Movement of Coliform Bacteria and Nutrients in Ground Water Flowing through Basalt and Sand Aquifers

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ABSTRACT

Large-scale deposition of animal manure can result in contamination of surface and ground water and in potential transfer of disease-causing enteric bacteria to animals or humans. We measured total coliform bacteria (TC), fecal coliform bacteria (FC), NO_3, NH_4, total P, and PO_4 in ground water flowing from basalt and sand aquifers, in wells into basalt and sand aquifers, in irrigation water, and in river water. Samples were collected monthly for 1 yr. Total coliform and FC numbers were always higher in irrigation water than in ground water, indicating that soil and sediment filtered most of these bacteria before they entered the aquifers. Total coliform and FC numbers in ground water were generally higher in the faster flowing basalt aquifer than in the sand aquifer, indicating that the slower flow and finer grain size may filter more TC and FC bacteria from water. At least one coliform bacterium/100 mL of water was found in ground water from both basalt and sand aquifers, indicating that ground water pumped from these aquifers is not necessarily safe for human consumption according to the American Public Health Association and the USEPA. The NO_3 concentrations were usually higher in water flowing from the sand aquifer than in water flowing from the basalt aquifer or in perched water tables in the basalt aquifer. The PO_4 concentrations were usually higher in water flowing from the basalt aquifer than in water flowing from the sand aquifer. The main concern is fecal contamination of these aquifers and health consequences that may arise from human consumption.

POLLUTION of surface flow and ground water from application of animal waste has been well documented (Mallin et al., 1997; Mawdsley et al., 1995). Liquid-waste discharge onto soil initiates solute and microbe movement that follows natural ground water drainage patterns and may contaminate ground water. Ground water is often used as a source of drinking water. Human consumption of water containing intestinal pathogens may spread disease. Therefore, it is critical to maintain the quality of our lakes and streams by keeping them free of intestinal pathogens and excess nutrients associated with wastewater. Total coliform bacteria (TC) and fecal coliform bacteria (FC) are sensitive and commonly used indicators of bacterial pathogen contamination of natural waters. Their presence implies the potential presence of microorganisms that may cause harmful effects in humans. The total coliform group of bacteria are an aerobic or facultatively anaerobic, gram-negative, non-sporeforming, rod-shaped bacteria that ferment lactose with gas production in 24 to 48 h. Total coliform bacteria are discharged in high numbers in animal and human feces, but not all total coliform bacteria are necessarily of fecal origin. These indicator bacteria have been found to be useful for determining safe drinking and recreational waters (Greenberg et al., 1992). The fecal coliform group of bacteria are a subset of the total coliform bacteria. Fecal coliform bacteria are more thermo-tolerant. These bacteria conform to all of the criteria used to define total coliform bacteria plus the requirement that they grow at 44.5°C. Fecal coliform bacteria are bacteria that originate from intestinal tracts of homothermic animals and are used to determine fecal contamination of water. This group of bacteria have been found to have an excellent positive correlation with fecal contamination of water from warm-blooded animals (Greenberg et al., 1992).

Increasing concentrations of N and P in surface runoff and ground water have resulted in concentrations in ground water exceeding the NO_3 and P standards (David and Gentry, 2000; Edwards et al., 2000; Sharpley et al., 2000; Waddell et al., 2000). Nitrogen in drinking water is a concern because concentrations in the range of 10 mg/L can contribute to methemogobinemia in infants. More recently, it has been linked to non-Hodgkin's lymphoma (Ward et al., 1996).

Increased N and P concentrations in water can alter the function and stability of many riparian and aquatic ecosystems. In the past few decades, intensive fertilization has contributed to the accumulation of these elements in many wetland and aquatic environments (Koch and Reddy, 1992; Lebo and Sharp, 1993; Vitousek et al., 1997; David and Gentry, 2000; Edwards et al., 2000; Sharpley et al., 2000). Changes in flora and fauna have been attributed to increased input of nutrients (Stevenson et al., 1993; Cooper and Brush, 1993; Koch and Reddy, 1992; Davis, 1991). Most wetland and aquatic ecosystems develop in conditions limited by N and P (Cooper and Brush, 1993; Koch and Reddy, 1992). Nutrients taken up by plants and microbes are made available by nutrient mineralization during the litter decomposition process (Cooper and Brush, 1993; Koch and Reddy, 1992). High concentrations of N in plants can shift allocation of carbon from defense compounds to sugars, lowering the plant defense to insect and disease attack (Entry et al., 1992; Waterman and Mole, 1989). Increased N and P in wetland ecosystems may also cause

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Abbreviations: FC, fecal coliform bacteria; TC, total coliform bacteria.

eutrophication, creating an abnormally high oxygen demand and often resulting in the death of many aquatic organisms (Cooper and Brush, 1993). High concentrations of N in soils are also known to influence soil microbial degradation patterns (Entry, 1999, 2000). High concentrations of N and P are known to be responsible for shifts in species composition in vegetation (Stevenson et al., 1993).

On the Snake River Plain near Hagerman, Idaho, formation of perched ground water systems coincided with a land use change from desert sagebrush to irrigated agriculture (Farmer, 1999; Vector, 1994). Perched water tables and associated ground water flow from basalt and sand aquifers is directly linked to irrigation of agricultural crops and leakage of water from irrigation canals (Farmer, 1999; Vector, 1994). The objective of this study was to determine the movement of TC, FC, N, and P in ground water flowing through basalt and sand aquifers.

