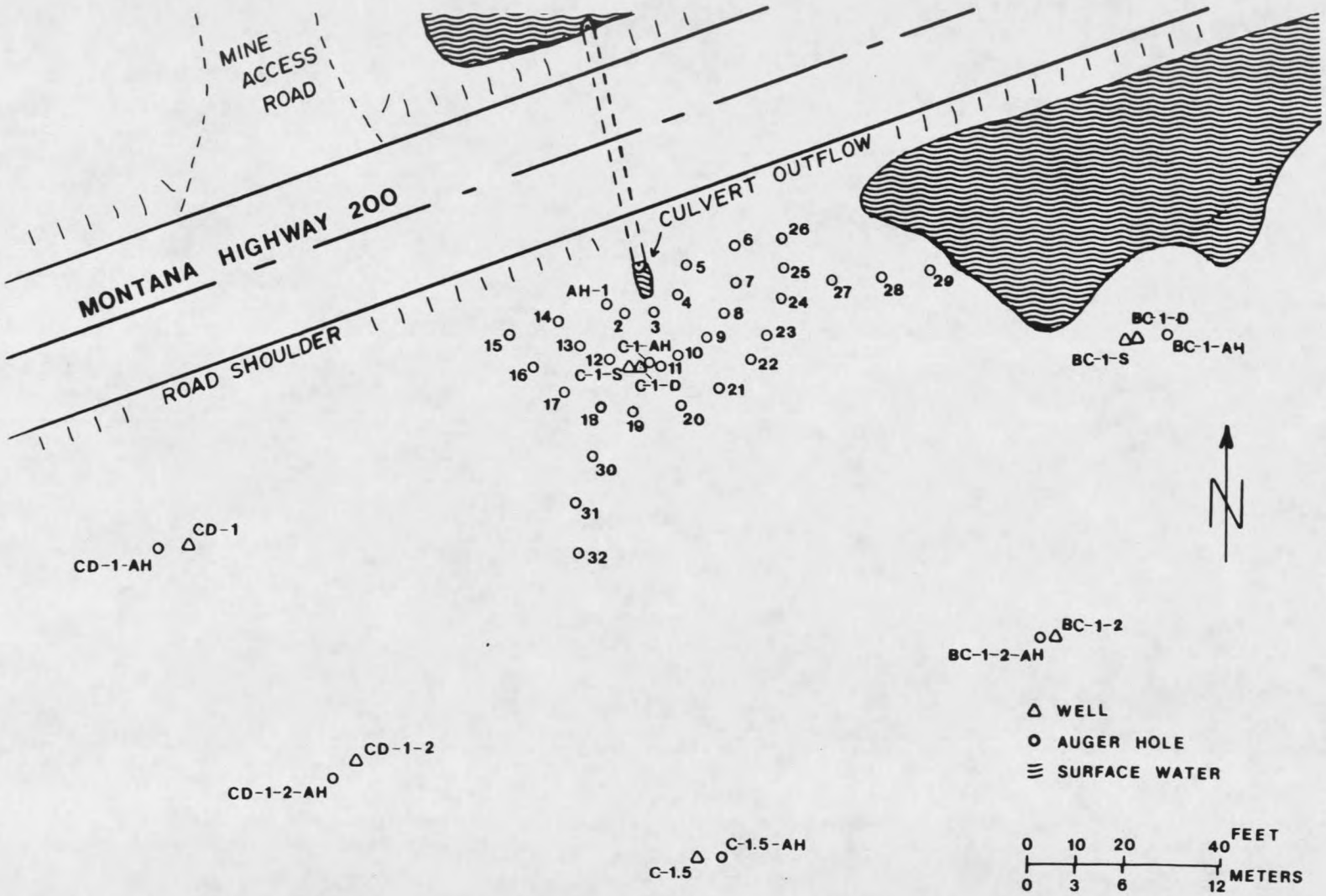

Figure 7. Detailed map of Figure 6 showing auger hole grid.

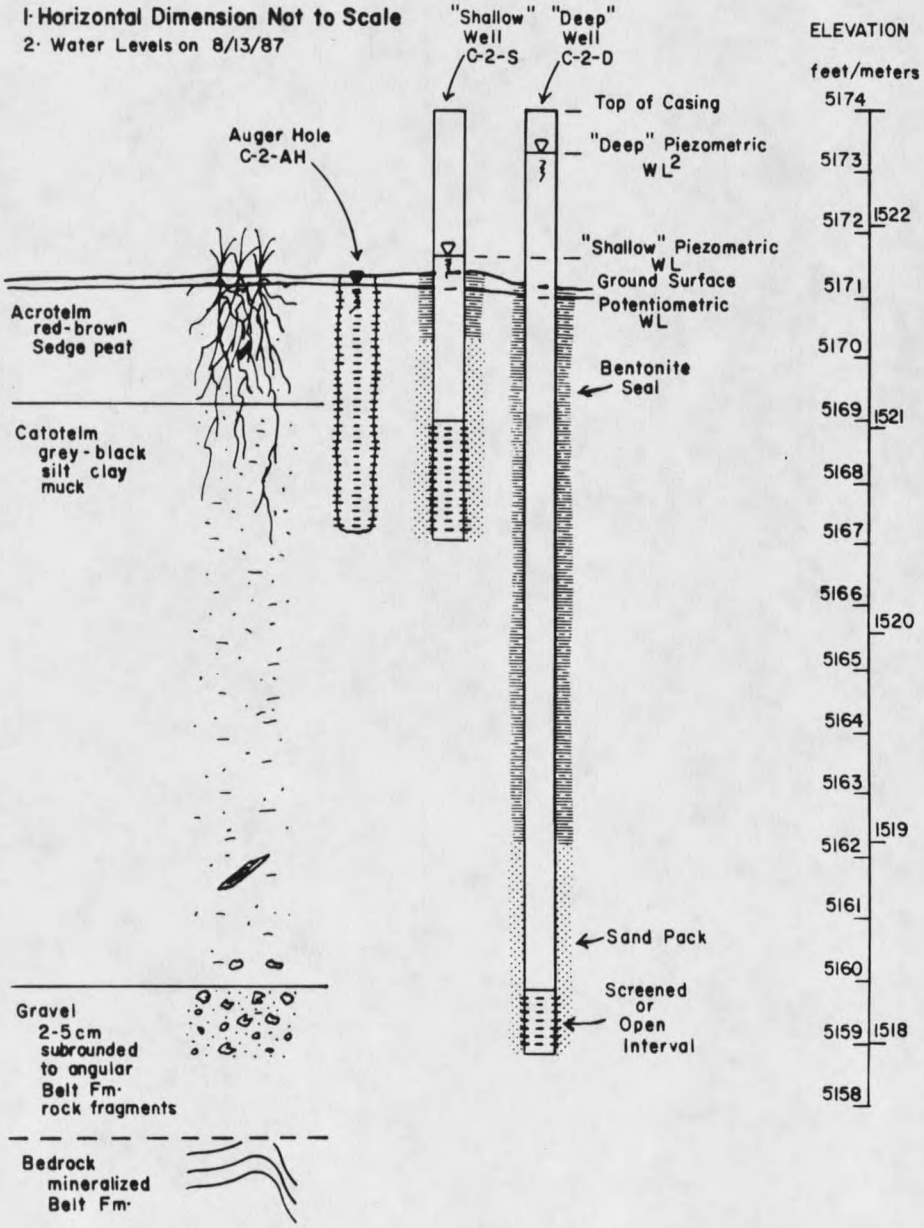

Figure 8. Example of study site instrumentation and lithology.

A Parshall flume equipped with a Stevens Type F recorder was installed June 15, 1987 on Swamp Gulch below the acid mine seep to quantify flow rates into the wetland. A Belfort weighing precipitation gauge was also installed at the site in June 1987. The position of both the flume and precipitation gauge are noted in Figure 6.

Aquifer Characteristics

Porosity, bulk density and particle density were determined on soil samples obtained during excavation of auger holes. Bulk density was determined using the Core Method described by Blake and Hartge (1986a). The Pycnometer Method was used to determine particle density (Blake and Hartge 1986b). Total porosity, n, was calculated with the following equation (Danielson and Sutherland 1986):

$$n = (1 - \rho b/\rho p), \qquad \text{(Eq. 2)}$$

where ρb = bulk density
ρp = particle density

Hydraulic Conductivity

Saturated hydraulic conductivity was measured in the field using both auger hole and seepage tube (piezometer) methods. A variable head method modified from the hydrostatic time-lag method of Hvorslev (1951), as reviewed by Cedegren (1977) (US Navy Method), was used to calculate saturated field hydraulic conductivity. This method is

based on the rate at which water rises or falls in a hole after a known volume (slug) has been removed or added. In the case of the auger holes, a bailer was used to remove a volume of water and the rate of water rise was measured using equipment designed similar to that described by vanBeers (1983). For the wells, a volume of a solid steel rod (173.86 cc) was added and the rate of water fall was measured using an electric tape.

Hydraulic conductivity was calculated for auger holes and wells, respectively, using the following equations:

$$K = \frac{R}{16DS} \times \frac{(h_2 - h_1)}{(t_2 - t_1)} \qquad \text{(Eq. 3)}$$

and

$$K = \frac{r^2}{2L} \ln\left(\frac{L}{R}\right) \frac{\ln(h_1/h_2)}{t_2 - t_1} \qquad \text{(Eq. 4)}$$

Where:
- R = radius of cavity
- D = depth of cavity below static water table
- S = shape factor coefficient
- h_1 = head at time one
- h_2 = head at time two
- t_1 = time one
- t_2 = time two
- r = radius of the well
- L = length of screen

Hydraulic conductivity was converted to velocity (V) (equation 1, page 4) to obtain a preliminary estimate on which to base the tracer test sample timing. These velocities determined from hydraulic conductivity also facilitated comparison with velocities determined by the tracer test.

Tracer Experiment

A preliminary dye tracer test was run using fluorescein dye. This experiment indicated preferential flow direction, helped determine the tracer input point and resulted in an even better idea of flow rates near the tracer input point. In this experiment approximately 7 grams of fluorescein powder was added to 18.9 l (5 gal) of water, mixed and introduced at different points along the mine drainage flow path. Tracer movement was monitored visually. Fluorescein was used only qualitatively because it becomes colorless in acidic conditions, photodegrades, and is easily sorbed.

Bromide was chosen as the tracer in the experiment for use in determining water flow velocities. Prior to adding bromide to the wetland, background (natural) bromide concentrations were measured. These background concentrations were measured using the bromide specific ion electrode as described below and by the EPA (1979) titrimetric Method 320.1. In the titration method the EPA (1979) found bromide recoveries from 83% to 99% and standard deviations from $\pm$.13 to $\pm$.44 for sample concentrations ranging from 0.3 to 20.3 mg/l. The titration method as used in this study indicated 100% recovery based on two laboratory spikes.

A natural gradient tracer experiment utilized 208 liters (55 gal) of wetland water at a concentration of 1000 mg/l bromide. This water was added at the point of highway

culvert outflow (surface water, Figure 7) at 10:30 AM on September 9, 1987 (time zero). Fluorescein dye (18.9 liters - 5 gal) was added at this time as a visual aid in bromide sampling. The tracer was added to the system as an extended slug input (1.46 hr) at a rate of 0.39 l/s (0.625 gpm).

Flow of the tracer plume was monitored by sampling the auger holes and wells and analyzing for bromide. Water sampling was done using portable peristaltic pumps. Care was taken in sampling so that a representative water sample was acquired, but not so much water that the flow field was greatly affected. This care usually amounted to pulling one well volume to rinse the sample bottle three times and taking the 100 ml sample with the second well volume.

Water samples were then analyzed for bromide in the field using a bromide selective ion electrode in conjunction with a pH/millivolt (mv) meter. Calibration curves (mv vs mg/l) were generated using standards measured under the same conditions as the samples. The bromide analysis procedure used is presented in Orion Research (1982). Using the bromide electrode the concentration range is from 0.4 to 79,900 mg/l with a ±2% reproducability (Orion Research 1982).

The sampling intervals at the start of the tracer experiment were nearly continuous near the input point. Sampling decreased to once every other day, by September 14 (124 hours). From September 26 (412 hours), to the end of

the field experiment, November 21, 1987 (1755 hours), sample sets were taken once each week. Water sampling was terminated after the tracer plume had passed a particular well or auger hole (below detection). November water sampling was hampered by freezing conditions. The passing of a tracer plume was determined from the bromide breakthrough curves.

Bromide breakthrough curves are presented as bromide concentration in milligrams per liter (mg/l) vs time in hours. Concentrations were generated from the sample analysis data for a particular site and calibration curves from the time of sample analysis. Times represent the time a particular sample was taken from the wetland. The average velocity of water flow was taken to be the distance from the tracer input point to a particular well or auger hole divided by the time of peak concentration for that site breakthrough curve.

RESULTS AND DISCUSSION

Wetland Aquifer Characteristics

Field evaluation of auger hole and well cores showed a fairly distinct boundary between the upper, undecomposed (fibric) organic matter (sedge peat) and the underlying moderately decomposed (hemic) organic matter. Little distinction was made between moderately and well decomposed zones which are grey to black organic matter muck with occasional sand and/or gravel (<5 cm) stringers and rotted wood pieces (<10 cm). The horizonization scheme used, distinguishes between two soil types 1) upper, undecomposed organic matter (acrotelm), and 2) underlying muck (catotelm) (Figure 8). The upper undecomposed zone is aerated and subject to fluctuating water conditions and water is transmitted comparatively faster in the upper zone compared to the underlying muck zone which is anaerobic and constantly waterlogged. In the wetland being studied, the acrotelm thickness ranges from 0.24 m (0.8 ft) to 1.04 m (3.4 ft) with an average of 0.58 m (1.9 ft) (Figure 9) and catotelm thickness ranges from 0.58 m (1.9 ft) to 4.30 m (14.1 ft) with an average of 2.16 m (7.1 ft) (Figure 10). This information is summarized in Table 2. Note from Figures 9

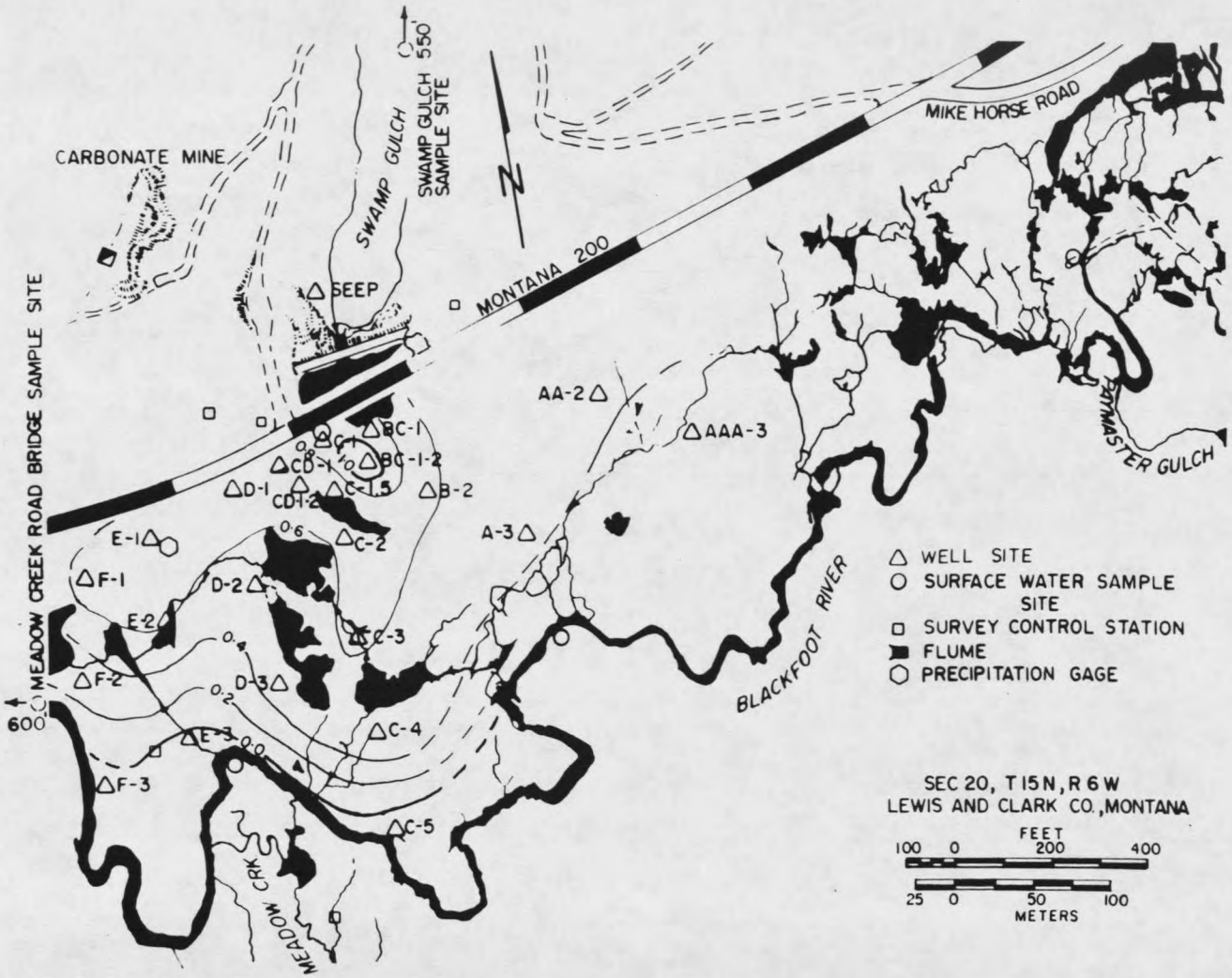

Figure 9. Acrotelm isopach map with 0.2 m (.7 ft) contours.

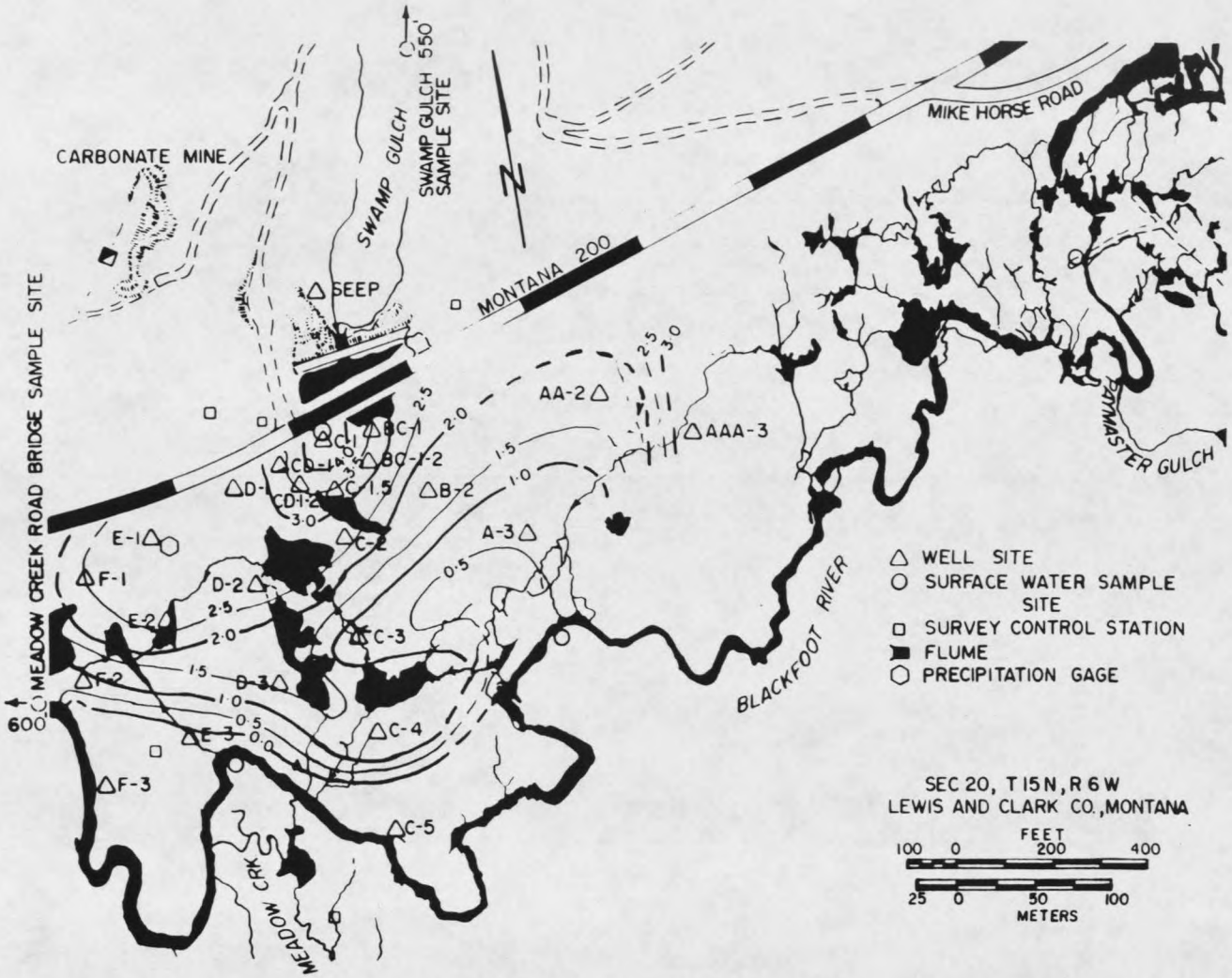

Figure 10. Catotelm isopach map with 0.5 m (1.6 ft) contours.

Table 2. Wetland stratigraphy and well completion data.

Site	Well TD-BGS*	Associated Auger Hole TD-BGS	Screen Legenth	Undecomposed OM+ Thickness or TD-BGS	Decomposed OM Thickness	Depth to Gravel BGS	/ Core TD
				Meters			
AAA-3-D	3.45		0.30	0.24	3.08	3.32	4.57
AAA-3-S	1.51		0.58				
AA-2-D	3.64		0.58	0.46	1.83	2.29	2.56
AA-2-S	1.32		0.58				
A-3	1.53		0.52	0.46	0.58	1.04	1.95
B-2-D	2.62	0.92	0.58	0.61	1.83	2.44	3.66
B-2-S	1.27		0.58				
BC-1-D	2.44		0.58	0.85			
BC-1-S	1.22		0.58				
BC-1-2	1.25	0.81	0.58	1.04			
C-1-D	4.89	1.01	0.58	0.91	4.29	5.21	5.25
C-1-S	1.22		0.58				
C-1.5	1.25	0.87	0.58	0.61			
C-2-D	3.78	1.22	0.30	0.61	2.76	3.43	3.78
C-2-S	1.31		0.58				
C-3-D	2.12		0.58	0.61	0.91	1.52	2.59
C-3-S	1.24		0.58				
C-4-D	1.94		0.46	0.46	1.39	1.84	3.11
C-4-S	1.22		0.58				
C-5-D	3.11		0.58	0.00	0.00	1.99	3.11
C-5-S	2.00		0.58				
CD-1-2	1.24	0.94	0.58	0.58			
CD-1	1.23	1.16	0.58	0.61			
D-1-D	3.99	1.04	0.58	0.61	2.68	3.29	4.27
D-1-S	1.31		0.58				
D-2-D	2.44		0.58	0.46	2.53	2.99	3.66
D-2-S	1.22		0.58				
D-3	1.28		0.58	0.46	1.55	2.01	2.44
E-1	1.26	0.91	0.58	0.61	2.67	3.28	3.66
E-2	1.37	0.80	0.58	0.61	2.74	3.35	3.66
E-3	1.27		0.58	0.00	0.00	1.07	1.98
F-1-D	2.52	0.91	0.58	0.61	2.50	3.11	
F-1-S	1.75		0.58				
F-2-D	2.13		0.58	0.30	0.91	1.22	2.23
F-2-S	1.10		0.58				
F-3	1.26		0.58	0.00	0.00	0.12	1.22
SEEP-D	2.20		0.58	0.00	0.00		
SEEP-S	0.50		0.58				

Notes: * Total Depth - Below Ground Surface
+ Organic Matter

and 10 that the greatest thickness for both zones are near the highway culvert outflow. These greater thicknesses (build up) may be due to sediment deposition from Swamp Gulch or metal precipitation originating from AMD water.

