



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

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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.

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USING A BROMIDE TRACER

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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.

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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
NO₃⁻ = 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:

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

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, "C_o." 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.

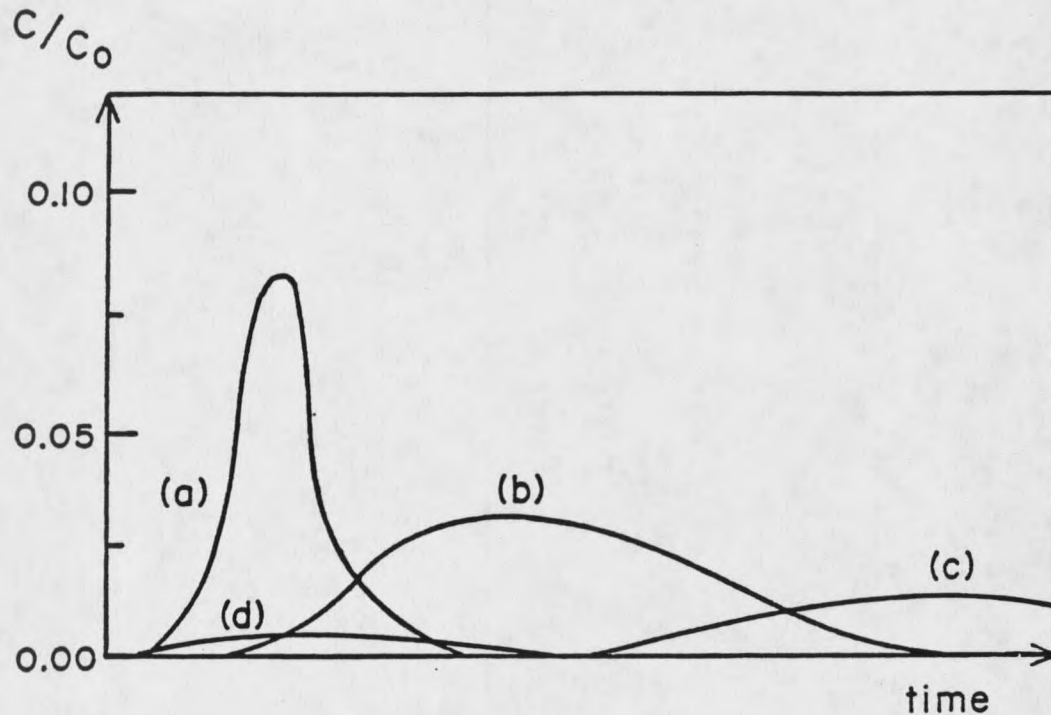


Figure 1. Breakthrough curves of four different tracer types: (a) is conservative, (b) some effect of sorption, (c) large effect of sorption, and (d) precipitated or destroyed (From Davis et al. 1985).