Values for bulk density, particle density and porosity were measured on 3 surface soil samples (acrotelm, 0 to 30 cm depth). Undisturbed samples were not possible below the 30 cm depth due to the sampling methods used and the nature of the wetland soils. The average bulk density of 0.26 g/cc (0.13 to 0.36 g/cc range) is higher than that found by other studies at this depth in a wetland (Sturges 1968 - 0.184 g/cc; Chason and Siegel 1986 - 0.06 to 0.165 g/cc and; Boelter 1969 - <.075 g/cc). The distinctness between the measured bulk density and that from other studies may be due to differing vegetation types and/or soil compaction during the sampling procedure.

Particle density values range between 2.08 and 2.94 g/cc with an average of 2.59 g/cc. This average density is less than the 2.65 g/cc used as an approximation for many mineral soils (Danielson and Sutherland 1986), but higher than the usual case for humus which is <1.5 g/cc (Blake and Hartge 1986b). The relatively intermediate, average particle density found is presumed to be the effect of the high organic matter content and high heavy metal loading in the wetland.

Bulk density and particle density were used to find the total porosity (equation 2). Total porosity ranged from 87.35% to 94.27% with an average of 90.30%. This average porosity is similar to that found by Boelter (1969) which was >90% (Table 1), but higher than that calculated by Girts (1986), 66.1% to 76.1%. The values found by Girts (1986) were for partially and greatly decomposed peat and assumed no water was held within plant tissues. Boelter (1969) noted that total porosity decreased with degree of decomposition or depth in a wetland.

Effective porosity is less than total porosity because in small pores the retention forces are greater than the weight of water. Effective porosity in practice may be considered equal to the specific yield of an unconfined aquifer (Kruseman and Ridder 1983). Generally, specific yield is the water yielded by gravity drainage from water bearing material (Lohman 1979). Boelter (1965) found specific yields in undecomposed peat ranged between 0.79 and 0.33 cc/cc and that moderately to well decomposed peat ranged from 0.22 to 0.10 cc/cc. The averages of the above ranges, 0.54 and 0.186 cc/cc respectively, were used as the effective porosity for converting field hydraulic conductivities to velocities. The decrease in effective porosity with decomposition is appropriate because the more decomposed peat materials have more small pores which are not easily drained. The screens of the deeper wells were

completed within or near the gravel zone lying below the wetland. The effective porosity of deep wells completed in gravel, as used in conductivity - to - velocity conversions, was 0.25 cc/cc (Driscoll 1986).

Results of water level measurements in both wells and auger holes (Appendix A) indicate both upward and downward vertical hydraulic gradients in parts of the wetland. The artesian gradient (upward vertical) can be explained by two different arguments: 1) a confined aquifer system at depth, or 2) the wetland serves as a groundwater discharge area. Hydraulic conductivities which will be discussed later, suggest that the wetland system is capable of transmitting water throughout the soil profile (not confined at depth). Therefore, the wetland is considered both a groundwater discharge or recharge area (site dependant). Field observations, such as at the culvert outflow, were that water flowing into the wetland also seeped into the soil profile and became groundwater. Surface flow channels which would disappear into the ground and seemed to reappear down gradient were also noticed in the wetland. Locations where wetlands function as groundwater discharge, recharge and flow-through areas are not uncommon (Winter and Carr 1980). Deep and shallow piezometric maps, a potentiometric and a topographic map are shown in Figures 11, 12, 13, and 14 respectively. A general comparison of these maps reveals that the hydraulic gradient does not change between water

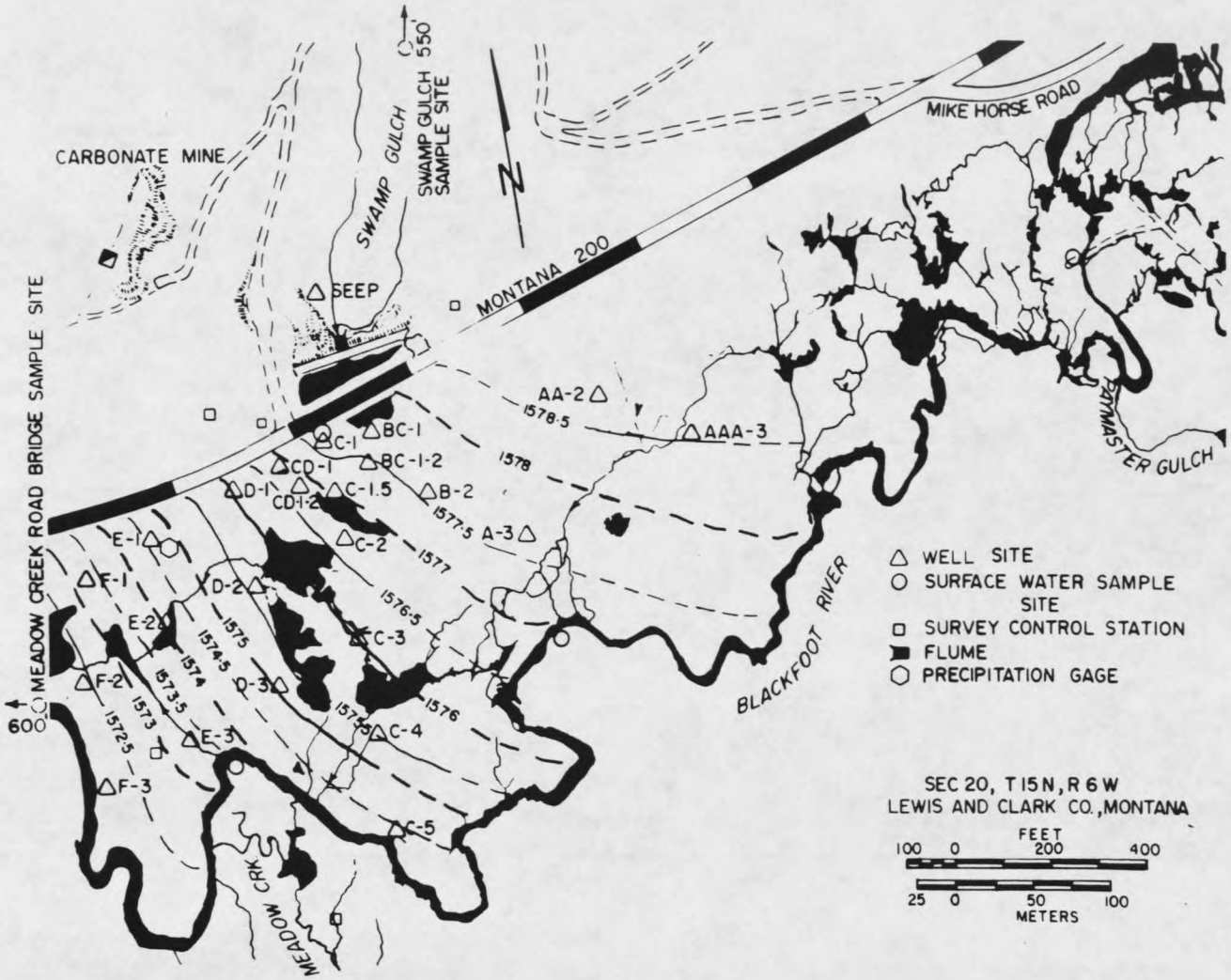

Figure 11. Deep piezometric map on 7/27/87 with 0.5 m contours.

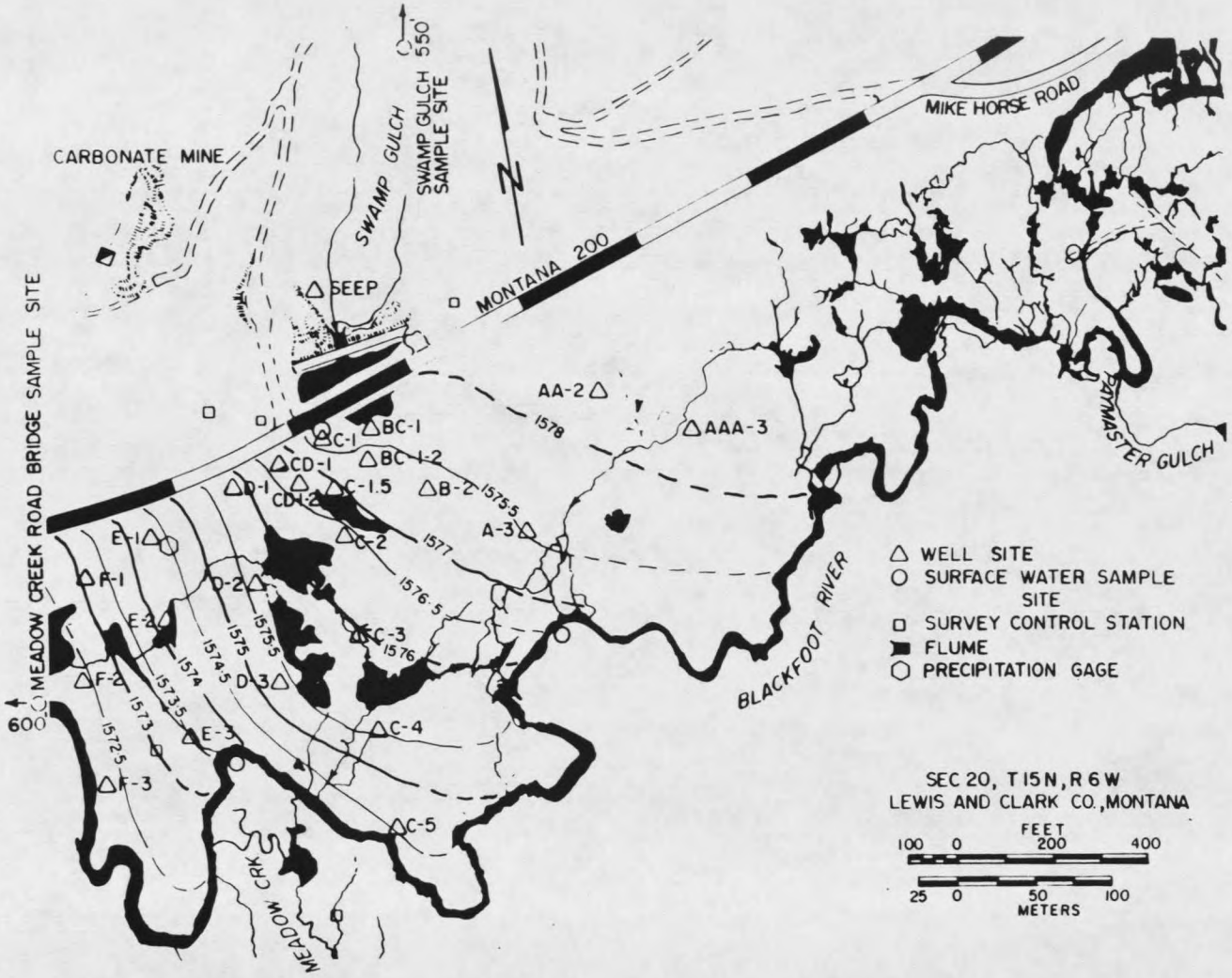

Figure 12. Shallow piezometric map on 7/27/87 with 0.5 m contours.

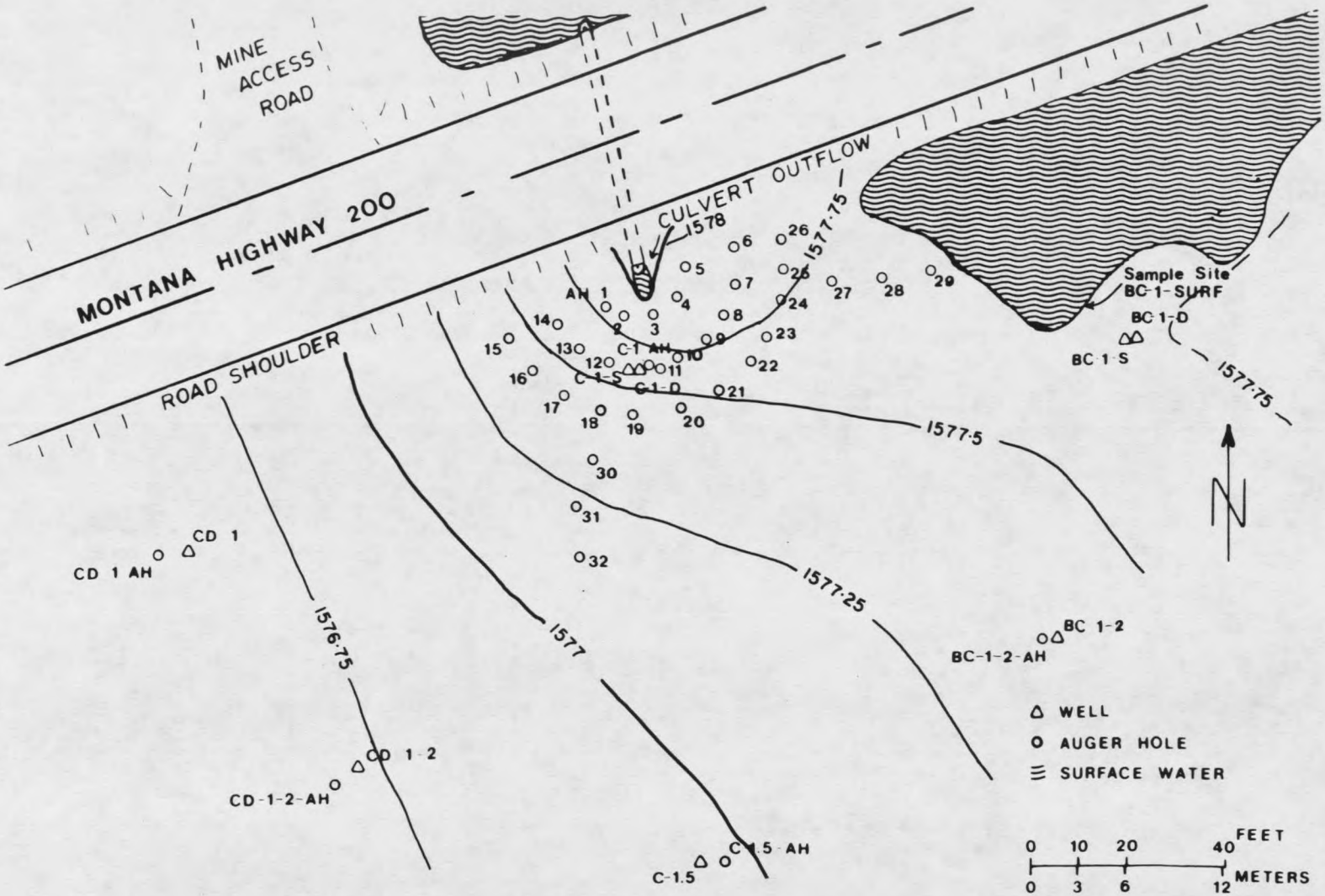

Figure 13. Potentiometric surface map on 8/14/87 with 0.025 m contours.

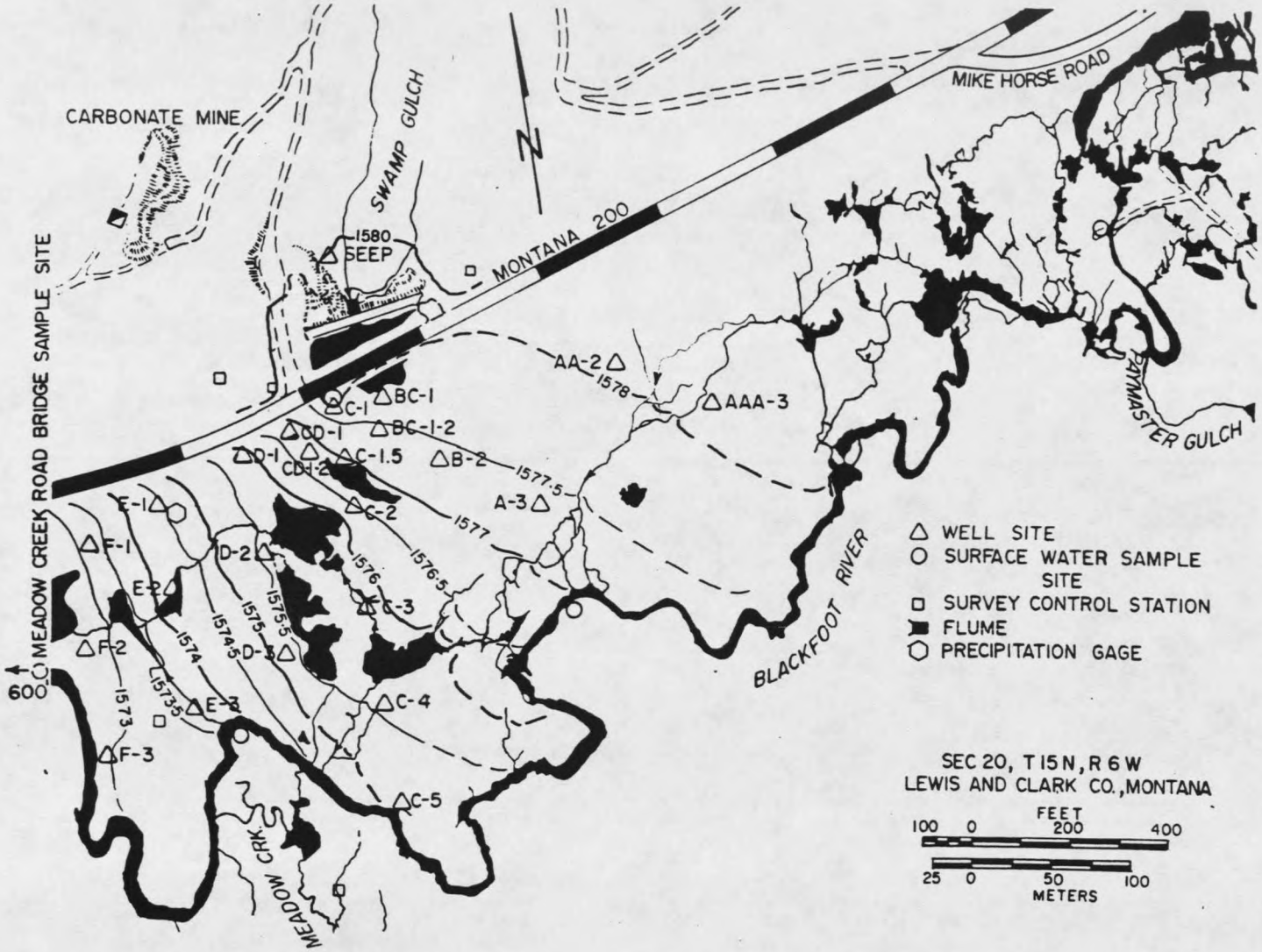

Figure 14. Topographic map with 0.5 m contours.

surfaces measured, and there is a hydrologic and topographic high near the culvert outlet. The average hydraulic gradient across the wetland where the hydraulic conductivity tests were performed is 0.025 m/m. The change in head within a shallow and deep well and auger hole nest is generally less than 0.30 m (1 ft). This relationship can be seen in Figure 8. Overall piezometric surface levels stayed constant throughout the study period. The potentiometric surface fluctuated approximately 0.30 m for short periods of time (days) during the tracer test. These fluctuations may be attributed to increased water use by phreatophytic plants (Meyboom 1967) during period of high air temperatures and the lack of evapotranspiration during the winter. This is further evidenced by slight diurnal fluctuations in water flow rate at the Swamp Gulch flume. The rate of water flow into the wetland from the culvert exhibited little change during the tracer study as indicated by the flume recorder charts (Appendix B). Precipitation during the tracer study was very low (Appendix C).

Hydraulic Conductivity

Hydraulic conductivity tests were run on auger holes and wells in the area of expected metal loading and expected tracer movement. This area was determined from soil and water chemistry data (Reclamation Research Unit and MDI 1988) and hydraulic gradients in the wetland. Field

determined hydraulic conductivity values and the calculated water velocities for each auger hole and well tested are given in Table 3. The field data are found in Appendix D.

When field hydraulic conductivity values were grouped, some differences were found between auger holes and wells (Table 4). Lowest conductivity values were found in the shallow wells with their screened intervals within the catotelm (well decomposed organic matter, muck). Highest conductivity values were found in the deep wells with their screened intervals within both the catotelm and the underlying gravel. Auger holes which have their open intervals within the acrotelm (undecomposed organic matter) had conductivities intermediate in comparison to the wells (Table 4). These values fall within the range of conductivities found in other wetlands studied (Figure 4). The range of hydraulic conductivities from the wetland, 1×10^{-2} to 1.5×10^{-5} cm/s, compares to the range commonly found for silty sand (Freeze and Cherry 1979). The decrease in conductivity with depth, excluding the deep wells completed in gravel, is a common occurrence when moving from the acrotelm to the catotelm (Chason and Siegel 1986).

Table 3. Field hydraulic conductivity (K) effective porosity (n_e), average hydraulic gradient (dh/dl) and calculated average velocity (V) for each site.

Site	K (cm/s)	n_e (cc/cc)	dh/dl (m/m)	V(cm/s)
B-2-AH	1.06×10^{-3}	.540	.025	4.91×10^{-5}
BC-1-2-AH	5.60×10^{-4}	.540	.025	2.59×10^{-5}
C-1-AH	7.02×10^{-4}	.540	.025	3.25×10^{-5}
C-1.5-AH	1.06×10^{-3}	.540	.025	4.91×10^{-5}
C-2-AH	9.53×10^{-4}	.540	.025	4.41×10^{-5}
CD-1-2-AH	1.18×10^{-3}	.540	.025	5.46×10^{-5}
CD-1-AH	4.54×10^{-4}	.540	.025	2.10×10^{-5}
D-1-AH	4.18×10^{-4}	.540	.025	1.94×10^{-5}
E-1-AH	3.40×10^{-4}	.540	.025	1.57×10^{-5}
E-2-AH	1.08×10^{-3}	.540	.025	5.00×10^{-5}
F-1-AH	1.11×10^{-3}	.540	.025	5.14×10^{-5}
B-2-D	1.01×10^{-2}	.250	.025	1.01×10^{-3}
B-2-S	1.71×10^{-4}	.186	.025	2.30×10^{-5}
BC-1-2	3.89×10^{-5}	.186	.025	5.20×10^{-6}
C-1-D	2.81×10^{-4}	.186	.025	3.78×10^{-5}
C-1-S	6.02×10^{-4}	.186	.025	8.09×10^{-5}
C-1.5	3.00×10^{-4}	.186	.025	4.03×10^{-5}
C-2-D	1.22×10^{-4}	.250	.025	1.22×10^{-5}
C-2-S	1.44×10^{-4}	.186	.025	1.94×10^{-5}
CD-1-2	2.22×10^{-4}	.186	.025	2.98×10^{-5}
CD-1	1.40×10^{-4}	.186	.025	1.88×10^{-5}
D-1-D	1.69×10^{-3}	.250	.025	1.69×10^{-4}
D-1-S	6.95×10^{-5}	.186	.025	9.30×10^{-6}
D-2-D	6.62×10^{-4}	.186	.025	8.90×10^{-5}
D-2-S	1.92×10^{-4}	.186	.025	2.58×10^{-5}
E-1	9.16×10^{-5}	.186	.025	1.23×10^{-5}
E-2	3.21×10^{-5}	.186	.025	4.30×10^{-6}
F-1-D	5.05×10^{-4}	.186	.025	6.79×10^{-5}
F-1-S	1.53×10^{-5}	.186	.025	2.10×10^{-6}

Table 4. Average hydraulic conductivity (K), from field results and calculated average velocity (V).

Site Type	Number of Cases	Mean K (cm/s)	Mean V (cm/s)
Auger Holes	11	8.11×10^{-4}	3.75×10^{-5}
Shallow Wells	15	1.68×10^{-4}	2.26×10^{-5}
Deep Wells	3	2.22×10^{-3}	2.31×10^{-4}
Overall	29	8.38×10^{-4}	7.14×10^{-5}

An argument to account for the small conductivity difference between auger holes and wells is that the tests measured part of the same zones. In viewing the depths of auger holes tested (Table 2) it is noted that these depths extended below the undecomposed organic matter (acrotelm). This view reveals that the auger holes also measured the decomposed organic matter zone (catotelm) layer thereby possibly reducing conductivity. A similar argument is true of the shallow wells some of which had the top of the screened interval and sand pack very near or within the acrotelm. The effect of this situation is that well tests measured a portion of the acrotelm in addition to the catotelm thereby overestimating the actual conductivity of the catotelm. The overall result is an average conductivity from the water table to shallow well total depths, but not the two distinct conductivity values that might be expected. This experience suggests the need for care in auger hole and well design and installation. The average conductivity of

both the auger holes and shallow wells is 4.9×10^{-4} cm/s and the velocity is 3.0×10^{-5} cm/s.

The hydraulic conductivity determined in this study is the effect of both vertical and horizontal conductivity. No distinction between vertical and horizontal conductivity was possible with the methods used in the field. Other studies (Girts 1986; Chason and Siegel 1986; and Dai and Sparling 1973) suggest that horizontal conductivity would be greater than vertical conductivity in the sedge peat wetland being studied.

Average velocities calculated using field hydraulic conductivities and equation 1 are shown in Tables 3 and 4. Velocities determined were lower than the associated field hydraulic conductivity. This order of magnitude change (Table 4) is explained (in part) by the effective porosity chosen for the velocity calculation. From equation 1 (page 4) it can be seen that as effective porosity decreases the water flow velocity will increase if the hydraulic conductivity and gradient remain constant. Another explanation for the lower velocities determined for the field sites measured is the small average hydraulic gradient in the wetland (0.025). The hydraulic gradient of the potentiometric surface in the area of tracer input, culvert outflow to C-1 is 0.058. Incorporating this increased gradient into velocity calculations increases the average velocity from

auger hole sites to 8.7 x 10^{-5} cm/s and velocity from shallow well sites to 5.2 x 10^{-5} cm/s.

Tracer Experiment

Water flow velocities were also determined in a bromide tracer experiment. Bromide was chosen as the primary tracer in this study for a number of reasons. Many authors have successfully used bromide as a tracer in a variety of environmental conditions (Onken et al. 1977; Smith and Davis 1974; Merrill et al. 1985; and Tennyson and Settergren 1980; to name a few). In addition, Girts (1986) and Bowmer (1987) successfully used bromide to trace wetland water systems. Davis et al. (1985) noted that bromide is perhaps the most commonly used ion tracer. Schmotzer et al. (1973) considered bromide to be as close as possible to the ideal tracer. Bromide is a good tracer choice, relative to other tracers, in the wetland system studied because it is inexpensive, stable, has a low limit of field detection with a specific ion electrode (0.4 mg/l), has low background concentrations, exhibits low toxicity and has low sorption. Data from this study indicate bromide is a good choice in the system studied. The relatively few disadvantages of bromide as a tracer are anion exclusion, anion exchange and the presence of other ions which interfere with operation of the electrode.

Bromide background concentrations and the concentrations of ions which interfere with the electrode were analyzed before the tracer was introduced to the wetland. Background concentrations were analyzed by both the specific ion electrode and by titration (Table 5). No auger hole background concentrations were above the 0.4 mg/l limit of detection using the bromide specific electrode. Well water which had background values above the electrode lower limit of detection, 0.4 mg/l, had that value subtracted before plotting the breakthrough curve. The subtraction of background values determined from the bromide electrode was necessary only for 5 wells. The average bromide value subtracted was 0.47 mg/l with a range from 0.43 to 0.55 mg/l. This subtraction was found to change the shape of the breakthrough curves, but not the placement of the concentration peak. Bromide background levels measured by titration were never larger than 0.2 mg/l and 80% of all the wetland samples measured were <0.1 mg/l (detection limit). Review of the two methods of analysis suggests that the titrimetric method may be more accurate than the field electrode method, especially at low bromide concentrations. The advantages of using the field millivolt meter and bromide electrode are quick, inexpensive results at the site. This allows for rapid on-site sampling decisions and no need to save a large number of samples for expensive laboratory analysis.

Table 5. Bromide background concentrations in the tracer study area of the Swamp Gulch wetland.

Site	Bromide Concentration (mg/l) Determined by Ion Electrode 9/8 - 9/87	Determined by Titration 7/28 - 31/87
AH-6	< 0.40	---
AH-14	< 0.40	---
AH-17	< 0.40	---
AH-22	< 0.40	---
AH-29	< 0.40	---
AH-32	< 0.40	---
BC-1-2[1]	0.43	---
BC-1-S	< 0.40	< 0.10
C-1-S[1]	0.44	< 0.10
C-1.5[1]	0.50	< 0.10
C-2-S	< 0.40	---
CD-1[1]	0.45	0.10
CD-1-2[1]	0.55	< 0.10
D-1-S	0.82	0.20
D-2-S	0.40	---
BLANK	< 0.40	< 0.10
BC-1-SURF	---	0.20

[1]Backgrounds values subtracted from breakthrough curve.

Ions which interfere with the bromide specific electrode, in order of increasing interference, include S^{-2}, CN^-, I^-, NH_3, CL^- and OH^- (Orion Research 1982). Strontium (Sr^{+2}) must be absent (Cole-Parmer 1987). Water quality analysis (Reclamation Research Unit and MDI 1988) of the acidic wetland system indicated that, of the interfering ions above, only chloride and strontium may cause inaccurate electrode readings. Williams (1979) related that a chloride concentration of 20 times the bromide concentration will cause error in the bromide determination. At the lower

limit of detection with the bromide specific electrode (0.4 mg/l) a chloride concentration of 8 mg/l can cause error. Water analysis at well D-1-S and surface water near BC-1 showed chloride concentrations of 16 mg/l and 8 mg/l respectively on 7/29/87 (Reclamation Research Unit and MDI 1988). The most likely source of this chloride is highway road salt runoff. All wetland sites sampling strontium showed less than the lower limit of detection (0.1 mg/l) except for well F-1-S which showed 0.1 mg/l. Chloride and strontium may thus have created limited variation in the readings for bromide during the tracer test.

The time involved in a uniform (natural) flow tracer method can be quite large and the method is usually limited to short or intermediate distances not more than 100 m (Davis et al. 1985). The velocities determined from the field hydraulic conductivities and preliminary tracer test suggested that the piezometer network might not be close enough to the tracer input point. In addition to variable velocities, conductivity was noticed to decrease with depth and this suggested that flow would be predominantly in the acrotelm. Therefore a grid of shallow sampling sites was installed nearer the tracer input point. Inexpensive auger holes were used as the sample sites. The preliminary dye tracer test exposed preferential water flow paths, consequentially auger holes 27 to 32 were placed along these paths (Figure 7).

Bromide standards ranging from 0.1 to 1000 mg/l were analyzed during each sample session to determine the corresponding mv value for that time period. An example of the resulting calibration curve is shown in Figure 15. Regression equations were determined for each calibration curve (Appendix E). The coefficient of determination, (r^2), for each regression was maintained at 0.99. Values which were below the 0.4 mg/l limit of detection were excluded from the regression. Field mv values for each sample site were converted to mg/l values using the regression equation for that corresponding time period. The many bromide mv and mg/l values generated and the associated sample time for each sample site are shown in Appendix F. Distilled water blanks were run during each sample session and all were less than the 0.4 mg/l limit of detection.

Bromide breakthrough curves were developed using actual bromide concentrations on the y axis instead of the commonly used concentration/concentration injected (c/co). This was done to facilitate calculations and has no effect on the shape of the breakthrough curve. Changing the y axis to concentration/concentration injected is commonly done in tracer studies to facilitate comparison of different types of tracers introduced at the same time.

An example of a bromide breakthrough curve generated is presented for site AH-14 in Figure 16. Based on the work by Davis et al. (1985) (Figure 1), the shape of this curve

indicates little sorption of tracer in the porous medium between the input point and sampling site. The curve shape (steep slopes) also exemplifies the expected result that bromide can be considered a fairly conservative tracer in the wetland studied.

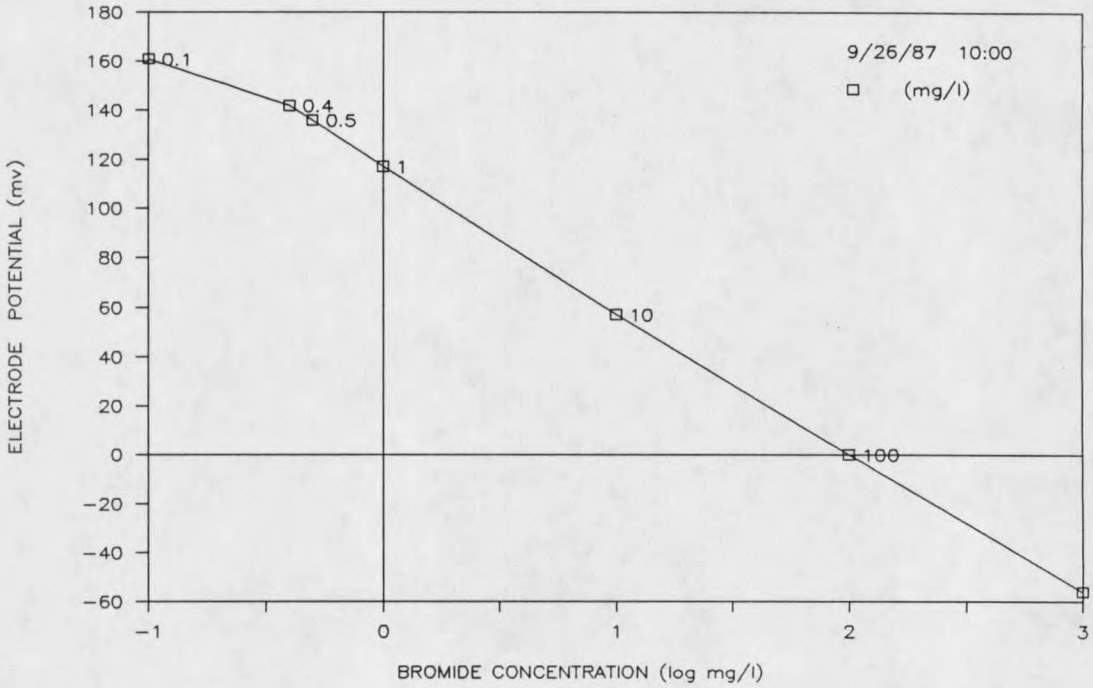

Figure 15. Typical calibration curve generated for the tracer study.

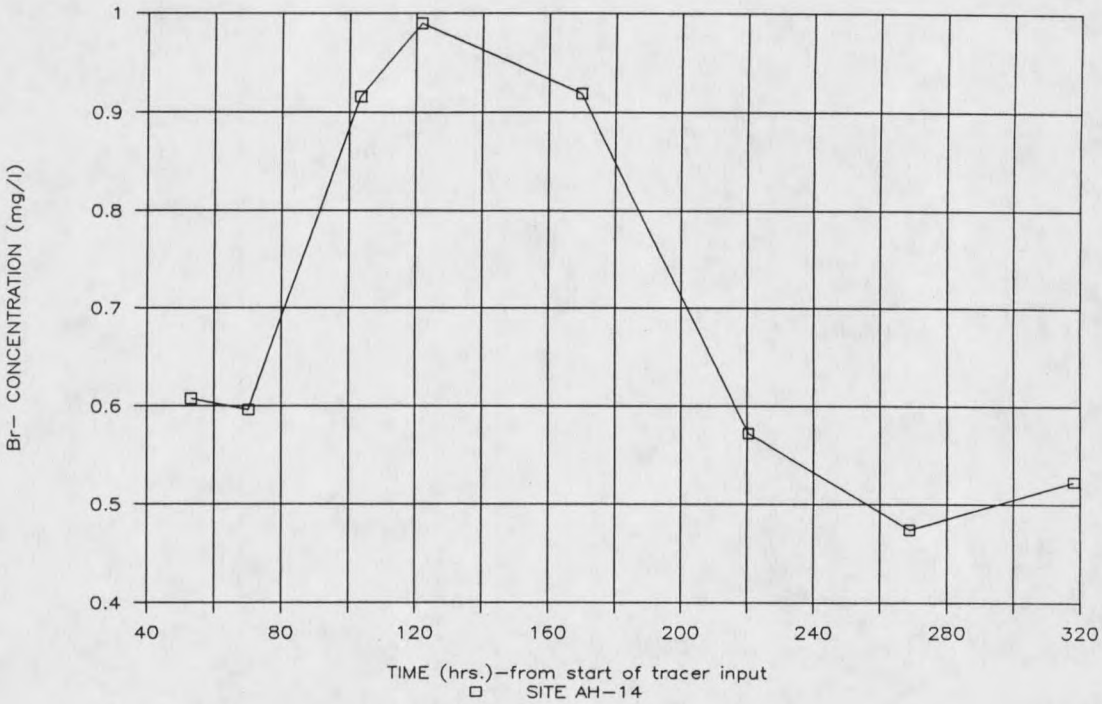

Figure 16. Tracer study breakthrough curve showing little effect of sorption.

There are many possible explanations for shapes of the breakthrough curves. Some of these explanations have been discussed earlier such as retardation by sorption and dilution by dispersion and diffusion. Site AH-25 generated data which resulted in only one point above the lower limit of detection. All the neighboring sites, 1.5 to 3.7 m (5 to 12 ft) away generated many bromide breakthrough curve points up to 4.8 mg/l. This suggests a zone of very low flow which is described as "dead zones" by Bowmer (1987). Sampling was not frequent enough to determine the exact breakthrough peak

at some sample sites. In the case of site AH-9 (Figure 17) the resultant curve is flat topped between hours 169 and 220. Both of these times were used for calculating velocity, in addition to the peaks at 30 and 54 hours. Subtraction of the background values resulted in no detectable tracer peaks on the breakthrough curve for some of the well sampling sites such as C-1-D, D-1-S, and D-2-S.

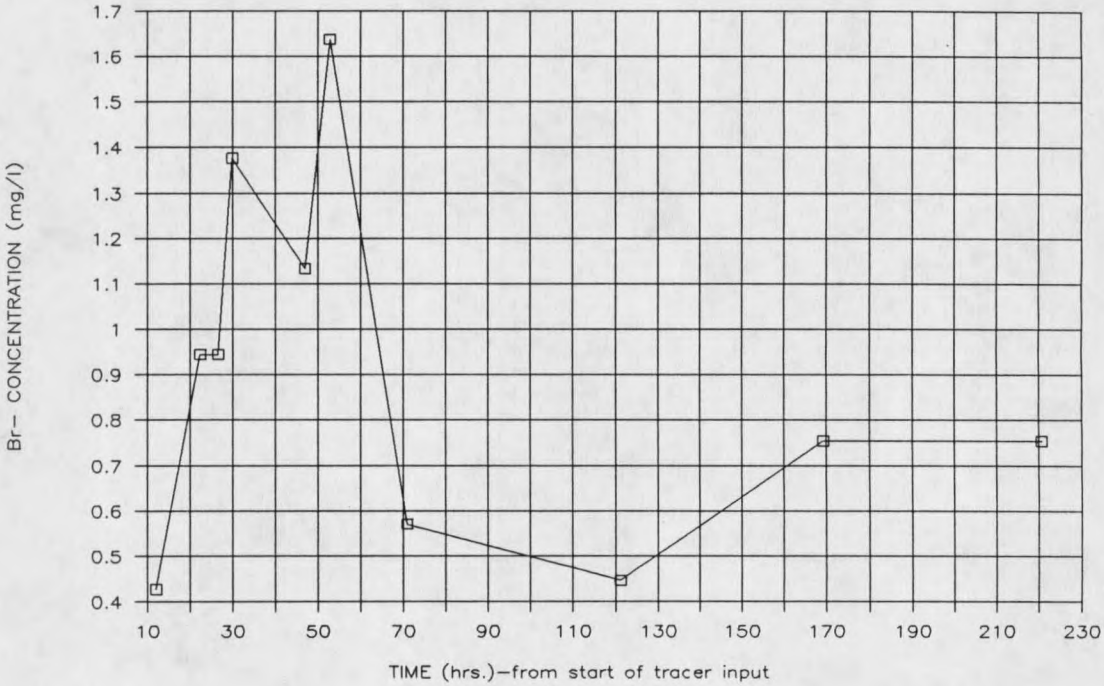

Figure 17. Example of infrequent sampling effect on breakthrough curve for site AH-9, 6.1 m from tracer input.

Placement of the breakthrough curve peak is important in that the associated time represents the passing of the tracer plume. This time is also used for determination of average velocity. Widely spaced sampling intervals may

cause the exact breakthrough curve peak to not be detected and the velocities determined may be too large or too small. Bromide values below the 0.4 mg/l limit of detection were not considered as possible peaks on the breakthrough curves. A common observation of the breakthrough curves shows more than one peak of tracer concentration. An example of such a curve is given in Figure 18 for site AH-19. This curve seems to indicate two bromide tracer plumes moving past the site with the second plume being more effected by sorption.

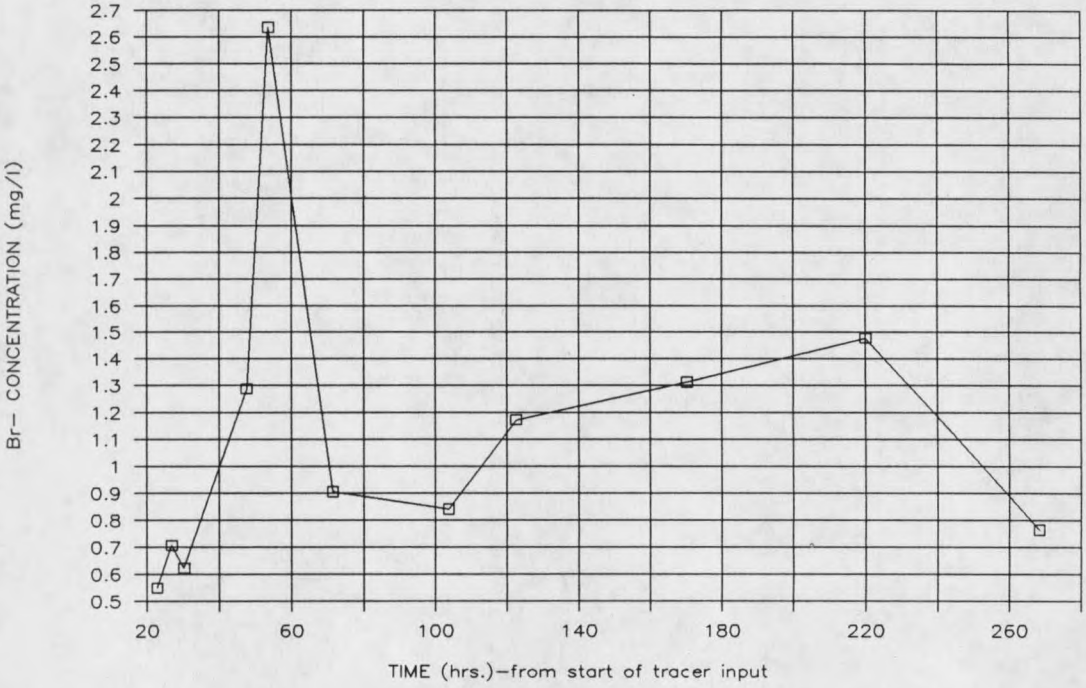

Figure 18. Breakthrough curve representing two tracer plumes at site AH-19, 9.1 m from tracer input.

How breakthrough curves acquire more than one concentration peak is not specifically discussed in the literature reviewed. Possible explanations of multiple breakthrough peaks could include: inadequate tracer mixing during input,

a heterogenous medium with layers of different flow velocity, periodic flushing, and cross contamination of samples. The inadequate mixing theory is negated by the breakthrough curve shape of the first sampling site encountered (Figure 19). This site, AH-3, showed no multiple peaks and exhibited a high concentration and short time interval to the breakthrough curve peak for this short distance from tracer input. A heterogenous medium is an entirely plausible explanation as layering was indicated during soil sampling (Table 2) and preferential flow paths were found in the wetland. These situations are also found in other wetlands (Ingram 1967; Dasberg and Neuman 1977; Sturges 1968). The possibility of samples being drawn from more than one zone of flow is good because many sampling sites have their screened interval in contact with more than one soil horizon (Figure 8 and Table 2). Periodic flushing (pulse flow) could cause multiple breakthrough peaks by flushing higher concentration water which was previously held in pore spaces during different flow rates. Periodic flushing is indicated by mildly fluctuating water levels during the study period (Appendix A). The diurnal variation noticed in flume charts could also contribute to this type of flow.

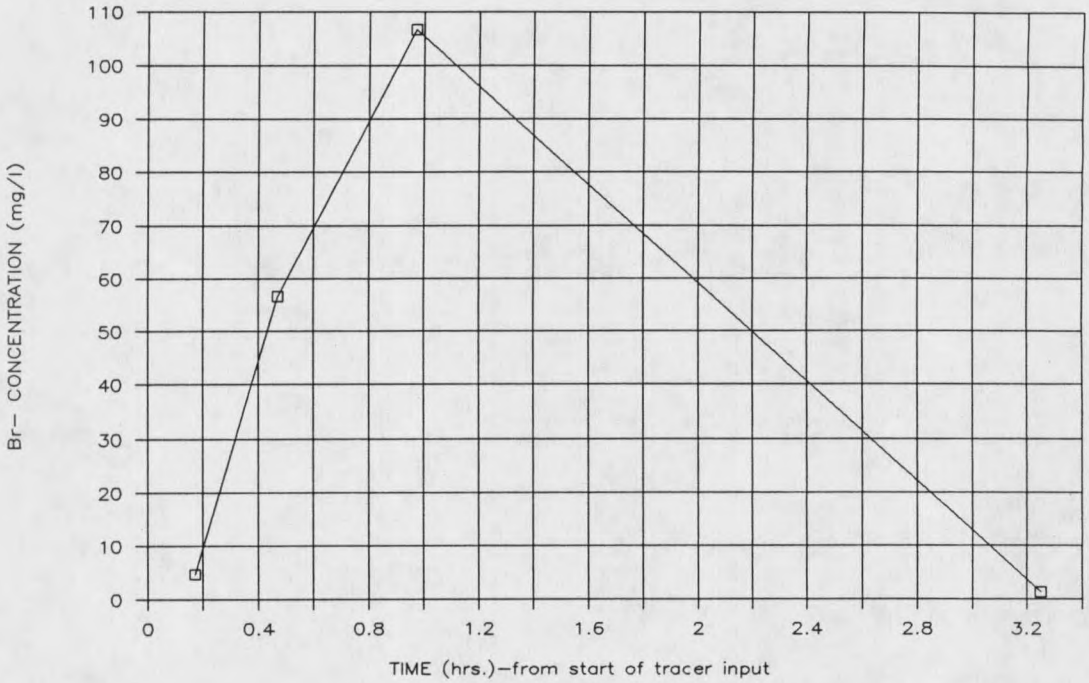

Figure 19. Steep breakthrough curve indicating adequate tracer mixing at site AH-3, 3 m from tracer input.