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

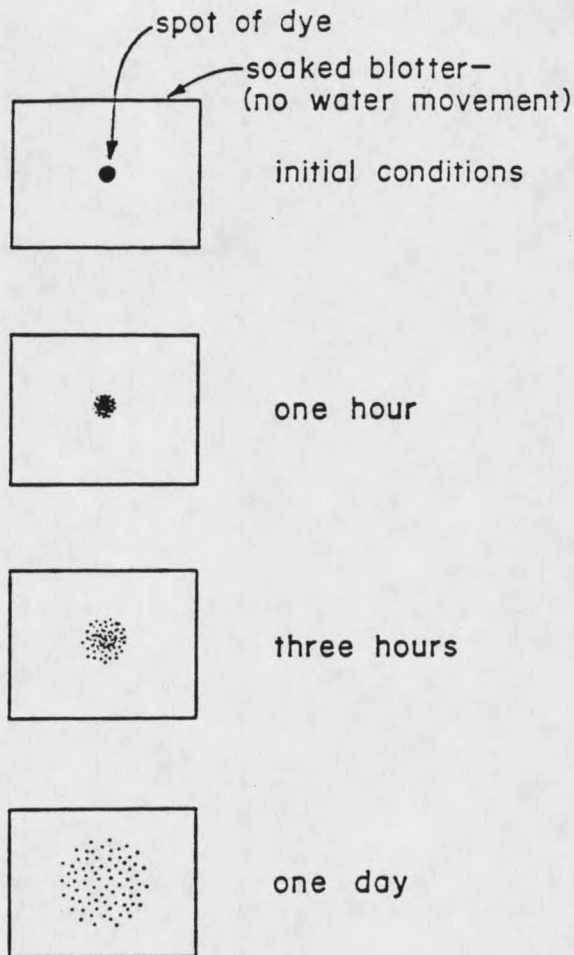


Figure 2. One dimensional example of movement by molecular diffusion (from Davis et al. 1985).

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.

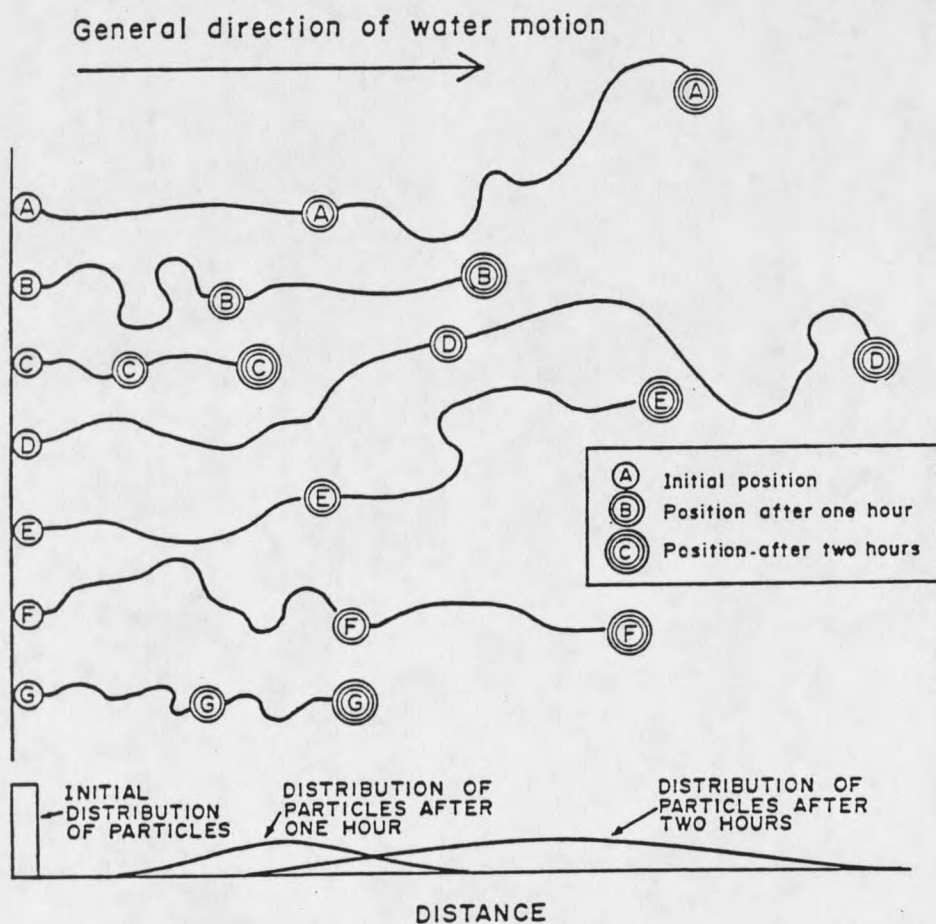


Figure 3. One dimensional example of hydrodynamic dispersion for tracer particles A - G (from Davis et al. 1985).

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 groundwater 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, CaBr₂ 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 LC₅₀

(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 LD₅₀ (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