The possibility of cross contamination of samples, analysis error and/or some other means of acquiring faulty values is one which must be considered in any experiment. Blank samples (distilled water) were run through the same analysis procedures as the wetland samples. These blank sample results are also shown in Appendix F. The bromide concentration in blanks never was greater than the 0.4 mg/l limit of detection and cross contamination was not a problem. Another explanation for multiple breakthrough curve peaks is error during analysis for bromide in the field. Analysis methods were constant throughout the study and should not have created the noted variation. The final

explanation for multiple peaks is a periodic contamination by the interfering ions, chloride and strontium which seems unlikely.

Given these possible explanations for multiple tracer peaks it seems that they are true bromide values and have been processed accordingly. The previously shown breakthrough curve for site AH-14 (Figure 16) yields a velocity of 1.4×10^{-3} cm/s (6.1 m/121.7 hr). Table 6 shows the velocities associated with the bromide breakthrough curve peak/peaks chosen for each site. The velocities shown represent the rate at which a tracer plume passed that particular site. Site locations are shown in Figure 7. The overall mean velocity represented by all of the sites and peaks is 2.6×10^{-2} cm/s with a range of 3.1×10^{-1} to 6.2×10^{-4} cm/s.

The velocities were compared in three different ways 1) between auger holes and wells, 2) between the highest peak of the breakthrough curve and the remaining peaks, and 3) between sample sites within the grid area, <18.3 m, and sites outside the grid area, 27 to 38 m (Figure 7). These results are shown in Table 7. Several observations were apparent: 1) there is little difference between bromide tracer velocities determined at auger holes and wells, 2) the velocities determined from other than the highest peak of the breakthrough curve are notably slower than from the remaining peaks, and 3) there is little difference (same

Table 6. Tracer velocities determined for each site, time and distance from tracer input and peak concentrations of bromide.

Site	Time hrs	Concen-tration mg/l	Distance m	Velocity cm/s
AH-1	29.6	1.2	3.0	0.00286
AH-1	53.1	1.6	3.0	0.00160
AH-2	0.8	3.5	3.0	0.10201
AH-3	1.0	106.7	3.0	0.08729
AH-4	29.7	2.6	3.0	0.00285
AH-4	52.6	1.8	3.0	0.00161
AH-5	47.1	1.9	3.0	0.00180
AH-5	52.6	2.2	3.0	0.00161
AH-6	168.9	1.0	6.1	0.00100
AH-7	6.2	4.8	6.1	0.02722
AH-7	52.6	1.8	6.1	0.00322
AH-8	6.2	3.6	6.1	0.02709
AH-8	29.8	2.4	6.1	0.00569
AH-8	169.1	1.1	6.1	0.00100
AH-9	29.8	1.4	6.1	0.00568
AH-9	52.7	1.6	6.1	0.00321
AH-9	169.1	0.8	6.1	0.00100
AH-9	220.6	0.8	6.1	0.00077
AH-10	52.8	1.1	6.1	0.00321
AH-10	220.6	0.6	6.1	0.00077
AH-11	0.8	82.8	6.1	0.21991
AH-11	1.2	82.8	6.1	0.13880
AH-11	169.7	0.6	6.1	0.00100
AH-12	0.7	72.9	6.1	0.24902
AH-13	1.5	13.4	6.1	0.11519
AH-13	6.1	9.3	6.1	0.02776
AH-13	53.1	3.5	6.1	0.00319
AH-13	169.9	1.9	6.1	0.00100
AH-14	121.7	1.0	6.1	0.00139
AH-15	122.4	1.0	9.1	0.00207
AH-16	220.3	0.7	9.1	0.00115
AH-16	318.1	0.7	9.1	0.00080
AH-16	411.6	0.6	9.1	0.00062
AH-17	220.3	1.9	9.1	0.00115
AH-18	3.6	36.0	9.1	0.06959
AH-18	268.5	4.1	9.1	0.00095
AH-19	53.5	2.6	9.1	0.00474
AH-19	220.1	1.5	9.1	0.00115
AH-20	53.6	1.6	9.1	0.00474
AH-20	268.4	0.8	9.1	0.00095
AH-21	220.1	1.5	9.1	0.00115
AH-22	53.7	1.5	9.1	0.00473
AH-22	220.0	2.3	9.1	0.00115
AH-23	220.3	4.1	9.1	0.00115
AH-24	53.8	0.7	9.1	0.00472
AH-24	268.0	0.7	9.1	0.00095
AH-25	267.8	0.6	9.1	0.00095
AH-26	267.8	1.3	9.1	0.00095
AH-26	410.7	0.9	9.1	0.00062
AH-27	53.9	1.1	12.2	0.00628
AH-27	410.9	2.1	12.2	0.00082
AH-28	1.4	20.5	15.2	0.31358
AH-29	123.1	1.0	18.3	0.00413
AH-29	268.0	0.4	18.3	0.00190
AH-30	1.4	52.0	12.2	0.24191
AH-30	220.2	3.3	12.2	0.00154
AH-30	317.9	3.9	12.2	0.00107
AH-31	1.4	42.1	15.2	0.30900
AH-31	317.9	1.7	15.2	0.00133
AH-31	411.5	2.1	15.2	0.00103
AH-32	3.6	29.3	18.3	0.14033
AH-32	268.6	1.8	18.3	0.00189
AH-32	411.5	0.7	18.3	0.00123
C-1-S	52.9	3.8	6.4	0.00336
C-1-S	121.5	3.1	6.4	0.00146
C-1-S	220.8	2.5	6.4	0.00081
C-1-AH	30.0	2.5	6.1	0.00565
C-1-AH	52.8	1.7	6.1	0.00321
C-1-AH	121.4	0.7	6.1	0.00139
C-1-AH	220.7	0.8	6.1	0.00077
BC-1-SURF	48.6	1.5	27.4	0.01569
BC-1-SURF	123.7	1.3	27.4	0.00616
BC-1-S	30.6	1.2	30.8	0.02795
BC-1-S	54.5	3.0	30.8	0.01568
BC-1-2	22.6	1.1	35.1	0.04303
BC-1-2	54.6	2.4	35.1	0.01784
BC-1-2	915.0	1.0	35.1	0.00106
BC-1-2-AH	54.6	0.5	34.1	0.01736
C-1.5	30.7	1.4	37.5	0.03389
C-1.5	54.8	3.9	37.5	0.01899
C-1.5	915.2	2.5	37.5	0.00114
C-1.5-AH	30.7	1.6	37.5	0.03392
C-1.5-AH	54.9	2.2	37.5	0.01898
C-1.5-AH	123.9	1.4	37.5	0.00841
C-1.5-AH	412.5	0.9	37.5	0.00252
CD-1-2	30.8	1.9	35.7	0.03221
CD-1-2	54.8	3.5	35.7	0.01808
CD-1-2	123.9	2.4	35.7	0.00799
CD-1-2	915.2	2.7	35.7	0.00108
CD-1-2-AH	54.8	2.9	37.2	0.01884
CD-1-2-AH	124.0	1.2	37.2	0.00833
CD-1-2-AH	269.2	0.8	37.2	0.00384
CD-1	54.7	3.3	32.9	0.01672
CD-1	124.0	1.8	32.9	0.00737
CD-1	915.3	1.3	32.9	0.00100
CD-1-AH	30.8	1.1	34.7	0.03134
CD-1-AH	54.7	3.1	34.7	0.01764
CD-1-AH	124.1	1.3	34.7	0.00778
CD-1-AH	220.9	0.9	34.7	0.00437
CD-1-AH	412.3	1.0	34.7	0.00234
CD-1-AH	915.4	0.4	34.7	0.00105

order of magnitude) in velocities determined near the tracer input and those velocities from farther away.

Table 7. Tracer velocity comparison.

Comparison Type	Number of Cases	Mean Velocity (cm/s)
Auger Holes	83	2.9×10^{-2}
Wells	18	1.4×10^{-2}
High Peaks	45	5.0×10^{-2}
Remaining Peaks	56	6.4×10^{-3}
Grid Area	70	3.1×10^{-2}
Outside Grid	31	1.4×10^{-2}
Overall	101	2.6×10^{-2}

The similar velocities observed at auger holes and wells can be explained by the fact that portions of the screened interval of most of the wells are within the same layers of conducting material (Table 2 and Figure 8) as the auger holes. The total depth of the shallow wells has little effect in that they are able to pick up tracer water from upper layers (acrotelm). This "pick up" can occur through the well sand pack which is usually 30 cm (1 ft) from ground surface, below the bentonite seal. The auger holes are subject to the acrotelm flowing water slightly sooner than the shallow wells as indicated by the slightly faster velocity. The comparison of the high peak and remaining peaks supports the theory of residual tracer water

being flushed through after the main tracer plume. These remaining tracer peaks could represent tracer water flowing through the less conductive (catotelm) peat layers hence reducing flow velocity. The higher velocities determined in the auger hole grid area, although within the same order of magnitude, may reflect the steeper gradient in the area near the culvert outflow. Considering all the velocities from the different comparisons it is concluded that the overall mean of 2.6×10^{-2} cm/s is the most representative of the wetland system measured.

The presence of preferential flow paths is demonstrated by results of the bromide tracer experiment. Breakthrough curves peak at just 1.4 hours from tracer input for sites AH-28 and AH-31, both 15.2 m (50 ft) from tracer input (Table 6). This results in a tracer plume of the shape represented in Figure 20. These preferential flow paths indicate the tracer is moving in both a south-southwesterly and easterly direction. The bromide concentration at site AH-31 is more than twice as high (52 mg/l) as site AH-28 (20.5 mg/l) at the same time (1.4 hrs) and indicates that more tracer is flowing in the south-southwesterly direction. This southwesterly skewed radial pattern is expected as the culvert outflow is a topographic high point and the regional hydraulic gradient and topographic slope is to the south-west. Preferential flow paths are found in man made wetlands (Bowmer 1987) and in natural systems are sometimes

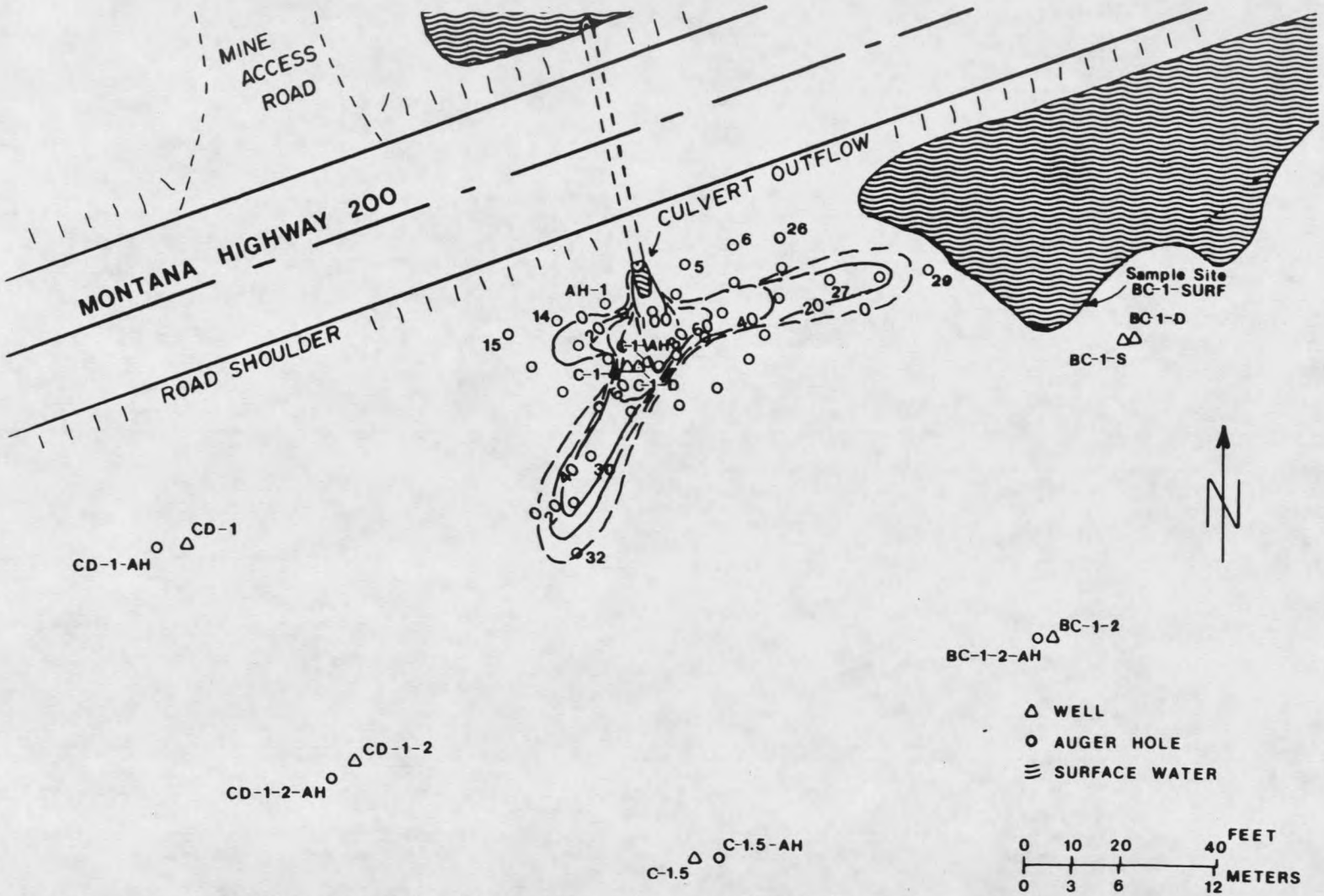

Figure 20. Bromide concentration isopach map, 0.95 to 1.5 hours from tracer start (20 mg/l contours).

called water tracks (Ingram 1967). Such paths may cause a substantial proportion of the water (tracer and/or AMD polluted) to travel through the system faster than predicted by the field hydraulic conductivities. Brooks (1984) recommended man made wetlands be designed to avoid channelization (preferential flow paths) and encourage low velocity sheet flow by use of flow obstructions. Effective iron removal from AMD increases in a wetland as flow rate through the wetland decreases (Burris 1984). The shape of the initial tracer plume (Figure 20) demonstrates the value of tracers used in heterogeneous flow systems.

Tracer flow velocities (mean = 2.6×10^{-2} cm/s) were faster than flow velocities estimated from field hydraulic conductivity (mean = 7.14×10^{-5} cm/s)(Tables 7 and 4). The relationship between tracer determined velocity and field conductivity determined velocity is complicated by a number of factors. The measurement of the conductivities and the tracer test were done at different times. In effect, the measures are of different systems, but in practice, are assumed the same in view of the minimal change noticed in the system over the study period. The field hydraulic conductivity determined velocities are more representative of the wetland at depth. The tracer velocities, which include preferential flow paths, are more representative of the true movement of AMD waters. The amount of area and time represented by the tracer test is large compared to the

small area and time that the field conductivities represent. This comparison indicates that the tracer velocities are closer to the true value than the conductivity determined values.

CONCLUSIONS

Bromide was found to be a good choice for tracing water movement in the wetland studied. Using the natural flow tracer technique, sufficient bromide concentrations were detected up to a distance of approximately 38 m from tracer input. The bromide specific ion electrode method of analysis was found to be adequate. This method could be improved by periodic double sampling and analysis with another method (titration) especially at low bromide concentrations.

The wide range of velocities determined from this study are the effect of a very heterogeneous wetland flow system and the methodology used in determining the velocities. Some of the heterogeneity involved a change in hydraulic gradient, changing flow rates and periodic flushing over time. Preferential flow paths and "dead zones" as a result of variable hydraulic conductivity also added to the heterogeneity. The most representative velocity of the AMD water in the wetland was that determined by the tracer experiment. These velocities were found to be a reflection of the heterogeneous system and ranged between 3.1×10^{-1} to

6.2×10^{-4} cm/s with a mean of 2.6×10^{-2} cm/s (73.7 ft/day).

Comparison of field hydraulic conductivity determined velocity to tracer determined velocity was accomplished by converting conductivity to velocity utilizing the estimated values of effective porosity and hydraulic gradient. The conductivity determined velocities are reasonable in that they estimate water flow velocity in the small area where conductivity was determined. When comparing the conductivity determined velocity to tracer velocity even the average velocity of auger hole sites (fastest of the conductivity determined velocities) was three orders of magnitude lower than average tracer velocity. This order of magnitude relationship does not change even if effective porosity is changed to 0.1 cc/cc (low) and the hydraulic gradient is changed to the steepest observed in the study area (0.058 m/m). This relationship indicates the comparison is that of two different systems. The tracer velocity represents preferential flow paths within the shallow (acrotelm) system and the conductivity represents that flow found at greater depth (catotelm).

The determination of water residence times in the wetland is contingent upon the velocity of the water system to be considered and the distance the water travels. The concern in this study involves the AMD water which emanates from the culvert outflow into the wetland. The velocity

representing this source is that of the tracer which was input at the same point that the AMD water is introduced to the wetland. The distance the AMD water travels, before complete problem amelioration, was not determinable from the tracer methods employed, but considering the wetland soil chemical data (Reclamation Research Unit and MDI 1988) a distance of 200 m will be used as an example. With this distance chosen and using the mean tracer velocity, the average residence time of AMD water in contact with the wetland soils is estimated to be 215 hours (9 days). This estimate is considered to be quite variable as noted earlier and represents a low flow regime (Autumn) in a steep gradient area of the wetland. Assuming the wetland studied is a viable system for the amelioration of AMD, the challenge in the design of man made wetland systems will be to determine how to emplace similar hydrologic characteristics, and limit preferential flow paths.

LITERATURE CITED

Alden, W.C. 1932. Physiography and Glacial Geology of Western Montana and Adjacent Areas. U.S. Geol. Surv. Prof. Paper 231. 200 p.

Alexander, H.C., J.A. Quick, Jr., and E.A. Bartlett. 1981. Static acute toxicity of sodium bromide to Fathead minnows. Bull. Environ. Contam. Toxicol. 27:326-331.

Aley, T. and M.W. Fletcher. 1976. Water tracer's cookbook: Journal of the Missouri Speleological Survey. V. 16, No. 3. 32 p.

Alt, D.D. and D.W. Hyndman. 1986. Roadside Geology of Montana. Mountain Press Pub. Co. Missoula, MT. 427 p.

Arts Manufacturing and Supply. 1987. 105 Harrison and Oregon Trail, American Falls, Idaho.

Baden, W. and R. Eggelsman. 1963. Zur Durchlassigkeit der Moorboden (On the permeability of marshland). Z. Kulturtech. Flurbereinig. 4:226-254. From Chason and Siegel (1986).

Baden, W. and R. Eggelsman. 1961. Moorhydrologische Untersuchungen am Westrand des Steinhuder Meeres zur Feststellung eines unterirdischen Seebflusses. Wasser Boden 13:403-410. From: Chason and Siegel (1986).

Baden, W. and R. Eggelsman. 1964. Der Wasserkreislauf eines Nordwestdeutschen Hochmoores. Schrifteur. Kurat. Kult. Hamburg. 12:1-156. From: Chason and Siegel (1986).

Barnes, G.D., B.S. Dhillon, and A.S. Hume. 1981. The Identification and Treatment of Bromides and Trihalomethanes in Potable Water from the Pearl River at Jackson, MS: Evaluation of Toxicity on Species Diversity. Water Resources Research Institute, Mississippi State, MS. 70 p.

Bear, J. 1972. Dynamics of Fluids in Porous Media. American Elsevier, New York, NY. 764 p.

Beers, W.F.J.van. 1983. The Auger Hole Method. International Institute for Land Reclamation and Improvement/ILRI, Wageningen, The Netherlands. 23 p.

Berg, W.A. and G.W. Thomas. 1959. Anion elution patterns from soils and soil clays. Soil Sci. Soc. Amer. Proc. 23:348-350.

Biggar, J.W. and D.R. Nielsen. 1962. Miscible displacement: II. Behavior of tracers. Soil Sci. Soc. Amer. Proc. 26:125-128.

Blake, G.R. and K.H. Hartge. 1986a. Bulk Density. In: A. Klute (ed). Methods of Soil Analysis, Part I, Second Edition. Agronomy 9:363-375.

Blake, G.R. and K.H. Hartge. 1986b. Particle Density. In: A. Klute (ed). Methods of Soil Analysis, Part I, Second Edition. Agronomy 9:377-382.

Boelter, D.H. 1969. Physical properties of peat as related to degree of decomposition. Soil Sci. Soc. Amer. Proc. 33:606-609.

Boelter, D.H. 1965. Hydraulic conductivity of peat. Soil Sci. 100(4):227-231.

Bohn, H.L., B.L. McNeal and G.A. O'Connor. 1985. Soil Chemistry, Second Edition. John Wiley and Sons. New York, NY. 340 p.

Bowmer, K.H. 1987. Nutrient Removal from Effluent by an Artificial Wetland: Influence of Rhizosphere Aeration and Preferential Flow Studies Using Bromide and Dye Tracers. Water Resource, 21(5):591-599.

Brodie, G.A., D.A. Hammer, and D.A. Tomljanovich. 1986. Man-Made Wetlands for Acid Mine Drainage Control. Procs. 8th Annual National Abandoned Mine Lands Conference. Billings, Montana.

Burris, J.E., D.W. Gerber and L.E. McHerron. 1984. Removal of iron and Manganese from water by Sphagnum moss. In: Treatment of Mine Drainage by Wetlands, J.E. Burris, ed. Pennsylvania State University, University Park, PA. 50 p.

Caruccio, F.T., and G. Geidel. 1978. Geochemical Factors Affecting Coal Mine Drainage Quality. pp. 129-148. In: Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Inc., Madison, Wisconsin.

Cedergren, H.R. 1977. Seepage, Drainage and Flow Nets. Second Ed. John Wiley and Sons, N.Y.

Chason, D.B. and D.I. Siegel. 1986. Hydraulic conductivity and related physical properties of peat, Lost River Peatland, Northern Minnesota. Soil Sci. 142(2):91-99.

Coffin, D.L. and K.R. Wilke. 1971. Water resources of the upper Blackfoot River Valley, west central Montana. Dept. of Natural Resources and Conservation. Technical Report Series of Water Resources Division. No. 1.

Cole-Parmer Instrument Co. 1987. Cole-Parmer (catalog). Chicago, IL. 960 p.

Dai, T.S. and J.H. Sparling. 1973. Measurement of hydraulic conductivity of peat. Canadian Jour. of Soil Sci. 53:21-26.

Danielson, R.E. and P.L. Sutherland. 1986. Porosity. In: A. Klute (ed). Methods of Soil Analysis, Part I, Second Edition. Agronomy 9:443-461.

Dasberg, S. and S.P. Neuman. 1977. Peat hydrology in the Hula Basin, Israel: I. Properties of Peat. Jour. of Hydrology. 32:219-239.

Davis, S.N., G.M. Thompson, H.W. Bentley and G. Stiles. 1980. Ground-water tracers--a short review. Ground Water, 18:14-23.

Davis, S.N., D.J. Campbell, H.W. Bentley and T.J. Flynn. 1985.An Introduction to Ground-Water Tracers. U.S. EPA, Ada, OK. EPA/600/2-85/022. 201 p.

Dowling, P.C. 1969. The hydraulic conductivity of peat. M. Eng. Sci. Thesis, University College Dublin (microfilm). From: Chason and Siegel (1986).

Driscoll, F.G. 1986. Groundwater and Wells. Second Edition. Johnson Division. St. Paul Minnesota. 1089 p.

Eggelsman, R. and T. Makela. 1964. Ein fluss von Entwasserung und landwirtschaftlicher Natzung auf die Durchlassigkeit des Moorbodens. Maataloust Aikakausk. 36:77-84. From Chason and Siegel (1986).

Environmental Protection Agency (EPA). 1979. Methods for Chemical Analysis of Water and Wastes. EPA-600/4-79-020.

Fetter, C.W. Jr. 1980. Applied Hydrogeology. Merrill Pub. Co., Columbus, OH. 488 p.

Freeze, R.A. and J.A. cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ. 604 p.

Fried, J.J. 1975. Developments in Water Science, Groundwater Pollution. Elsevier, New York, NY. 330 p.

Galvin, L.F. 1976. Physical properties of Irish peat. In: J. Agric. Res. 15:207-221. From: Chason and Siegel (1986).

Galvin, L.F. and E.T. Hanranahan. 1968. Steady state drainage flow in peat. Highway Res. Rec. 203:77-90. From: Chason and Siegel (1986).

Girts, M.A. 1986. The hydrology of Sphagnum - Dominated Appalachian Wetlands in West Virginia. M.S. Thesis College of Arts and Sciences of West Virginia University. 203 p.

Girts, M.A. and R.L.P. Kleinmann. 1986. Constructing Wetlands for Treatment of Mine Water. Society of Mine Engineers Fall Meeting. St. Louis, Missouri, 23 p.

Grim, R.E. 1968. Clay Mineralogy, 2nd ed. McGraw-Hill, New York, NY. 596 p.

Gustafsson, E. and C.E. Klockars. 1981. Studies on groundwater transport in fractured crystalline rock under controlled conditions using nonradioactive tracers. Swedish Nuclear Fuel Supply Co. Stockholm. Div. KBS. 64 p.

Hvorslev, M.T. 1951. Time lag and soil permeability in groundwater observations. Bull. 36. U.S. Army Corps of Engineers, Waterways Exp. Sta. Vicksburg, Miss.

Ingram, H.A.P. 1983. Hydrology. In:Ecosystems of the world, vol. 4A, Mires: Swamp, bog, fen and moor, general studies. A. J. P. Gore (ed.) Elsevier, New York.

Ingram, H.A.P. 1967. Problems of hydrology and plant distribution in mires. Jour. of Ecology. 55:711-724.

Ingram, H.A.P., D.W. Rycroft and D.J.A. Williams. 1974. Anomalous transmission of water through certain peat. Jour. of Hydrology. 22:213-218.

Irwin, R. W. 1970. Soil water characteristics of some Ontario peat. Proc. 3rd Int. Peat Congr. Quebec, Canada (1968) pp. 219-223. From: Chason and Siegel (1986).

Kleinmann, R.L.P. 1985. Treatment of Acid Mine Water By Wetlands. pp 48-52. In: Control of Acid Mine Drainage, U.S. Bureau of Mines Information Circular, 9027.

Knight, A.H., R. Boggie, and H. Shepherd. 1971. The effect of groundwater level on water movement in peat: A study using titrated water. The Macaulay Institute for Soil Research, Craigiebuckler, Aberdeen, pp. 633-641.

Kruseman G.P. and N.A. De Ridder. 1983. Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement/ILRI, Wageningen, The Netherlands. 200 p.

Lee, R., J.A. Cherry, and J.F. Pickens. 1980. Groundwater transport of a salt tracer through a sandy lakebed. Limnol. Oceanogr. 25(1):46-61.

Lenda, A. and A. Zuber. 1970. Tracer dispersion in groundwater experiments: In: Isotope Hydrology (Proc. Symp. VIenna, 1970), IAEA, pp 619-641.

Lesica, P. 1986. Vegetation and Flora of Pine Butte Fen, Teton County, Montana. Great Basin Naturalist 46(1):22-32.

Lohman, S.W. 1979. Ground-Water Hydraulics. U.S. Geol. Surv. Prof. Paper 708. 70 p.

Martin, J.P., G.K. Helmkamp and J.O. Ervin. 1956. Effect of bromide from a soil fumigant and from $CaBr_2$ on growth and chemical composition of citrus plants. Soil Sci. Soc. Amer. Proc. 20(2)209-212.

Mathur, S.P. and R.S. Farnham. 1985. Geochemistry of Humic Substances in Natural and Cultivated Peatlands. In: Humic Substances in Soil, Sediment, and Water. (G.R. Aiken, D.M. McKnight, R.L. Wershaw and P. McCarthy, eds.) Wiley-Interscience, NY, pp. 53-85.

Mattson, S. 1929. The laws of soil colloidal behavior: 1. Soil Sci., 28(3):179-220.

McClernan, H.G. 1983. Metallic Mineral Deposits of Lewis and Clark County, Montana. Memoir 52, Montana Bureau of Mines and Geology. 73 p.

Merck Index. 1983. The Merck Index. M. Windholz, ed. Merck and Co., Inc. Rahway, NJ.

Merrill, S.D., S.J. Smith and J.F. Power. 1985. Effect of disturbed soil thickness on soil water use and movement under perennial grass. Soil Sci. Soc. Amer. Jour. 49:196-202.

Meyboom, P. 1967. Groundwater Studies in the Assiniboine River Drainage Basin, Part II Hydrologic Characteristics of Phreatophytic Vegetation in South-Central Saskatchewan. Geological Survey of Canada, Bulletin 139. 64 p.

Montana Department of Highways. 1975. General Highway Map of Lewis and Clark County Montana. Helena, Montana.

National Oceanic and Atmospheric Administration (NOAA). 1987. Climatological Summary of Montana. U.S. Department of Commerce.

Onken, A.B., C.W. Wendt, R.S. Hargrove, and O.C. Wilke. 1977. Relative movement of bromide and nitrate in soils under three irrigation systems. Soil Sci. Soc. Amer. Jour. 41:50-52.

Orion Research. 1982. Instruction Manual, Halide Electrodes Model 94-35 and Model 94-53. Cambridge, Massachusetts. 28 p.

Paivenen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta For. Fenn. 129:1-70. From: Chason and Siegel (1986).

Pardee, J.T. and F.C. Schrader. 1933. Metalliferous deposits of the greater Helena Mining District. U.S. Geol. Survey Bulletin 842. U.S. Government Printing Office, Washington, D.C.

Reclamation Research Unit and MDI. 1988. Hydrochemical, Microbiological and Vegetational Effects of a Natural Wetland on the Control of Acid Mine Drainage. Reclamation Research Unit, Montana State University, Bozeman, MT. Report No. 8805.

Reed, S.C., R.K. Bastian and W. Jewell. 1980. Engineering assessment of aquaculture systems for wastewater treatment: an overview. In: Aquaculture Systems for Wastewater Treatment, Seminar Proceedings and Engineering Assessment. U.S. EPA Washington, D.C. EPA 430/9-80-006. pp. 1-11.

Reichmuth, D.R. 1986. Fluvial Systems in the Wetlands Environment, preliminary draft. Geomax, P.C. Bozeman, MT. 45 p.

Robinson, R.A., R.H. Stokes. 1959. Electrolyte Solutions. Academic Press Inc., New York, NY. 559 p.

Romanov, V.V. 1968. Hydrophysics of bogs. N. Kaner (tr.) Heimann (ed.). Israel Prog. Sci. Transl., Jerusalem. From: Chason and Siegel (1986).

Schmotzer, J.K., W.A. Jester and R.R. Parizek. 1973. Groundwater tracing with post sampling activation analysis. Jour. of Hydrology, 20:217-236.

Shea, T.K. 1947. Geology and Mines of the Upper Blackfoot Valley, Montana. B.S. Thesis, Department of Geology, Montana School of Mines, Butte, Montana. p. 24.

Skibityke, H.E. and G.M. Robinson. 1963. Dispersion in groundwater flowing through heterogeneous materials. U.S. Geol. Surv. Prof. Paper. 386-B.

Slichter, C.S. 1902. The motions of underground waters: U.S. Geological Survey Water Supply Paper No. 67. 106 p.

Smith, S.J. and R.J. Davis. 1974. Relative movement of bromide and nitrate through soils. Journal of Environ. Quality, 3(2):152-155.

Soil Conservation Service (SCS). 1981. Average Annual Precipitation, Montana. U.S. Department of Agriculture, Bozeman, Montana.

Soil Survey Staff. 1975. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook No.436. U.S. Dept. of Agriculture, Soil Conservation Service. U.S. Government Printing Office, Washington, D.C.

Stanley, G. 1987. A Scientist's Dream. Ducks Unlimited 51(6):72-79.

Sturges, D.L. 1968. Hydrologic properties of peat from a Wyoming mountain bog. Soil Sci. 106(4):262-264.

Subramonian, D.C.S. and T.J. Sorg. 1986. Removing dissolved inorganic contaminants from water. Environ. Sci. Technol. 20(11):1072-1080.

Tennyson, L.L. and C.D. Settergren. 1980. Percolate water and bromide movement in the root zone of effluent irrigation sites. Water Resources Bull. 16(3):433-437.

Thomas, G.W. and A.R. Swoboda. 1970. Anion exclusion effects on chloride movement in soils. Soil Sci. 110(3):163-166.

Thurman, E.M. 1985. Organic Geochemistry of Natural Waters. Martinus Nijhoff/Dr. W. Junk Pub., Dordrecht. 497 p.

Vinogradov, A.P. 1959. The Geochemistry of Rare and Dispersed Chemical Elements in Soils. Consultants Bureau, Inc. New York, NY. 209 p.

Weisel, G.F. and R.L. Newell. 1970. Quality and seasonal fluctuation of headwater streams in western Montana. Missoula, Montana: Montana Forest and Conservation Experiment Station, School of Forestry.

Wieder, R.K., G.E. Lang and A.E. Whitehouse. 1984. The Use of Freshwater Wetlands to Treat Acid Mine Drainage. In: Burris, J.E. (ed.), Treatment of Mine Drainage by Wetlands, Contribution No. 264 of the Dept. of Biology, The Pennsylvania State University.

Wieder, R.K. and G.E. Lang. 1984. Influence of Wetlands and Coal Mining on Stream Water Chemistry. Water, Air, and Soil Pollution 23:381-396.

Williams, W.J. 1979. Handbook of Anion Determination. Butterworth Inc. Boston Massachusetts. 630 p.

Winter, T.C. and M.R. Carr. 1980. Hydrologic setting of wetlands in the Cottonwood Lake area, Stutsman County, North Dakota. U.S. Geol. Surv., Water-Resources Investigations 80-99, Denver, Co. 42 p.

Yamamoto, S. 1970. Study on permeability of soils, especially of peat soil (in Japanese with English summary). Mem. Fac. Agric., Hokkaido Univ. 7:307-411. From: Chason and Siegel (1986).

APPENDICES

APPENDIX A
WATER ELEVATION MEASUREMENTS FOR THE SWAMP GULCH WETLAND

Table 8. Water elevation measurements for the Swamp Gulch wetland.

Site	Ground Elevation	Elevation TOC1	WS2 Elevation 4/29/87	WS Elevation 6/3/87	WS Elevation 7/27/87	Potientiometric WS 8/13/87	WS Elevation 8/13/87	WS Elevation 1/13/88
				Meters				
culvert bottom	1577.22			1578.04				
AAA-3-D	1578.39	1579.22	1578.57		1578.53			
AAA-3-S	1578.38	1579.16	1578.48		1578.47			
AA-2-D	1578.17	1579.10	1578.85		1578.86			1578.81
AA-2-S	1578.18	1579.13	1578.40		1578.41			1578.24
A-3	1577.24	1578.13	1577.46		1577.53			
B-2-D	1577.31	1578.14	1577.52		1577.54	1577.30	1577.56	1577.58
B-2-S	1577.32	1578.14	1577.32		1577.33		1577.32	1577.35
BC-1-D	1577.78	1578.58	1576.51		1577.94	1577.75		1577.72
BC-1-S	1577.77	1578.50	1577.76		1577.83			1577.72
BC-1-2	1577.43	1578.21	1577.36		1577.39	1577.38	1577.45	1577.38
C-1-D	1577.82	1578.46			1577.77	1577.67	1577.68	1577.64
C-1-S	1577.75	1578.42	1577.91		1577.88		1577.84	1577.72
C-1.5	1577.02	1577.80	1577.00		1576.99	1576.98	1576.97	1577.01
C-2-D	1576.21	1577.06	1576.89		1576.87	1576.19	1576.84	1576.97
C-2-S	1576.24	1577.06	1576.37		1576.32		1576.32	1576.33
C-3-D	1575.94	1576.97	1576.09		1576.08			
C-3-S	1575.96	1576.99	1576.07		1576.08			
C-4-D	1575.58	1576.36	1575.54		1575.51			1575.30
C-4-S	1575.49	1576.37	1575.55		1575.55			1575.25
C-5-D	1575.24	1576.04	1574.71		1574.57			
C-5-S	1575.18	1575.98	1574.68		1574.56			
CD-1-2	1576.88	1577.68	1576.87		1576.88	1576.74	1576.76	1576.82
CD-1	1576.83	1577.62	1576.79		1576.81	1576.71	1576.74	1576.80
D-1-D	1575.93	1576.75	1576.11		1576.04	1575.84	1576.00	1575.99
D-1-S	1575.90	1576.73	1575.84		1575.91		1575.90	1575.96
D-2-D	1575.68	1576.52	1575.76		1575.72		1575.71	1575.71
D-2-S	1575.68	1576.49	1575.73		1575.73		1575.73	1575.74
D-3		1575.99	1575.19		1575.21			
E-1	1574.30	1575.10	1574.33		1574.32	1574.27	1574.31	1574.38
E-2	1574.31	1575.10	1574.24		1574.22	1574.31	1574.20	1574.25
E-3	1573.78	1574.72	1573.60		1573.51			
F-1-D	1573.13	1573.97				1573.10	1573.12	1573.13
F-1-S	1573.13	1573.98					1573.11	
F-2-D	1572.64	1573.61	1572.50		1572.43			1572.43
F-2-S	1572.59	1573.56	1572.54		1572.47			1572.44
F-3	1572.98	1573.80	1572.55		1572.47			
SEEP-D	1580.14	1580.95	1579.98		1579.92			1579.65
SEEP-S	1580.15	1580.95	1580.06		1579.98			1579.65

1 Top Of Casing
2 Water Surface

APPENDIX B
SWAMP GULCH FLOW AT THE TAILINGS DAM FLUME

Table 9. Swamp Gulch total daily flow (m^3) at the tailings dam flume.

Date	June	July	August	September	October	November
1		36.84	73.97	18.92	24.95	18.92
2		36.84	71.68	17.95	24.95	18.92
3		36.84	73.94	17.50	23.39	18.92
4		36.84	70.55	15.15	21.86	18.92
5		36.84	63.52	14.75	24.95	18.92
6		36.84	62.79	17.50	29.85	18.92
7		36.84	74.74	18.92	29.85	18.92
8		36.84	68.68	18.92	29.85	20.36
9		36.84	40.16	18.92	28.18	27.05
10		152.73	17.50	18.92	28.24	17.11
11		122.37	16.11	18.92	31.58	21.86
12		86.57	16.82	18.92	32.43	21.86
13		76.27	22.37	17.50	34.15	23.39
14		71.68	42.17	17.50	32.43	23.39
15	27.16	64.97	38.69	16.11	35.03	12.23
16	160.89	59.19	31.58	16.11	37.78	20.25
17	99.94	418.74	29.85	17.50	38.06	
18	171.62	731.79	28.18	18.92	26.99	
19	127.75	358.76	23.39	20.36	17.50	
20	78.90	238.74	21.86	20.36	16.11	
21	64.63	210.76	18.92	18.92	16.11	
22	57.43	213.56	18.92	18.92	16.11	
23	54.29	363.88	18.92	20.36	16.11	
24	53.27	191.33	19.88	20.36	16.79	
25	51.23	142.48	74.82	21.86	17.50	
26	45.00	120.47	38.23	20.36	18.92	
27	38.69	113.70	29.59	21.86	17.50	
28	36.84	111.04	29.57	23.39	18.92	
29	36.84	105.80	23.39	26.54	17.50	
30	36.84	98.13	22.37	26.54	16.79	
31		85.92	20.84		18.92	
Total	1141.32	4470.74	1204.00	578.78	759.32	319.93
Max	171.62	731.79	74.82	26.54	38.06	27.05
Min	36.84	36.84	16.11	14.75	16.11	12.23

APPENDIX C
PRECIPITATION FOR THE SWAMP GULCH WETLAND

Table 10. Precipitation for the Swamp Gulch Wetland.

Date	cm	in
6/09	0.25	0.10
6/10	0.25	0.10
6/16	1.02	0.40
6/17	0.30	0.12
6/18	1.27	0.50
6/21	0.13	0.05
TOTAL	3.22	1.27
7/01	0.13	0.05
7/05	0.13	0.05
7/09	0.13	0.05
7/10	2.34	0.92
7/16	0.71	0.28
7/17	5.72	2.25
7/18	0.89	0.35
7/20	0.08	0.03
7/21	0.10	0.04
7/22	1.42	0.56
7/30	0.18	0.07
TOTAL	11.83	4.65
8/07	0.20	0.08
8/10	0.13	0.05
8/14	0.71	0.28
8/15	0.25	0.10
8/16	0.10	0.04
8/24	0.05	0.02
8/25	1.07	0.42
8/26	0.03	0.01
8/27	0.03	0.01
8/28	0.05	0.02
TOTAL	2.62	1.03
9/27	0.08	0.03
9/30	0.10	0.04
TOTAL	0.18	0.07
10/15	0.08	0.03
10/16	0.38	0.15
TOTAL	0.46	0.18
11/02	0.13	0.05
11/03	0.20	0.08
11/14	0.25	0.10
11/19	1.07	0.42
TOTAL	1.65	0.65

Date	cm	in
12/02	0.36	0.14
12/04	0.20	0.08
12/08	0.18	0.07
12/09	0.25	0.10
12/11	1.52	0.60
---	---	---
12/12/87 - 01/11/88		
	4.24	1.67+
1/13	0.18	0.07
1/14	0.38	0.15
1/15	0.10	0.04
1/20	0.31	0.12
1/22	0.23	0.09
1/23	0.13	0.05
1/30	0.20	0.08
1/31	0.15	0.06
TOTAL 12/87 - 1/88		
	5.92	2.33
2/01	0.05	0.02
2/02	0.18	0.07
2/03	0.48	0.19
2/04	0.20	0.08
2/06	0.05	0.02
2/07	0.64	0.25
2/08	1.35	0.53
2/09	0.28	0.11
2/10	0.08	0.03
2/11	0.10	0.04
2/12	0.30	0.12
2/13	0.05	0.02
2/14	0.41	0.16
2/15	0.66	0.26
2/17	0.05	0.02
2/21	0.76	0.30
2/22	0.13	0.05
TOTAL	5.77	2.27

APPENDIX D
HYDRAULIC CONDUCTIVITY FIELD DATA

Table 11. Hydraulic conductivity field data.

Site: B-2-AH
Test date: 8/13/87
Test type: Rising head

Volume bailed: 910 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 91.44 cm
Water level below ground surface: 0.91 cm
Initial water level from datum: 54.86 cm
t2-t1: 45 sec
h2-h1: 18.29 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	74.68
10	60.05
20	57.30
30	56.69
30	56.69
45	56.39
60	56.08
90	55.78
120	55.78
150	55.47
180	55.47
240	55.47
300	55.17

Site: BC-1-2-AH
Test date: 8/13/87
Test type: Rising head

Volume bailed: 840 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 76.20 cm
Water level below ground surface: 4.57 cm
Initial water level from datum: 58.52 cm
t2-t1: 90 sec
h2-h1: 16.15 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	76.81
10	71.02
20	66.75
30	64.31
45	62.18
60	61.57
90	60.66
120	60.05
150	59.74
180	59.44
240	59.13
300	59.13

Site: C-1-AH
Test date: 8/14/87
Test type: Rising head

Volume bailed: 1070 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 70.10 cm
Water level below ground surface: 15.24 cm
Initial water level from datum: 71.93 cm
t2-t1: 90 sec
h2-h1: 18.59 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	95.40
10	86.87
20	85.65
30	83.82
45	81.99
60	79.25
90	76.81
120	75.29
150	74.68
180	74.07
240	73.46
300	73.15

Site: C-1.5-AH
Test date: 8/13/87
Test type: Rising head

Volume bailed: 1110 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 82.30 cm
Water level below ground surface: 4.57 cm
Initial water level from datum: 60.96 cm
t2-t1: 60 sec
h2-h1: 21.95 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	85.34
10	68.88
20	66.45
30	64.92
45	64.01
60	63.40
75	63.09
90	62.79
120	62.48
150	61.87
180	61.87
240	61.57
300	61.26

Table 11.--Continued

Site: C-2-AH

Test date: 8/14/87
Test type: Rising head

Volume bailed: 1060 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 121.92 cm
Water level below ground surface: 3.05 cm
Initial water level from datum: 56.39 cm
t2-t1: 45 sec
h2-h1: 21.95 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	79.55
10	60.35
20	59.44
30	58.52
45	57.61
60	57.30
90	57.00
120	56.69
150	56.69
180	56.69
240	56.39
300	56.39

Site: CD-1-2-AH

Test date: 8/13/87
Test type: Rising head

Volume bailed: 1200 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 82.30 cm
Water level below ground surface: 13.72 cm
Initial water level from datum: 69.19 cm
t2-t1: 60 sec
h2-h1: 24.08 cm

Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	95.40
10	81.99
20	75.59
30	73.76
45	72.54
60	71.32
75	71.02
90	70.71
120	70.41
150	70.10
180	70.10
240	69.80
300	69.49

Site: CD-1-AH

Test date: 8/13/87
Test type: Rising head

Volume bailed: 1000 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 106.68 cm
Water level below ground surface: 12.19 cm
Initial water level from datum: 65.84 cm
t2-t1: 90 sec
h2-h1: 18.29 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	87.48
10	79.25
20	75.90
30	73.76
45	71.63
60	70.71
75	69.80
90	69.19
120	68.58
150	68.28
180	67.97
240	67.67
300	67.36

Site: D-1-AH

Test date: 8/14/87
Test type: Rising head

Volume bailed: 810 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 94.49 cm
Water level below ground surface: 9.14 cm
Initial water level from datum: 62.18 cm
t2-t1: 90 sec
h2-h1: 14.94 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	79.86
10	77.72
20	74.37
30	71.63
45	68.58
60	67.06
90	64.92
120	64.01
150	63.40
180	63.09
240	63.09
300	63.09

Table 11.--Continued

Site: E-1-AH

Test date: 8/14/87
Test type: Rising head

Volume bailed: 665 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 88.39 cm
Water level below ground surface: 3.05 cm
Initial water level from datum: 58.52 cm
t2-t1: 90 sec
h2-h1: 11.28 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	73.15
10	65.53
20	65.23
30	64.62
45	63.70
60	62.79
90	61.87
120	60.96
150	60.35
180	60.05
240	59.74
300	59.74

Site: E-2-AH

Test date: 8/14/87
Test type: Rising head

Volume bailed: 1050 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 79.25 cm
Water level below ground surface: 0.30 cm
Initial water level from datum: 54.86 cm
t2-t1: 60 sec
h2-h1: 21.64 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	78.03
10	59.44
20	57.61
30	57.30
45	56.69
60	56.39
90	55.78
120	55.78
150	55.47
180	55.47
240	55.17
300	55.17

Site: F-1-AH

Test date: 8/14/87
Test type: Rising head

Volume bailed: 1045 ml
Hole radius: 3.81 cm
Hole depth below water surface (D): 88.39 cm
Water level below ground surface: 3.05 cm
Initial water level from datum: 55.17 cm
t2-t1: 45 sec
h2-h1: 18.59 cm
Test data:

Time from slug removal (sec)	Water level from datum (cm)
0	78.03
10	61.87
20	60.96
30	60.35
45	59.44
60	58.83
90	58.52
120	57.91
150	57.61
180	57.61
240	57.30
300	57.00

Site: B-2-D

Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 57.9 cm
t2-t1: 10 sec
h1: 38.1 cm
h2: 1.52 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	19.81
10	56.39
20	56.39
30	56.39
45	56.39
60	56.39
90	56.69
120	56.69
150	57.00
180	57.00
240	57.00

Table 11.--Continued

Site: B-2-S Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 81.99 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 14.33 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	43.89
10	49.68
20	51.21
30	52.43
45	54.86
60	56.69
90	59.74
120	63.09
150	65.84
180	67.67
240	71.02
300	73.46

Site: BC-1-2 Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 86.56 cm
t2-t1: 300 sec
h1: 38.1 cm
h2: 26.21 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	48.46
10	54.25
20	54.25
30	54.86
45	55.47
60	55.78
90	56.39
120	57.00
150	57.61
180	57.91
240	58.83
300	60.35
600	63.70

Site: C-1-D Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 77.11 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 7.62 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	39.01
10	54.25
20	56.39
30	59.44
50	60.05
60	60.96
80	62.79
100	64.62
120	66.75
150	68.28
180	69.49
240	71.32
300	73.15
600	75.29

Site: C-1-S Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 57.61 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 1.22 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	19.51
10	42.67
20	44.81
30	47.85
45	49.38
60	50.90
75	52.12
90	53.04
120	54.56
150	55.47
180	56.39
240	57.30
300	57.61

Table 11.--Continued

Site: C-1.5 Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 57.9 cm
Initial water level from top of casing: 83.52 cm
t2-t1: 150 sec
h1: 38.1 cm
h2: 9.14 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	45.42
10	54.86
20	57.30
30	59.44
45	61.57
60	64.01
75	66.45
90	68.28
120	71.63
150	74.37
180	76.50
240	79.55
300	81.69

Site: C-2-D Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 21.34 cm
t2-t1: 300 sec
h1: 38.1 cm
h2: 17.68 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
20	0.00
30	0.30
45	0.91
60	1.22
90	1.52
120	1.83
150	2.13
180	2.44
240	3.05
300	3.66
600	6.71

Site: C-2-S Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 74.07 cm
t2-t1: 150 sec
h1: 38.1 cm
h2: 19.2 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	35.97
10	43.28
20	45.11
30	46.02
45	47.24
60	48.46
90	50.90
120	53.04
150	54.86
180	56.39
240	59.44
300	61.57

Site: CD-1-2 Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 91.44 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 10.67 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	53.34
10	61.57
30	64.01
45	67.06
60	68.88
75	70.71
90	72.85
120	75.90
150	78.33
180	80.77
240	83.52
300	85.95

Table 11.--Continued

Site: CD-1 Test date: 8/13/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 87.78 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 17.07 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	49.68
10	59.44
20	62.18
30	62.79
45	63.40
60	64.62
75	65.53
90	66.45
120	67.97
150	70.10
180	70.71
240	72.85
300	74.68
600	80.16

Site: D-1-D Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 74.68 cm
t2-t1: 90 sec
h1: 38.1 cm
h2: 0.3 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	36.58
10	71.63
20	73.15
30	73.76
60	74.07
90	74.37
150	74.37
240	74.68

Site: D-1-S Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 82.3 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 25.6 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	44.20
10	47.85
20	50.60
30	51.82
45	52.43
60	53.04
90	53.95
120	54.86
150	55.78
180	56.69
240	58.52
300	60.35
630	66.45

Site: D-2-D Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 81.38 cm
t2-t1: 120 sec
h1: 38.1 cm
h2: 3.05 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	43.28
10	60.96
20	64.62
30	67.06
45	69.80
60	71.93
90	74.37
120	76.81
150	78.33
180	78.94
240	80.16
300	80.77

Table 11.--Continued

Site: D-2-S

Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 75.9 cm
t2-t1: 150 sec
h1: 38.1 cm
h2: 15.24 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	37.80
10	39.62
20	42.06
30	44.20
45	46.63
60	49.07
90	53.64
120	57.00
150	60.66
180	62.79
240	66.45
300	69.49

Site: E-1

Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 79.25 cm
t2-t1: 150 sec
h1: 38.1 cm
h2: 22.56 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	41.15
10	50.60
20	51.21
30	52.12
60	52.73
90	53.95
120	54.86
150	56.08
180	56.69
240	57.91
300	60.96
600	64.62

Site: E-2

Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 89.92 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 31.7 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	51.82
10	56.39
20	56.69
30	57.00
45	57.30
120	57.61
150	57.91
300	58.83
600	60.66

Site: F-1-D

Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 85.04 cm
t2-t1: 180 sec
h1: 38.1 cm
h2: 2.13 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	46.94
10	61.57
20	65.53
30	70.10
45	73.15
60	76.20
90	78.94
120	80.77
150	81.38
180	82.91
240	83.82
300	84.43

Table 11.--Continued

Site: F-1-S

Test date: 8/14/87
Test type: Falling head

Standpipe radius (r): 1.08 cm
Intake point radius (R): 2.54 cm
Screen legenth (L): 30.5 cm
Initial water level from top of casing: 87.78 cm
t2-t1: 300 sec
h1: 38.1 cm
h2: 32.92 cm
Test data:

Time from slug addition (sec)	Water level from top of casing (cm)
0	49.68
10	54.56
20	54.86
120	54.86
300	54.86
1500	55.17

APPENDIX E
REGRESSION EQUATIONS GENERATED FROM CALIBRATION CURVE DATA

Table 12. Calibration curve regression summary.

Time of Measurement (hours)*	Y Intersept	Slope	r^2
Background	117.91	-57.32	0.999
0-1.5	99.44	-54.46	0.999
1.5-7	114.04	-55.91	0.999
7-32	101.66	-55.08	0.999
32-50	100.98	-54.30	0.999
50-60	112.44	-58.03	0.999
60-90	110.66	-54.88	0.994
90-110	111.96	-53.90	0.991
110-130	110.77	-54.82	0.993
130-250	125.88	-58.15	0.999
250-280	109.26	-57.83	0.999
280-320	117.57	-58.37	0.999
320-420	111.48	-57.51	0.999
420-1000	116.47	-57.31	0.999
1000-2000	119.44	-57.47	0.999

* Calibration measurement from start of tracer experiment.

y = Y Intersept + (x) Slope
y axis = electrode potential (mv)
x axis = Br- concentration (log mg/l)

APPENDIX F
FIELD DATA GENERATED FROM THE BROMIDE TRACER EXPERIMENT

Table 13. Field data generated from the bromide tracer experiment.

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-1	09/09/87	1146	187	1.3	0.0	3.0
AH-1	09/09/87	1302	186	2.5	0.1	3.0
AH-1	09/09/87	1620	162	5.8	0.1	3.0
AH-1	09/10/87	830	153	22.0	0.1	3.0
AH-1	09/10/87	1234	118	26.1	0.5	3.0
AH-1	09/10/87	1609	97	29.6	1.2	3.0
AH-1	09/11/87	834	116	46.1	0.5	3.0
AH-1	09/11/87	1534	101	53.1	1.6	3.0
AH-1	09/12/87	855	119	70.4	0.7	3.0
AH-1	09/13/87	1721	120	102.8	0.7	3.0
AH-1	09/14/87	1120	124	120.8	0.6	3.0
AH-1	09/16/87	1107	158	168.6	0.3	3.0
AH-1	09/18/87	1405	158	219.6	0.3	3.0
AH-1	09/20/87	1404	148	267.6	0.2	3.0
AH-1	09/22/87	1526	158	316.9	0.2	3.0
AH-1	09/24/87	1557	166	365.4	0.1	3.0
AH-1	09/26/87	1256	163	410.4	0.1	3.0
AH-1	10/03/87	1635	181	582.1	0.1	3.0
AH-2	09/09/87	1120	70	0.8	3.5	3.0
AH-2	09/09/87	1400	89	3.5	2.8	3.0
AH-2	09/09/87	1622	97	5.9	2.0	3.0
AH-2	09/10/87	831	109	22.0	0.7	3.0
AH-2	09/10/87	1237	109	26.1	0.7	3.0
AH-2	09/10/87	1610	112	29.7	0.7	3.0
AH-2	09/11/87	837	114	46.1	0.6	3.0
AH-2	09/11/87	1503	127	52.5	0.6	3.0
AH-2	09/12/87	858	157	70.5	0.1	3.0
AH-2	09/13/87	1724	168	102.9	0.1	3.0
AH-2	09/14/87	1122	159	120.9	0.1	3.0
AH-2	09/16/87	1109	175	168.7	0.1	3.0
AH-2	09/18/87	1406	172	219.6	0.2	3.0
AH-2	09/20/87	1406	178	267.6	0.1	3.0
AH-2	09/22/87	1529	191	317.0	0.1	3.0
AH-2	09/24/87	1559	188	365.5	0.1	3.0
AH-2	09/26/87	1300	188	410.5	0.1	3.0
AH-2	10/03/87	1640	185	582.2	0.1	3.0
AH-3	09/09/87	1033	162	0.1	0.1	3.0
AH-3	09/09/87	1040	63	0.2	4.7	3.0
AH-3	09/09/87	1058	4	0.5	56.6	3.0
AH-3	09/09/87	1128	-11	1.0	106.7	3.0
AH-3	09/09/87	1345	108	3.2	1.3	3.0
AH-3	09/09/87	1622	153	5.9	0.2	3.0
AH-3	09/10/87	829	214	22.0	0.0	3.0
AH-4	09/09/87	1122	190	0.9	0.0	3.0
AH-4	09/09/87	1321	193	2.9	0.0	3.0
AH-4	09/10/87	852	90	22.4	1.6	3.0
AH-4	09/10/87	1308	84	26.6	2.1	3.0
AH-4	09/10/87	1613	79	29.7	2.6	3.0
AH-4	09/11/87	941	91	47.2	1.5	3.0
AH-4	09/11/87	1504	98	52.6	1.8	3.0
AH-4	09/12/87	900	130	70.5	0.4	3.0
AH-4	09/13/87	1726	152	102.9	0.2	3.0
AH-4	09/14/87	1125	156	120.9	0.1	3.0
AH-4	09/16/87	1120	164	168.8	0.2	3.0
AH-4	09/18/87	1409	169	219.7	0.2	3.0
AH-4	09/20/87	1411	174	267.7	0.1	3.0
AH-4	09/22/87	1535	192	317.1	0.1	3.0
AH-4	09/24/87	1601	186	365.5	0.1	3.0
AH-4	09/26/87	1302	184	410.5	0.1	3.0
AH-4	10/03/87	1642	200	582.2	0.0	3.0
AH-5	09/09/87	1124	196	0.9	0.0	3.0
AH-5	09/09/87	1323	189	2.9	0.1	3.0
AH-5	09/09/87	1640	190	6.2	0.0	3.0
AH-5	09/10/87	851	109	22.4	0.7	3.0
AH-5	09/10/87	1307	96	26.6	1.3	3.0
AH-5	09/10/87	1612	88	29.7	1.8	3.0
AH-5	09/11/87	939	86	47.1	1.9	3.0
AH-5	09/11/87	1509	93	52.6	2.2	3.0
AH-5	09/12/87	902	130	70.5	0.4	3.0
AH-5	09/13/87	1730	155	103.0	0.2	3.0
AH-5	09/14/87	1128	160	121.0	0.1	3.0
AH-5	09/16/87	1116	170	168.8	0.2	3.0
AH-5	09/18/87	1411	172	219.7	0.2	3.0
AH-5	09/20/87	1413	162	267.7	0.1	3.0
AH-5	09/22/87	1537	188	317.1	0.1	3.0
AH-5	09/24/87	1603	183	365.6	0.1	3.0
AH-5	09/26/87	1304	183	410.6	0.1	3.0
AH-5	10/03/87	1645	199	582.2	0.0	3.0
AH-6	09/09/87	1130	184	1.0	0.0	6.1
AH-6	09/09/87	2216	171	11.8	0.1	6.1
AH-6	09/10/87	850	183	22.3	0.0	6.1
AH-6	09/10/87	1306	181	26.6	0.0	6.1
AH-6	09/11/87	935	168	47.1	0.1	6.1
AH-6	09/11/87	1503	159	52.5	0.2	6.1
AH-6	09/12/87	905	150	70.6	0.2	6.1

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-6	09/13/87	1733	117	103.0	0.8	6.1
AH-6	09/14/87	1130	112	121.0	0.9	6.1
AH-6	09/16/87	1127	125	168.9	1.0	6.1
AH-6	09/18/87	1415	129	219.8	0.9	6.1
AH-6	09/20/87	1415	131	267.8	0.4	6.1
AH-6	09/22/87	1539	156	317.1	0.2	6.1
AH-6	09/24/87	1605	158	365.6	0.1	6.1
AH-6	09/26/87	1306	158	410.6	0.1	6.1
AH-6	10/03/87	1647	186	582.3	0.1	6.1
AH-7	09/09/87	1127	158	0.9	0.1	6.1
AH-7	09/09/87	1133	130	1.1	0.3	6.1
AH-7	09/09/87	1325	115	2.9	1.0	6.1
AH-7	09/09/87	1643	76	6.2	4.8	6.1
AH-7	09/09/87	2221	85	11.8	2.0	6.1
AH-7	09/10/87	849	92	22.3	1.5	6.1
AH-7	09/10/87	1304	135	26.6	0.2	6.1
AH-7	09/10/87	1614	106	29.7	0.8	6.1
AH-7	09/11/87	930	97	47.0	1.2	6.1
AH-7	09/11/87	1509	98	52.6	1.8	6.1
AH-7	09/12/87	907	129	70.6	0.5	6.1
AH-7	09/13/87	1735	124	103.1	0.6	6.1
AH-7	09/14/87	1131	122	121.0	0.6	6.1
AH-7	09/16/87	1132	142	169.0	0.5	6.1
AH-7	09/18/87	1413	149	219.7	0.4	6.1
AH-7	09/20/87	1433	137	268.1	0.3	6.1
AH-7	09/22/87	1556	149	317.4	0.3	6.1
AH-7	09/24/87	1607	162	365.6	0.1	6.1
AH-7	09/26/87	1309	155	410.6	0.2	6.1
AH-7	10/03/87	1650	203	582.3	0.0	6.1
AH-8	09/09/87	1043	194	0.2	0.0	6.1
AH-8	09/09/87	1136	167	1.1	0.1	6.1
AH-8	09/09/87	1645	83	6.2	3.6	6.1
AH-8	09/09/87	2224	79	11.9	2.6	6.1
AH-8	09/10/87	847	87	22.3	1.9	6.1
AH-8	09/10/87	1303	88	26.6	1.8	6.1
AH-8	09/10/87	1617	81	29.8	2.4	6.1
AH-8	09/11/87	927	89	47.0	1.7	6.1
AH-8	09/11/87	1510	97	52.7	1.8	6.1
AH-8	09/12/87	910	129	70.7	0.5	6.1
AH-8	09/13/87	1737	139	103.1	0.3	6.1
AH-8	09/14/87	1135	128	121.1	0.5	6.1
AH-8	09/16/87	1135	124	169.1	1.1	6.1
AH-8	09/18/87	1503	125	220.6	1.0	6.1
AH-8	09/20/87	1436	144	268.1	0.2	6.1
AH-8	09/22/87	1559	155	317.5	0.2	6.1
AH-8	09/24/87	1610	169	365.7	0.1	6.1
AH-8	09/26/87	1330	165	411.0	0.1	6.1
AH-8	10/03/87	1652	201	582.4	0.0	6.1
AH-9	09/09/87	1140	197	1.2	0.0	6.1
AH-9	09/09/87	2228	122	12.0	0.4	6.1
AH-9	09/10/87	845	103	22.2	0.9	6.1
AH-9	09/10/87	1301	103	26.5	0.9	6.1
AH-9	09/10/87	1618	94	29.8	1.4	6.1
AH-9	09/11/87	924	98	46.9	1.1	6.1
AH-9	09/11/87	1513	100	52.7	1.6	6.1
AH-9	09/12/87	918	124	70.8	0.6	6.1
AH-9	09/13/87	1740	135	103.2	0.4	6.1
AH-9	09/14/87	1139	130	121.2	0.5	6.1
AH-9	09/16/87	1138	133	169.1	0.8	6.1
AH-9	09/18/87	1504	133	220.6	0.8	6.1
AH-9	09/20/87	1438	159	268.1	0.1	6.1
AH-9	09/22/87	1601	188	317.5	0.1	6.1
AH-9	09/24/87	1632	175	366.0	0.1	6.1
AH-9	09/26/87	1333	175	411.1	0.1	6.1
AH-9	10/03/87	1719	202	582.8	0.0	6.1
AH-10	09/09/87	1118	188	0.8	0.0	6.1
AH-10	09/09/87	1319	190	2.8	0.0	6.1
AH-10	09/09/87	1717	188	6.8	0.1	6.1
AH-10	09/10/87	846	161	22.3	0.1	6.1
AH-10	09/10/87	1300	150	26.5	0.1	6.1
AH-10	09/10/87	1619	130	29.8	0.3	6.1
AH-10	09/11/87	921	117	46.9	0.5	6.1
AH-10	09/11/87	1515	111	52.8	1.1	6.1
AH-10	09/12/87	915	128	70.8	0.5	6.1
AH-10	09/13/87	1744	143	103.2	0.3	6.1
AH-10	09/14/87	1141	143	121.2	0.3	6.1
AH-10	09/16/87	1142	142	169.2	0.5	6.1
AH-10	09/18/87	1507	140	220.6	0.6	6.1
AH-10	09/20/87	1440	126	268.2	0.5	6.1
AH-10	09/22/87	1603	146	317.6	0.3	6.1
AH-10	09/24/87	1634	157	366.1	0.2	6.1
AH-10	09/26/87	1336	147	411.1	0.2	6.1
AH-10	10/03/87	1721	172	582.9	0.1	6.1
AH-11	09/09/87	1040	184	0.2	0.0	6.1
AH-11	09/09/87	1048	42	0.3	11.3	6.1
AH-11	09/09/87	1116	-5	0.8	82.8	6.1

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-11	09/09/87	1143	-5	1.2	82.8	6.1
AH-11	09/09/87	1629	101	6.0	1.7	6.1
AH-11	09/09/87	2234	156	12.1	0.1	6.1
AH-11	09/10/87	840	192	22.2	0.0	6.1
AH-11	09/10/87	1252	181	26.4	0.0	6.1
AH-11	09/10/87	1623	195	29.9	0.0	6.1
AH-11	09/11/87	900	191	46.5	0.0	6.1
AH-11	09/11/87	1517	186	52.8	0.1	6.1
AH-11	09/12/87	925	170	70.9	0.1	6.1
AH-11	09/13/87	1750	186	103.3	0.0	6.1
AH-11	09/14/87	1156	144	121.4	0.2	6.1
AH-11	09/16/87	1214	137	169.7	0.6	6.1
AH-11	09/18/87	1511	197	220.7	0.1	6.1
AH-11	09/20/87	1524	180	268.9	0.1	6.1
AH-11	09/22/87	1609	202	317.6	0.0	6.1
AH-11	09/24/87	1638	195	366.1	0.0	6.1
AH-11	09/26/87	1338	186	411.1	0.1	6.1
AH-11	10/03/87	1725	202	582.9	0.0	6.1
AH-12	09/09/87	1050	67	0.3	3.9	6.1
AH-12	09/09/87	1111	-2	0.7	72.9	6.1
AH-12	09/09/87	1709	84	6.7	3.5	6.1
AH-12	09/09/87	2241	78	12.2	2.7	6.1
AH-12	09/10/87	835	138	22.1	0.2	6.1
AH-12	09/10/87	1250	159	26.3	0.1	6.1
AH-12	09/10/87	1635	131	30.1	0.3	6.1
AH-12	09/11/87	858	130	46.5	0.3	6.1
AH-12	09/11/87	1531	154	53.0	0.2	6.1
AH-12	09/12/87	853	138	70.4	0.3	6.1
AH-12	09/13/87	1753	154	103.4	0.2	6.1
AH-12	09/14/87	1207	132	121.6	0.4	6.1
AH-12	09/16/87	1220	137	169.8	0.6	6.1
AH-12	09/18/87	1500	129	220.5	0.9	6.1
AH-12	09/20/87	1521	176	268.9	0.1	6.1
AH-12	09/22/87	1643	194	318.2	0.1	6.1
AH-12	09/24/87	1708	183	366.6	0.1	6.1
AH-12	09/26/87	1414	180	411.7	0.1	6.1
AH-12	10/03/87	1727	180	583.0	0.1	6.1
AH-13	09/09/87	1101	145	0.5	0.1	6.1
AH-13	09/09/87	1158	38	1.5	13.4	6.1
AH-13	09/09/87	1315	66	2.8	7.2	6.1
AH-13	09/09/87	1636	60	6.1	9.3	6.1
AH-13	09/09/87	2238	64	12.1	4.8	6.1
AH-13	09/10/87	832	89	22.0	1.7	6.1
AH-13	09/10/87	1247	84	26.3	2.1	6.1
AH-13	09/10/87	1635	87	30.1	1.9	6.1
AH-13	09/11/87	839	83	46.1	2.1	6.1
AH-13	09/11/87	1537	81	53.1	3.5	6.1
AH-13	09/12/87	850	106	70.3	1.2	6.1
AH-13	09/13/87	1755	109	103.4	1.1	6.1
AH-13	09/14/87	1210	98	121.7	1.7	6.1
AH-13	09/16/87	1222	110	169.9	1.9	6.1
AH-13	09/18/87	1459	117	220.5	1.4	6.1
AH-13	09/20/87	1519	156	268.8	0.2	6.1
AH-13	09/22/87	1641	185	318.2	0.1	6.1
AH-13	09/24/87	1706	181	366.6	0.1	6.1
AH-13	09/26/87	1411	181	411.7	0.1	6.1
AH-13	10/03/87	1750	202	583.3	0.0	6.1
AH-14	09/09/87	1059	188	0.5	0.0	6.1
AH-14	09/09/87	1313	189	2.7	0.1	6.1
AH-14	09/10/87	834	189	22.1	0.0	6.1
AH-14	09/10/87	1239	184	26.1	0.0	6.1
AH-14	09/10/87	1638	181	30.1	0.0	6.1
AH-14	09/11/87	842	147	46.2	0.1	6.1
AH-14	09/11/87	1540	125	53.2	0.6	6.1
AH-14	09/12/87	847	123	70.3	0.6	6.1
AH-14	09/13/87	1758	114	103.5	0.9	6.1
AH-14	09/14/87	1211	111	121.7	1.0	6.1
AH-14	09/16/87	1225	128	169.9	0.9	6.1
AH-14	09/18/87	1454	140	220.4	0.6	6.1
AH-14	09/20/87	1516	128	268.8	0.5	6.1
AH-14	09/22/87	1638	134	318.1	0.5	6.1
AH-14	09/24/87	1702	141	366.5	0.3	6.1
AH-14	09/26/87	1409	136	411.6	0.4	6.1
AH-14	10/03/87	1747	184	583.3	0.1	6.1
AH-15	09/09/87	1103	191	0.6	0.0	9.1
AH-15	09/09/87	1312	190	2.7	0.0	9.1
AH-15	09/10/87	922	190	22.9	0.0	9.1
AH-15	09/10/87	1240	185	26.2	0.0	9.1
AH-15	09/10/87	1639	189	30.1	0.0	9.1
AH-15	09/11/87	845	182	46.2	0.0	9.1
AH-15	09/11/87	1543	172	53.2	0.1	9.1
AH-15	09/12/87	943	160	71.2	0.1	9.1
AH-15	09/13/87	1800	120	103.5	0.7	9.1
AH-15	09/14/87	1255	111	122.4	1.0	9.1
AH-15	09/16/87	1229	127	170.0	1.0	9.1
AH-15	09/18/87	1452	132	220.4	0.8	9.1

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-15	09/20/87	1515	129	268.8	0.5	9.1
AH-15	09/22/87	1636	146	318.1	0.3	9.1
AH-15	09/24/87	1700	157	366.5	0.2	9.1
AH-15	09/26/87	1407	154	411.6	0.2	9.1
AH-15	10/03/87	1745	171	583.2	0.1	9.1
AH-15	10/17/87	1249	173	914.3	0.1	9.1
AH-16	09/09/87	1105	190	0.6	0.0	9.1
AH-16	09/09/87	1311	189	2.7	0.1	9.1
AH-16	09/09/87	1710	188	6.7	0.1	9.1
AH-16	09/09/87	2205	189	11.6	0.0	9.1
AH-16	09/10/87	926	186	22.9	0.0	9.1
AH-16	09/10/87	1242	183	26.2	0.0	9.1
AH-16	09/10/87	1640	187	30.2	0.0	9.1
AH-16	09/11/87	848	184	46.3	0.0	9.1
AH-16	09/11/87	1546	171	53.3	0.1	9.1
AH-16	09/12/87	947	179	71.3	0.1	9.1
AH-16	09/13/87	1803	181	103.5	0.1	9.1
AH-16	09/14/87	1258	166	122.5	0.1	9.1
AH-16	09/16/87	1230	156	170.0	0.3	9.1
AH-16	09/18/87	1450	135	220.3	0.7	9.1
AH-16	09/20/87	1511	125	268.7	0.5	9.1
AH-16	09/22/87	1635	128	318.1	0.7	9.1
AH-16	09/24/87	1658	131	366.5	0.5	9.1
AH-16	09/26/87	1403	124	411.6	0.6	9.1
AH-16	10/03/87	1743	164	583.2	0.1	9.1
AH-16	10/17/87	1251	181	914.4	0.1	9.1
AH-17	09/09/87	1107	193	0.6	0.0	9.1
AH-17	09/09/87	1309	188	2.6	0.1	9.1
AH-17	09/09/87	1711	190	6.7	0.0	9.1
AH-17	09/09/87	2215	192	11.8	0.0	9.1
AH-17	09/10/87	927	182	22.9	0.0	9.1
AH-17	09/10/87	1253	170	26.4	0.1	9.1
AH-17	09/10/87	1641	151	30.2	0.1	9.1
AH-17	09/11/87	849	127	46.3	0.3	9.1
AH-17	09/11/87	1550	118	53.3	0.8	9.1
AH-17	09/12/87	952	127	71.4	0.5	9.1
AH-17	09/13/87	1808	123	103.6	0.6	9.1
AH-17	09/14/87	1302	112	122.5	0.9	9.1
AH-17	09/16/87	1233	118	170.1	1.4	9.1
AH-17	09/18/87	1448	110	220.3	1.9	9.1
AH-17	09/20/87	1507	100	268.6	1.4	9.1
AH-17	09/22/87	1632	112	318.0	1.2	9.1
AH-17	09/24/87	1655	127	366.4	0.5	9.1
AH-17	09/26/87	1403	125	411.6	0.6	9.1
AH-17	10/03/87	1741	174	583.2	0.1	9.1
AH-17	10/17/87	1254	188	914.4	0.1	9.1
AH-18	09/09/87	1054	202	0.4	0.0	9.1
AH-18	09/09/87	1156	56	1.4	6.3	9.1
AH-18	09/09/87	1409	27	3.6	36.0	9.1
AH-18	09/09/87	1607	37	5.6	23.9	9.1
AH-18	09/09/87	2146	51	11.3	8.3	9.1
AH-18	09/10/87	822	80	21.9	2.5	9.1
AH-18	09/10/87	1244	78	26.2	2.7	9.1
AH-18	09/10/87	1642	68	30.2	4.1	9.1
AH-18	09/11/87	850	74	46.3	3.1	9.1
AH-18	09/11/87	1553	75	53.4	4.4	9.1
AH-18	09/12/87	956	104	71.4	1.3	9.1
AH-18	09/13/87	1810	111	103.7	1.0	9.1
AH-18	09/14/87	1304	105	122.6	1.3	9.1
AH-18	09/16/87	1237	119	170.1	1.3	9.1
AH-18	09/18/87	1446	118	220.3	1.4	9.1
AH-18	09/20/87	1500	74	268.5	4.1	9.1
AH-18	09/22/87	1621	90	317.9	3.0	9.1
AH-18	09/24/87	1653	106	366.4	1.2	9.1
AH-18	09/26/87	1353	104	411.4	1.4	9.1
AH-18	10/03/87	1739	163	583.1	0.1	9.1
AH-18	10/17/87	1303	165	914.5	0.1	9.1
AH-19	09/09/87	1341	189	3.2	0.1	9.1
AH-19	09/09/87	1644	182	6.2	0.1	9.1
AH-19	09/09/87	2221	144	11.8	0.2	9.1
AH-19	09/10/87	919	116	22.8	0.6	9.1
AH-19	09/10/87	1320	110	26.8	0.7	9.1
AH-19	09/10/87	1644	113	30.2	0.6	9.1
AH-19	09/11/87	1003	95	47.5	1.3	9.1
AH-19	09/11/87	1603	88	53.5	2.6	9.1
AH-19	09/12/87	958	113	71.5	0.9	9.1
AH-19	09/13/87	1812	116	103.7	0.8	9.1
AH-19	09/14/87	1307	107	122.6	1.2	9.1
AH-19	09/16/87	1243	119	170.2	1.3	9.1
AH-19	09/18/87	1437	116	220.1	1.5	9.1
AH-19	09/20/87	1456	116	268.4	0.8	9.1
AH-19	09/22/87	1619	147	317.8	0.3	9.1
AH-19	09/24/87	1645	162	366.2	0.1	9.1
AH-19	09/26/87	1350	148	411.3	0.2	9.1
AH-19	10/03/87	1729	185	583.0	0.1	9.1
AH-19	10/17/87	1306	184	914.6	0.1	9.1

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-20	09/09/87	1339	191	3.1	0.0	9.1
AH-20	09/09/87	2230	194	12.0	0.0	9.1
AH-20	09/10/87	918	185	22.8	0.0	9.1
AH-20	09/10/87	1319	167	26.8	0.1	9.1
AH-20	09/10/87	1647	143	30.3	0.2	9.1
AH-20	09/11/87	1006	109	47.6	0.7	9.1
AH-20	09/11/87	1605	101	53.6	1.6	9.1
AH-20	09/12/87	1000	124	71.5	0.6	9.1
AH-20	09/13/87	1823	136	103.9	0.4	9.1
AH-20	09/14/87	1309	136	122.7	0.3	9.1
AH-20	09/16/87	1245	145	170.2	0.5	9.1
AH-20	09/18/87	1425	134	219.9	0.7	9.1
AH-20	09/20/87	1453	116	268.4	0.8	9.1
AH-20	09/22/87	1617	142	317.8	0.4	9.1
AH-20	09/24/87	1643	162	366.2	0.1	9.1
AH-20	09/26/87	1348	161	411.3	0.1	9.1
AH-20	10/03/87	1716	186	582.8	0.1	9.1
AH-20	10/17/87	1308	188	914.6	0.1	9.1
AH-21	09/09/87	1337	189	3.1	0.1	9.1
AH-21	09/10/87	915	187	22.8	0.0	9.1
AH-21	09/10/87	1317	184	26.8	0.0	9.1
AH-21	09/10/87	1649	182	30.3	0.0	9.1
AH-21	09/11/87	1007	144	47.6	0.2	9.1
AH-21	09/11/87	1609	119	53.6	0.8	9.1
AH-21	09/12/87	1002	121	71.5	0.7	9.1
AH-21	09/13/87	1826	115	103.9	0.9	9.1
AH-21	09/14/87	1313	110	122.7	1.0	9.1
AH-21	09/16/87	1250	122	170.3	1.2	9.1
AH-21	09/18/87	1433	115	220.1	1.5	9.1
AH-21	09/20/87	1451	112	268.4	0.9	9.1
AH-21	09/22/87	1615	136	317.8	0.5	9.1
AH-21	09/24/87	1640	152	366.2	0.2	9.1
AH-21	09/26/87	1346	148	411.3	0.2	9.1
AH-21	10/03/87	1714	180	582.7	0.1	9.1
AH-21	10/17/87	1311	185	914.7	0.1	9.1
AH-22	09/09/87	1335	189	3.1	0.1	9.1
AH-22	09/09/87	2233	191	12.1	0.0	9.1
AH-22	09/10/87	914	173	22.7	0.1	9.1
AH-22	09/10/87	1316	151	26.8	0.1	9.1
AH-22	09/10/87	1650	152	30.3	0.1	9.1
AH-22	09/11/87	1010	112	47.7	0.6	9.1
AH-22	09/11/87	1612	103	53.7	1.4	9.1
AH-22	09/12/87	1006	123	71.6	0.6	9.1
AH-22	09/13/87	1827	124	104.0	0.6	9.1
AH-22	09/14/87	1315	113	122.8	0.9	9.1
AH-22	09/16/87	1252	119	170.4	1.3	9.1
AH-22	09/18/87	1431	105	220.0	2.3	9.1
AH-22	09/20/87	1448	106	268.3	1.1	9.1
AH-22	09/22/87	1613	132	317.7	0.6	9.1
AH-22	09/24/87	1630	148	366.0	0.2	9.1
AH-22	09/26/87	1344	143	411.2	0.3	9.1
AH-22	10/03/87	1712	184	582.7	0.1	9.1
AH-22	10/17/87	1313	181	914.7	0.1	9.1
AH-23	09/09/87	1334	188	3.1	0.1	9.1
AH-23	09/09/87	1647	187	6.3	0.1	9.1
AH-23	09/09/87	2236	194	12.1	0.0	9.1
AH-23	09/10/87	912	189	22.7	0.0	9.1
AH-23	09/10/87	1315	175	26.8	0.1	9.1
AH-23	09/10/87	1653	171	30.4	0.1	9.1
AH-23	09/11/87	1012	124	47.7	0.4	9.1
AH-23	09/11/87	1615	111	53.8	1.1	9.1
AH-23	09/12/87	1008	120	71.6	0.7	9.1
AH-23	09/13/87	1833	144	104.0	0.2	9.1
AH-23	09/14/87	1317	94	122.8	2.0	9.1
AH-23	09/16/87	1255	102	170.4	2.6	9.1
AH-23	09/18/87	1449	90	220.3	4.1	9.1
AH-23	09/20/87	1446	88	268.3	2.3	9.1
AH-23	09/22/87	1611	110	317.7	1.4	9.1
AH-23	09/24/87	1628	119	366.0	0.7	9.1
AH-23	09/26/87	1341	116	411.2	0.8	9.1
AH-23	10/03/87	1709	170	582.6	0.1	9.1
AH-23	10/17/87	1315	150	914.8	0.3	9.1
AH-23	10/23/87	1527	158	1061.0	0.2	9.1
AH-24	09/09/87	1334	184	3.1	0.1	9.1
AH-24	09/09/87	1651	186	6.3	0.1	9.1
AH-24	09/09/87	2240	191	12.2	0.0	9.1
AH-24	09/10/87	858	187	22.5	0.0	9.1
AH-24	09/10/87	1313	177	26.7	0.0	9.1
AH-24	09/10/87	1655	180	30.4	0.0	9.1
AH-24	09/11/87	951	137	47.4	0.2	9.1
AH-24	09/11/87	1618	121	53.8	0.7	9.1
AH-24	09/12/87	1012	139	71.7	0.3	9.1
AH-24	09/13/87	1835	152	104.1	0.2	9.1
AH-24	09/14/87	1319	129	122.8	0.5	9.1
AH-24	09/16/87	1257	153	170.4	0.3	9.1
AH-24	09/18/87	1421	148	219.8	0.4	9.1

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-24	09/20/87	1429	118	268.0	0.7	9.1
AH-24	09/22/87	1546	136	317.3	0.5	9.1
AH-24	09/24/87	1617	139	365.8	0.3	9.1
AH-24	09/26/87	1318	134	410.8	0.4	9.1
AH-24	10/03/87	1707	179	582.6	0.1	9.1
AH-24	10/17/87	1143	174	913.2	0.1	9.1
AH-25	09/09/87	1329	182	3.0	0.1	9.1
AH-25	09/09/87	1652	190	6.4	0.0	9.1
AH-25	09/09/87	2247	192	12.3	0.0	9.1
AH-25	09/10/87	857	184	22.4	0.0	9.1
AH-25	09/10/87	1312	179	26.7	0.0	9.1
AH-25	09/10/87	1656	178	30.4	0.0	9.1
AH-25	09/11/87	948	161	47.3	0.1	9.1
AH-25	09/11/87	1621	147	53.9	0.2	9.1
AH-25	09/12/87	1014	161	71.7	0.1	9.1
AH-25	09/13/87	1834	175	104.1	0.1	9.1
AH-25	09/14/87	1321	142	122.8	0.3	9.1
AH-25	09/16/87	1300	176	170.5	0.1	9.1
AH-25	09/18/87	1420	168	219.8	0.2	9.1
AH-25	09/20/87	1420	124	267.8	0.6	9.1
AH-25	09/22/87	1544	143	317.2	0.4	9.1
AH-25	09/24/87	1615	152	365.8	0.2	9.1
AH-25	09/26/87	1315	143	410.8	0.3	9.1
AH-25	10/03/87	1657	187	582.5	0.1	9.1
AH-25	10/17/87	1140	186	913.2	0.1	9.1
AH-26	09/09/87	1327	166	3.0	0.1	9.1
AH-26	09/09/87	1713	170	6.7	0.1	9.1
AH-26	09/09/87	2246	169	12.3	0.1	9.1
AH-26	09/10/87	856	169	22.4	0.1	9.1
AH-26	09/10/87	1311	152	26.7	0.1	9.1
AH-26	09/10/87	1657	162	30.4	0.1	9.1
AH-26	09/11/87	945	145	47.2	0.1	9.1
AH-26	09/11/87	1623	124	53.9	0.6	9.1
AH-26	09/12/87	1017	131	71.8	0.4	9.1
AH-26	09/13/87	1831	160	104.0	0.1	9.1
AH-26	09/14/87	1324	119	122.9	0.7	9.1
AH-26	09/16/87	1303	182	170.6	0.1	9.1
AH-26	09/18/87	1417	130	219.8	0.8	9.1
AH-26	09/20/87	1417	102	267.8	1.3	9.1
AH-26	09/22/87	1541	134	317.2	0.5	9.1
AH-26	09/24/87	1613	126	365.7	0.6	9.1
AH-26	09/26/87	1313	114	410.7	0.9	9.1
AH-26	10/03/87	1655	198	582.4	0.0	9.1
AH-26	10/17/87	1137	188	913.1	0.1	9.1
AH-27	09/09/87	1347	130	3.3	0.5	12.2
AH-27	09/09/87	1655	140	6.4	0.3	12.2
AH-27	09/10/87	859	156	22.5	0.1	12.2
AH-27	09/10/87	1342	147	27.2	0.1	12.2
AH-27	09/10/87	1659	130	30.5	0.3	12.2
AH-27	09/11/87	954	116	47.4	0.5	12.2
AH-27	09/11/87	1625	111	53.9	1.1	12.2
AH-27	09/12/87	1022	137	71.9	0.3	12.2
AH-27	09/13/87	1829	170	104.0	0.1	12.2
AH-27	09/14/87	1329	124	123.0	0.6	12.2
AH-27	09/16/87	1307	162	170.6	0.2	12.2
AH-27	09/18/87	1423	149	219.9	0.4	12.2
AH-27	09/20/87	1423	111	267.9	0.9	12.2
AH-27	09/22/87	1549	155	317.3	0.2	12.2
AH-27	09/24/87	1619	139	365.8	0.3	12.2
AH-27	09/26/87	1322	93	410.9	2.1	12.2
AH-27	10/03/87	1700	183	582.5	0.1	12.2
AH-27	10/17/87	1145	182	913.2	0.1	12.2
AH-28	09/09/87	1151	28	1.4	20.5	15.2
AH-28	09/09/87	1351	147	3.4	0.3	15.2
AH-28	09/09/87	1656	156	6.4	0.2	15.2
AH-28	09/10/87	900	150	22.5	0.1	15.2
AH-28	09/10/87	1341	148	27.2	0.1	15.2
AH-28	09/10/87	1701	127	30.5	0.3	15.2
AH-28	09/11/87	957	144	47.5	0.2	15.2
AH-28	09/11/87	1628	136	54.0	0.4	15.2
AH-28	09/12/87	1025	125	71.9	0.6	15.2
AH-28	09/13/87	1826	149	103.9	0.2	15.2
AH-28	09/14/87	1331	122	123.0	0.6	15.2
AH-28	09/16/87	1309	168	170.7	0.2	15.2
AH-28	09/18/87	1425	152	219.9	0.3	15.2
AH-28	09/20/87	1426	140	267.9	0.3	15.2
AH-28	09/22/87	1550	156	317.3	0.2	15.2
AH-28	09/24/87	1621	147	365.9	0.2	15.2
AH-28	09/26/87	1325	113	410.9	0.9	15.2
AH-28	10/03/87	1702	169	582.5	0.1	15.2
AH-28	10/17/87	1147	157	913.3	0.2	15.2
AH-28	10/23/87	1531	173	1061.0	0.1	15.2
AH-28	10/31/87	1353	189	1251.4	0.1	15.2
AH-29	09/09/87	1352	163	3.4	0.1	18.3
AH-29	09/09/87	1657	157	6.5	0.2	18.3
AH-29	09/10/87	902	163	22.5	0.1	18.3

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
AH-29	09/10/87	1339	165	27.1	0.1	18.3
AH-29	09/10/87	1703	145	30.6	0.2	18.3
AH-29	09/11/87	959	146	47.5	0.1	18.3
AH-29	09/11/87	1630	139	54.0	0.3	18.3
AH-29	09/12/87	1027	154	72.0	0.2	18.3
AH-29	09/13/87	1824	149	103.9	0.2	18.3
AH-29	09/14/87	1334	111	123.1	1.0	18.3
AH-29	09/16/87	1311	168	170.7	0.2	18.3
AH-29	09/18/87	1427	152	219.9	0.3	18.3
AH-29	09/20/87	1428	130	268.0	0.4	18.3
AH-29	09/22/87	1553	160	317.4	0.2	18.3
AH-29	09/24/87	1623	152	365.9	0.2	18.3
AH-29	09/26/87	1328	143	411.0	0.3	18.3
AH-29	10/03/87	1704	166	582.6	0.1	18.3
AH-29	10/17/87	1150	140	913.3	0.4	18.3
AH-29	10/23/87	1529	178	1061.0	0.1	18.3
AH-29	10/31/87	1354	185	1251.4	0.1	18.3
AH-30	09/09/87	1109	62	0.7	4.9	12.2
AH-30	09/09/87	1154	6	1.4	52.0	12.2
AH-30	09/09/87	1606	25	5.6	39.1	12.2
AH-30	09/09/87	2143	37	11.2	14.9	12.2
AH-30	09/10/87	821	91	21.9	1.6	12.2
AH-30	09/10/87	1324	101	26.9	1.0	12.2
AH-30	09/10/87	1723	96	30.9	1.3	12.2
AH-30	09/11/87	857	103	46.5	0.9	12.2
AH-30	09/11/87	1555	92	53.4	2.2	12.2
AH-30	09/12/87	1035	103	72.1	1.4	12.2
AH-30	09/13/87	1815	101	103.8	1.6	12.2
AH-30	09/14/87	1443	111	124.2	1.0	12.2
AH-30	09/16/87	1326	102	170.9	2.6	12.2
AH-30	09/18/87	1443	96	220.2	3.3	12.2
AH-30	09/20/87	1502	114	268.5	0.8	12.2
AH-30	09/22/87	1625	83	317.9	3.9	12.2
AH-30	09/24/87	1647	87	366.3	2.7	12.2
AH-30	09/26/87	1356	82	411.4	3.2	12.2
AH-30	10/03/87	1737	194	583.1	0.0	12.2
AH-30	10/17/87	1300	193	914.5	0.1	12.2
AH-31	09/09/87	1112	186	0.7	0.0	15.2
AH-31	09/09/87	1152	11	1.4	42.1	15.2
AH-31	09/09/87	1603	37	5.5	23.9	15.2
AH-31	09/09/87	2139	93	11.2	1.4	15.2
AH-31	09/10/87	820	131	21.8	0.3	15.2
AH-31	09/10/87	1325	120	26.9	0.5	15.2
AH-31	09/10/87	1725	116	30.9	0.6	15.2
AH-31	09/11/87	854	125	46.4	0.4	15.2
AH-31	09/11/87	1558	119	53.5	0.8	15.2
AH-31	09/12/87	1033	141	72.0	0.3	15.2
AH-31	09/13/87	1818	154	103.8	0.2	15.2
AH-31	09/14/87	1441	149	124.2	0.2	15.2
AH-31	09/16/87	1330	164	171.0	0.2	15.2
AH-31	09/18/87	1442	143	220.2	0.5	15.2
AH-31	09/20/87	1504	101	268.6	1.4	15.2
AH-31	09/22/87	1627	104	317.9	1.7	15.2
AH-31	09/24/87	1648	105	366.3	1.3	15.2
AH-31	09/26/87	1358	93	411.5	2.1	15.2
AH-31	10/03/87	1734	138	583.1	0.4	15.2
AH-31	10/17/87	1258	185	914.5	0.1	15.2
AH-32	09/09/87	1407	32	3.6	29.3	18.3
AH-32	09/09/87	1611	48	5.7	15.2	18.3
AH-32	09/09/87	2138	91	11.1	1.6	18.3
AH-32	09/10/87	818	136	21.8	0.2	18.3
AH-32	09/10/87	1327	138	26.9	0.2	18.3
AH-32	09/10/87	1727	127	30.9	0.3	18.3
AH-32	09/11/87	856	146	46.4	0.1	18.3
AH-32	09/11/87	1600	138	53.5	0.4	18.3
AH-32	09/12/87	1030	148	72.0	0.2	18.3
AH-32	09/13/87	1820	152	103.8	0.2	18.3
AH-32	09/14/87	1438	138	124.1	0.3	18.3
AH-32	09/16/87	1432	177	172.0	0.1	18.3
AH-32	09/18/87	1440	174	220.2	0.1	18.3
AH-32	09/20/87	1507	94	268.6	1.8	18.3
AH-32	09/22/87	1629	138	318.0	0.5	18.3
AH-32	09/24/87	1650	144	366.3	0.3	18.3
AH-32	09/26/87	1400	119	411.5	0.7	18.3
AH-32	10/03/87	1731	173	583.0	0.1	18.3
AH-32	10/17/87	1256	194	914.4	0.0	18.3
C-1-S	09/09/87	1405	127	3.6	0.6	6.4
C-1-S	09/09/87	1718	132	6.8	0.5	6.4
C-1-S	09/09/87	2155	134	11.4	0.3	6.4
C-1-S	09/10/87	837	101	22.1	1.0	6.4
C-1-S	09/10/87	1257	109	26.4	0.7	6.4
C-1-S	09/10/87	1629	89	30.0	1.7	6.4
C-1-S	09/11/87	903	79	46.5	2.5	6.4
C-1-S	09/11/87	1522	79	52.9	3.8	6.4
C-1-S	09/12/87	928	93	71.0	2.1	6.4
C-1-S	09/13/87	1724	107	102.9	1.2	6.4

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
C-1-S	09/14/87	1200	84	121.5	3.1	6.4
C-1-S	09/16/87	1210	111	169.7	1.8	6.4
C-1-S	09/18/87	1515	103	220.8	2.5	6.4
C-1-S	09/20/87	1531	88	269.0	2.3	6.4
C-1-S	09/22/87	1648	130	318.3	0.6	6.4
C-1-S	09/24/87	1714	133	366.7	0.4	6.4
C-1-S	09/26/87	1438	134	412.1	0.4	6.4
C-1-S	10/03/87	1800	168	583.5	0.1	6.4
C-1-S	10/17/87	1322	152	914.9	0.2	6.4
C-1-S	10/23/87	1517	193	1060.8	0.1	6.4
C-1-S	10/31/87	1401	192	1251.5	0.1	6.4
C-1-D	09/09/87	1720	138	6.8	0.4	6.4
C-1-D	09/10/87	942	133	23.2	0.3	6.4
C-1-D	09/10/87	1255	144	26.4	0.2	6.4
C-1-D	09/10/87	1633	130	30.1	0.3	6.4
C-1-D	09/11/87	910	127	46.7	0.3	6.4
C-1-D	09/11/87	1527	131	53.0	0.5	6.4
C-1-D	09/12/87	936	145	71.1	0.2	6.4
C-1-D	09/13/87	1720	158	102.8	0.1	6.4
C-1-D	09/14/87	1201	122	121.5	0.6	6.4
C-1-D	09/16/87	1206	170	169.6	0.2	6.4
C-1-D	09/18/87	1518	144	220.8	0.5	6.4
C-1-D	09/20/87	1527	121	268.9	0.6	6.4
C-1-D	09/22/87	1700	166	318.5	0.1	6.4
C-1-D	09/24/87	1710	158	366.7	0.1	6.4
C-1-D	09/26/87	1435	138	412.1	0.3	6.4
C-1-D	10/03/87	1755	171	583.4	0.1	6.4
C-1-D	10/17/87	1320	146	914.8	0.3	6.4
C-1-D	10/23/87	1520	183	1060.8	0.1	6.4
C-1-D	10/31/87	1358	180	1251.5	0.1	6.4
C-1-AH	09/10/87	841	85	22.2	2.0	6.1
C-1-AH	09/10/87	1259	88	26.5	1.8	6.1
C-1-AH	09/10/87	1628	80	30.0	2.5	6.1
C-1-AH	09/11/87	919	98	46.8	1.1	6.1
C-1-AH	09/11/87	1516	99	52.8	1.7	6.1
C-1-AH	09/12/87	922	135	70.9	0.4	6.1
C-1-AH	09/13/87	1747	129	103.3	0.5	6.1
C-1-AH	09/14/87	1154	121	121.4	0.7	6.1
C-1-AH	09/16/87	1217	139	169.8	0.6	6.1
C-1-AH	09/18/87	1509	132	220.7	0.8	6.1
C-1-AH	09/20/87	1443	176	268.2	0.1	6.1
C-1-AH	09/22/87	1606	176	317.6	0.1	6.1
C-1-AH	09/24/87	1636	178	366.1	0.1	6.1
C-1-AH	09/26/87	1433	168	412.1	0.1	6.1
C-1-AH	10/03/87	1723	198	582.9	0.0	6.1
BC-1-SURF	09/09/87	1358	126	3.5	0.6	27.4
BC-1-SURF	09/09/87	1659	139	6.5	0.4	27.4
BC-1-SURF	09/09/87	2135	116	11.1	0.6	27.4
BC-1-SURF	09/10/87	904	134	22.6	0.3	27.4
BC-1-SURF	09/10/87	1337	118	27.1	0.5	27.4
BC-1-SURF	09/10/87	1705	108	30.6	0.8	27.4
BC-1-SURF	09/11/87	1104	91	48.6	1.5	27.4
BC-1-SURF	09/11/87	1700	104	54.5	1.4	27.4
BC-1-SURF	09/12/87	1106	113	72.6	0.9	27.4
BC-1-SURF	09/13/87	1727	127	103.0	0.5	27.4
BC-1-SURF	09/14/87	1409	104	123.7	1.3	27.4
BC-1-SURF	09/16/87	1315	190	170.8	0.1	27.4
BC-1-SURF	09/18/87	1541	135	221.2	0.7	27.4
BC-1-SURF	09/20/87	1600	138	269.5	0.3	27.4
BC-1-SURF	09/22/87	1725	148	318.9	0.3	27.4
BC-1-SURF	09/24/87	1741	142	367.2	0.3	27.4
BC-1-SURF	09/26/87	1510	140	412.7	0.3	27.4
BC-1-SURF	10/03/87	1830	177	584.0	0.1	27.4
BC-1-SURF	10/17/87	1326	137	914.9	0.4	27.4
BC-1-SURF	10/23/87	1612	195	1061.7	0.1	27.4
BC-1-SURF	10/31/87	1455	176	1252.4	0.1	27.4
BC-1-SURF	11/07/87	1352	197	1419.4	0.0	27.4
BC-1-SURF	11/14/87	1106	158	1584.6	0.2	27.4
BC-1-SURF	11/21/87	1431	189	1756.0	0.1	27.4
BC-1-S	09/09/87	2140	174	11.2	0.1	30.8
BC-1-S	09/10/87	907	160	22.6	0.1	30.8
BC-1-S	09/10/87	1336	169	27.1	0.1	30.8
BC-1-S	09/10/87	1706	98	30.6	1.2	30.8
BC-1-S	09/11/87	1107	108	48.6	0.7	30.8
BC-1-S	09/11/87	1701	85	54.5	3.0	30.8
BC-1-S	09/12/87	1104	163	72.6	0.1	30.8
BC-1-S	09/13/87	1733	171	103.0	0.1	30.8
BC-1-S	09/14/87	1410	155	123.7	0.2	30.8
BC-1-S	09/16/87	1317	192	170.8	0.1	30.8
BC-1-S	09/18/87	1545	175	221.2	0.1	30.8
BC-1-S	09/20/87	1558	134	269.5	0.4	30.8
BC-1-S	09/22/87	1720	188	318.8	0.1	30.8
BC-1-S	09/24/87	1745	177	367.2	0.1	30.8
BC-1-S	09/26/87	1414	149	411.7	0.2	30.8
BC-1-S	10/03/87	1827	201	584.0	0.0	30.8
BC-1-S	10/17/87	1328	127	915.0	0.7	30.8

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
BC-1-S	10/23/87	1615	171	1061.8	0.1	30.8
BC-1-S	10/31/87	1453	203	1252.4	0.0	30.8
BC-1-S	11/07/87	1356	197	1419.4	0.0	30.8
BC-1-S	11/14/87	1108	209	1584.6	0.0	30.8
BC-1-S	11/21/87	1434	193	1756.1	0.1	30.8
BC-1-2	09/09/87	1702	142	6.5	0.3	35.0
BC-1-2	09/09/87	2150	120	11.3	0.5	35.0
BC-1-2	09/10/87	908	100	22.6	1.1	35.0
BC-1-2	09/10/87	1332	108	27.0	0.8	35.0
BC-1-2	09/10/87	1709	103	30.6	0.9	35.0
BC-1-2	09/11/87	1110	88	48.7	1.7	35.0
BC-1-2	09/11/87	1704	90	54.6	2.4	35.0
BC-1-2	09/12/87	1110	121	72.7	0.7	35.0
BC-1-2	09/13/87	1747	158	103.3	0.1	35.0
BC-1-2	09/14/87	1414	102	123.7	1.4	35.0
BC-1-2	09/16/87	1414	159	171.7	0.3	35.0
BC-1-2	09/18/87	1538	140	221.1	0.6	35.0
BC-1-2	09/20/87	1553	113	269.4	0.9	35.0
BC-1-2	09/22/87	1717	167	318.8	0.1	35.0
BC-1-2	09/24/87	1738	152	367.1	0.2	35.0
BC-1-2	09/26/87	1507	119	412.6	0.7	35.0
BC-1-2	10/03/87	1820	175	583.8	0.1	35.0
BC-1-2	10/17/87	1333	116	915.0	1.0	35.0
BC-1-2	10/23/87	1606	193	1061.6	0.1	35.0
BC-1-2	10/31/87	1446	199	1252.3	0.0	35.0
BC-1-2	11/07/87	1345	186	1419.2	0.1	35.0
BC-1-2	11/14/87	1058	190	1584.5	0.1	35.0
BC-1-2	11/21/87	1427	183	1756.0	0.1	35.0
BC-1-2-AH	09/09/87	1704	153	6.6	0.2	34.1
BC-1-2-AH	09/09/87	2145	174	11.2	0.1	34.1
BC-1-2-AH	09/10/87	909	143	22.6	0.2	34.1
BC-1-2-AH	09/10/87	1333	155	27.1	0.1	34.1
BC-1-2-AH	09/10/87	1710	134	30.7	0.3	34.1
BC-1-2-AH	09/11/87	1112	120	48.7	0.5	34.1
BC-1-2-AH	09/11/87	1707	132	54.6	0.5	34.1
BC-1-2-AH	09/12/87	1112	141	72.7	0.3	34.1
BC-1-2-AH	09/13/87	1749	140	103.3	0.3	34.1
BC-1-2-AH	09/14/87	1418	139	123.8	0.3	34.1
BC-1-2-AH	09/16/87	1324	185	170.9	0.1	34.1
BC-1-2-AH	09/18/87	1536	168	221.1	0.2	34.1
BC-1-2-AH	09/20/87	1551	134	269.4	0.4	34.1
BC-1-2-AH	09/22/87	1715	179	318.8	0.1	34.1
BC-1-2-AH	09/24/87	1735	166	367.1	0.1	34.1
BC-1-2-AH	09/26/87	1504	173	412.6	0.1	34.1
BC-1-2-AH	10/03/87	1819	187	583.8	0.1	34.1
BC-1-2-AH	10/17/87	1335	158	915.1	0.2	34.1
BC-1-2-AH	10/23/87	1608	170	1061.6	0.1	34.1
BC-1-2-AH	10/31/87	1444	177	1252.2	0.1	34.1
BC-1-2-AH	11/07/87	1349	164	1419.3	0.2	34.1
BC-1-2-AH	11/14/87	1100	165	1584.5	0.2	34.1
BC-1-2-AH	11/21/87	1425	173	1755.9	0.1	34.1
C-1.5	09/09/87	1614	142	5.7	0.3	37.5
C-1.5	09/09/87	2132	116	11.0	0.6	37.5
C-1.5	09/10/87	1815	105	31.8	0.9	37.5
C-1.5	09/10/87	1330	115	27.0	0.6	37.5
C-1.5	09/10/87	1714	93	30.7	1.4	37.5
C-1.5	09/11/87	1042	98	48.2	1.1	37.5
C-1.5	09/11/87	1720	78	54.8	3.9	37.5
C-1.5	09/12/87	1117	125	72.8	0.6	37.5
C-1.5	09/13/87	1751	135	103.3	0.4	37.5
C-1.5	09/14/87	1421	99	123.8	1.6	37.5
C-1.5	09/16/87	1438	164	172.1	0.2	37.5
C-1.5	09/18/87	1533	145	221.1	0.5	37.5
C-1.5	09/20/87	1545	106	269.2	1.1	37.5
C-1.5	09/22/87	1709	164	318.6	0.2	37.5
C-1.5	09/24/87	1729	154	367.0	0.2	37.5
C-1.5	09/26/87	1458	115	412.5	0.9	37.5
C-1.5	10/03/87	1814	169	583.7	0.1	37.5
C-1.5	10/17/87	1342	94	915.2	2.5	37.5
C-1.5	10/23/87	1558	182	1061.5	0.1	37.5
C-1.5	10/31/87	1440	182	1252.2	0.1	37.5
C-1.5	11/07/87	1334	184	1419.1	0.1	37.5
C-1.5	11/14/87	1052	186	1584.4	0.1	37.5
C-1.5-AH	09/09/87	1405	125	3.6	0.6	37.5
C-1.5-AH	09/09/87	1616	151	5.8	0.2	37.5
C-1.5-AH	09/09/87	2134	153	11.1	0.1	37.5
C-1.5-AH	09/10/87	816	112	21.8	0.7	37.5
C-1.5-AH	09/10/87	1328	115	27.0	0.6	37.5
C-1.5-AH	09/10/87	1712	91	30.7	1.6	37.5
C-1.5-AH	09/11/87	1045	116	48.2	0.5	37.5
C-1.5-AH	09/11/87	1723	92	54.9	2.2	37.5
C-1.5-AH	09/12/87	1115	136	72.8	0.3	37.5
C-1.5-AH	09/13/87	1754	126	103.4	0.6	37.5
C-1.5-AH	09/14/87	1423	102	123.9	1.4	37.5
C-1.5-AH	09/16/87	1436	156	172.1	0.3	37.5
C-1.5-AH	09/18/87	1530	130	221.0	0.8	37.5

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
C-1.5-AH	09/20/87	1547	125	269.3	0.5	37.5
C-1.5-AH	09/22/87	1711	143	318.7	0.4	37.5
C-1.5-AH	09/24/87	1731	134	367.0	0.4	37.5
C-1.5-AH	09/26/87	1500	115	412.5	0.9	37.5
C-1.5-AH	10/03/87	1616	178	581.8	0.1	37.5
C-1.5-AH	10/17/87	1340	149	915.2	0.3	37.5
C-1.5-AH	10/23/87	1500	165	1060.5	0.2	37.5
C-1.5-AH	10/31/87	1442	167	1252.2	0.1	37.5
C-1.5-AH	11/07/87	1336	178	1419.1	0.1	37.5
C-1.5-AH	11/14/87	1050	187	1584.3	0.1	37.5
CD-1-2	09/09/87	1723	132	6.9	0.5	35.7
CD-1-2	09/09/87	2155	111	11.4	0.7	35.7
CD-1-2	09/10/87	811	95	21.7	1.3	35.7
CD-1-2	09/10/87	1348	101	27.3	1.0	35.7
CD-1-2	09/10/87	1715	86	30.8	1.9	35.7
CD-1-2	09/11/87	1048	77	48.3	2.8	35.7
CD-1-2	09/11/87	1717	81	54.8	3.5	35.7
CD-1-2	09/12/87	1123	110	72.9	1.0	35.7
CD-1-2	09/13/87	1803	129	103.5	0.5	35.7
CD-1-2	09/14/87	1425	90	123.9	2.4	35.7
CD-1-2	09/16/87	1441	158	172.2	0.3	35.7
CD-1-2	09/18/87	1529	136	221.0	0.7	35.7
CD-1-2	09/20/87	1543	115	269.2	0.8	35.7
CD-1-2	09/22/87	1707	157	318.6	0.2	35.7
CD-1-2	09/24/87	1726	132	366.9	0.4	35.7
CD-1-2	09/26/87	1454	100	412.4	1.6	35.7
CD-1-2	10/03/87	1811	176	583.7	0.1	35.7
CD-1-2	10/17/87	1344	92	915.2	2.7	35.7
CD-1-2	10/23/87	1552	188	1061.4	0.1	35.7
CD-1-2	10/31/87	1433	186	1252.0	0.1	35.7
CD-1-2	11/07/87	1326	184	1418.9	0.1	35.7
CD-1-2	11/14/87	1042	187	1584.2	0.1	35.7
CD-1-2-AH	09/09/87	1724	161	6.9	0.1	37.2
CD-1-2-AH	09/09/87	1724	161	6.9	0.1	37.2
CD-1-2-AH	09/09/87	2159	176	11.5	0.0	37.2
CD-1-2-AH	09/10/87	812	156	21.7	0.1	37.2
CD-1-2-AH	09/10/87	1349	133	27.3	0.3	37.2
CD-1-2-AH	09/10/87	1716	128	30.8	0.3	37.2
CD-1-2-AH	09/11/87	1050	123	48.3	0.4	37.2
CD-1-2-AH	09/11/87	1719	86	54.8	2.9	37.2
CD-1-2-AH	09/12/87	1126	164	72.9	0.1	37.2
CD-1-2-AH	09/13/87	1806	127	103.6	0.5	37.2
CD-1-2-AH	09/14/87	1428	106	124.0	1.2	37.2
CD-1-2-AH	09/16/87	1444	202	172.2	0.1	37.2
CD-1-2-AH	09/18/87	1526	183	220.9	0.1	37.2
CD-1-2-AH	09/20/87	1540	116	269.2	0.8	37.2
CD-1-2-AH	09/22/87	1705	189	318.6	0.1	37.2
CD-1-2-AH	09/24/87	1723	168	366.9	0.1	37.2
CD-1-2-AH	09/26/87	1450	159	412.3	0.1	37.2
CD-1-2-AH	10/03/87	1809	183	583.6	0.1	37.2
CD-1-2-AH	10/17/87	1346	184	915.3	0.1	37.2
CD-1-2-AH	11/23/87	1554	180	1805.4	0.1	37.2
CD-1-2-AH	10/31/87	1435	192	1252.1	0.1	37.2
CD-1-2-AH	11/07/87	1328	187	1419.0	0.1	37.2
CD-1-2-AH	11/14/87	1044	196	1584.2	0.1	37.2
CD-1	09/09/87	1627	142	6.0	0.3	32.9
CD-1	09/09/87	2203	117	11.6	0.5	32.9
CD-1	09/10/87	805	93	21.6	1.4	32.9
CD-1	09/10/87	1345	116	27.2	0.6	32.9
CD-1	09/10/87	1720	94	30.8	1.4	32.9
CD-1	09/11/87	1055	92	48.4	1.5	32.9
CD-1	09/11/87	1711	82	54.7	3.4	32.9
CD-1	09/12/87	1131	109	73.0	1.1	32.9
CD-1	09/13/87	1811	136	103.7	0.4	32.9
CD-1	09/14/87	1430	97	124.0	1.8	32.9
CD-1	09/16/87	1446	164	172.3	0.2	32.9
CD-1	09/18/87	1522	137	220.9	0.6	32.9
CD-1	09/20/87	1535	113	269.1	0.9	32.9
CD-1	09/22/87	1702	166	318.5	0.1	32.9
CD-1	09/24/87	1718	146	366.8	0.2	32.9
CD-1	09/26/87	1443	114	412.2	0.9	32.9
CD-1	10/03/87	1804	180	583.6	0.1	32.9
CD-1	10/17/87	1350	110	915.3	1.3	32.9
CD-1	10/23/87	1534	178	1061.1	0.1	32.9
CD-1	10/31/87	1410	177	1251.7	0.1	32.9
CD-1	11/07/87	1311	187	1418.7	0.1	32.9
CD-1	11/14/87	1034	189	1584.1	0.1	32.9
CD-1	11/21/87	1403	176	1755.5	0.1	32.9
CD-1-AH	09/09/87	1631	135	6.0	0.4	34.8
CD-1-AH	09/09/87	2207	117	11.6	0.5	34.8
CD-1-AH	09/10/87	809	117	21.6	0.5	34.8
CD-1-AH	09/10/87	1346	115	27.3	0.6	34.8
CD-1-AH	09/10/87	1718	100	30.8	1.1	34.8
CD-1-AH	09/11/87	1059	105	48.5	0.8	34.8
CD-1-AH	09/11/87	1714	84	54.7	3.1	34.8
CD-1-AH	09/12/87	1128	120	73.0	0.7	34.8

Table 13.--Continued

Site	Date	Time of Day	Meter Reading mv	Hours From Start	Bromide Concen-tration mg/l	Distance meters
CD-1-AH	09/13/87	1814	126	103.7	0.6	34.8
CD-1-AH	09/14/87	1434	104	124.1	1.3	34.8
CD-1-AH	09/16/87	1450	171	172.3	0.2	34.8
CD-1-AH	09/18/87	1525	129	220.9	0.9	34.8
CD-1-AH	09/20/87	1537	115	269.1	0.8	34.8
CD-1-AH	09/22/87	1704	165	318.6	0.1	34.8
CD-1-AH	09/24/87	1721	128	366.9	0.5	34.8
CD-1-AH	09/26/87	1447	111	412.3	1.0	34.8
CD-1-AH	10/03/87	1806	168	583.6	0.1	34.8
CD-1-AH	10/17/87	1353	137	915.4	0.4	34.8
CD-1-AH	10/23/87	1536	181	1061.1	0.1	34.8
CD-1-AH	10/31/87	1412	190	1251.7	0.1	34.8
CD-1-AH	11/07/87	1309	190	1418.7	0.1	34.8
CD-1-AH	11/14/87	1036	197	1584.1	0.0	34.8
BLANK	09/10/87	1354	171	27.4	0.1	0.0
BLANK	09/10/87	1724	180	30.9	0.0	0.0
BLANK	09/11/87	1052	148	48.4	0.1	0.0
BLANK	09/11/87	1708	141	54.6	0.3	0.0
BLANK	09/12/87	1859	172	80.5	0.1	0.0
BLANK	09/13/87	1821	164	103.8	0.1	0.0
BLANK	09/14/87	1436	150	124.1	0.2	0.0
BLANK	09/16/87	1113	191	168.7	0.1	0.0
BLANK	09/18/87	1500	175	220.5	0.1	0.0
BLANK	09/20/87	1409	169	267.6	0.1	0.0
BLANK	09/22/87	1531	187	317.0	0.1	0.0
BLANK	09/24/87	1704	178	366.6	0.1	0.0
BLANK	09/26/87	1452	170	412.4	0.1	0.0
BLANK	10/03/87	1452	193	580.4	0.1	0.0
BLANK	10/17/87	1330	158	915.0	0.2	0.0
BLANK	10/23/87	1522	202	1060.9	0.0	0.0
BLANK	10/31/87	1404	220	1251.6	0.0	0.0
BLANK	11/07/87	1313	205	1418.7	0.0	0.0
BLANK	11/14/87	1044	199	1584.2	0.0	0.0
BLANK	11/21/87	1420	201	1755.8	0.0	0.0
B BLANK	09/10/87	1545	176	29.2	0.0	0.0
B BLANK	09/10/87	1819	155	31.8	0.1	0.0
B BLANK	09/11/87	1201	155	49.5	0.1	0.0
B BLANK	09/11/87	1814	143	55.7	0.3	0.0
B BLANK	09/12/87	1333	165	75.0	0.1	0.0
B BLANK	09/14/87	1639	160	126.2	0.1	0.0
B BLANK	09/16/87	1312	180	170.7	0.1	0.0
B BLANK	09/20/87	1805	166	271.6	0.1	0.0
B BLANK	09/26/87	1302	189	410.5	0.0	0.0
B BLANK	09/26/87	1657	184	414.4	0.1	0.0
B BLANK	10/17/87	1323	193	914.9	0.1	0.0
D-1-AH	10/23/87	1548	171	1061.3	0.1	61.0
D-1-AH	10/31/87	1420	165	1251.8	0.2	61.0
D-1-AH	11/07/87	1321	161	1418.8	0.2	61.0
D-1-AH	11/14/87	1031	161	1584.0	0.2	61.0
D-1-AH	11/21/87	1410	165	1755.7	0.2	61.0
D-1-S	10/23/87	1541	182	1061.2	0.1	61.0
D-1-S	10/31/87	1416	174	1251.8	0.1	61.0
D-1-S	11/07/87	1317	170	1418.8	0.1	61.0
D-1-S	11/14/87	1026	169	1583.9	0.1	61.0
D-1-S	11/21/87	1407	169	1755.6	0.1	61.0
D-1-D	10/23/87	1544	184	1061.2	0.1	61.0
D-1-D	10/31/87	1418	185	1251.8	0.1	61.0
D-1-D	11/07/87	1319	182	1418.8	0.1	61.0
D-1-D	11/14/87	1024	183	1583.9	0.1	61.0