MATERIALS AND METHODS

Geologic Setting

The study site lies in Hagerman Fossil Beds National Monument on the Snake River Plain in southern Idaho. The Hagerman Fossil Beds are fossil-bearing sediments that form the western wall of the Hagerman Valley. The bluff is part of the Bruneau Plateau with the Snake River located at the base (Fig. 1). The surface of the bluff has an average elevation of 1100 m, which is 100 m above the Snake River. The deeply incised canyons range from 800 to 1600 m in length with slope angles from 35 to 70 degrees. The Snake River Plain is a major volcanic feature in the northern portion of the Basin and Range geologic region (Bonnichsen and Breckenridge, 1982).

In the area of the sand aquifer, the Idaho Formation is composed of six layers containing three perched aquifers (Fig. 2). Layer 1 is the Tuana Gravel Formation composed of gravel, sand, and subordinate silt and clays. Paleo-stream channels have cut and filled into the Glenns Ferry Formation at 1203 m (Saddler, 1997). The Tuana Formation is underlain by the Glenns Ferry Formation (Layer 2), which overlies a basement basalt flow. It extends from an elevation of 978 to 1203 m and is approximately 38 m thick. It is composed of 75% silty clays with the remaining 25% consisting of sandy stream facies. The middle system stream facies (Layer 3) is composed of fine-grained sands and is within the Glenns Ferry Formation. Layer 3 acts as the middle aquifer. Layer 4 extends from the stream facies down to an elevation of 957 m and consists of silty clays, typical of the Glenns Ferry Formation. Layer 5 is dominated by a stream facies composed of fine-grained sands and extends to 954 m and is acting as the lower aquifer. Paleo-stream channels have cut into the underlying carbonaceous shale (Layer 6) and are composed of fine-grained sands. The carbonaceous shale is approximately 6 m thick and crops out at an elevation of 954 to 960 m. It is composed of primarily finely laminated clays with deposits of diatoms and ash (Lorkowski and Hauser, personal communication, 1996).

In the area of the basalt aquifer, the Idaho Formation is also composed of six layers containing three perched aquifers (Fig. 3). The uppermost layer is the Tuana Gravel Formation, underlain by the Glenns Ferry Formation (Layer 2). Basalt intruded into the Glenns Ferry Formation comprises Layer 3. This basalt averages 8 m thickness and outcrops at 978 m. The basalt flow is underlain by the same stream facies as in the sand aquifer area and is composed of silty clays, typical of the Glenns Ferry Formation here. Layer 5 is dominated by a stream facies composed of fine-grained sands and is also acting as the lower aquifer in this area. The carbonaceous shale, composed of primarily finely laminated clays with deposits of diatoms and ash, is Layer 6.

Hydrology

The presence of perched ground water systems coincided with land use change from desert sagebrush to irrigated agriculture (Farmer, 1999). Since 1970, the Bell Rapids Mutual Irrigation District has operated and maintained an irrigation system that pumps 5.5×10^9 L of water from the Snake River to irrigate 7695 ha on the plateau (Vector, 1994). Perched ground water began to discharge on the hillsides during the mid 1970s with slope failures occurring since 1979. Discharge from the basalt aquifer is calculated to be 5.1×10^7 L/yr and discharge from the sand aquifer is significantly less than the basalt aquifer and is calculated at 2.5×10^7 L/yr (Farmer, 1999). The basalt aquifer lies from 10 m below the soil surface at the northern end and dips at 1 to 3% to 85 m below the soil surface at the southern point, which is the outflow. The sand aquifer lies 50 m below the surface. Tracer studies with flourescent dye showed that water from the surface percolates into the basalt aquifer in approximately 3 d, moves at an average rate of 30 m/d, and flows a distance of 5100 m. Therefore, irrigation water applied to the soil would flow from the basalt aquifer approximately 6 mo after application. In contrast, water from the surface percolates into the sand aquifer in approximately 90 d, moves at an average rate of 0.3 m/d, and flows a distance of 200 m. Therefore, irrigation water applied to the soil would flow from the basalt aquifer 21 mo after application.

Vegetation

The area is classified as a temperate semi-desert ecosystem (Bailey, 1998). The climate has cool, moist winters and hot, dry summers with annual precipitation of 175 to 305 mm, two-thirds of which occurs during October through March. Average annual temperature ranges from 9 to 10°C. Soils are typically well-drained loams and silt loams derived from loess deposits overlying basalt (Collett, 1980). Vegetation throughout the general area was historically dominated by basin big sagebrush (*Artemisia tridentata* Nutt.) and perennial bunch grasses.

Experimental Design

The study was arranged in a complete random design consisting of ground water from aquifer type (basalt or sand), wells into aquifer types, irrigation canal water, and Snake River water. In March 1999, three plots were randomly established in each basalt and sand aquifer on the south side of the Snake River Canyon in the Hagerman Fossil Bed National Monument. Plots were spaced 40 to 90 m apart and were 30 m long (across the hillside) by 10 m wide (downhill) (Fig. 1). Three 10-cm-diameter by 2.0-m-long plastic PVC pipes were randomly set horizontally 1.0 m into the aquifers to reduce possible microbial contamination from wildlife in the area. Wells were located from 3 to 10 m apart in each plot. Water flowed freely from each pipe during all months of the year. In addition, one 20-cm-diameter well was drilled vertically into each aquifer from the top of the plateau. Monthly triplicate samples were taken from horizontal wells, vertical wells, the irrigation canal, and the Snake River during a 12-mo period (July 1999 through June 2000).

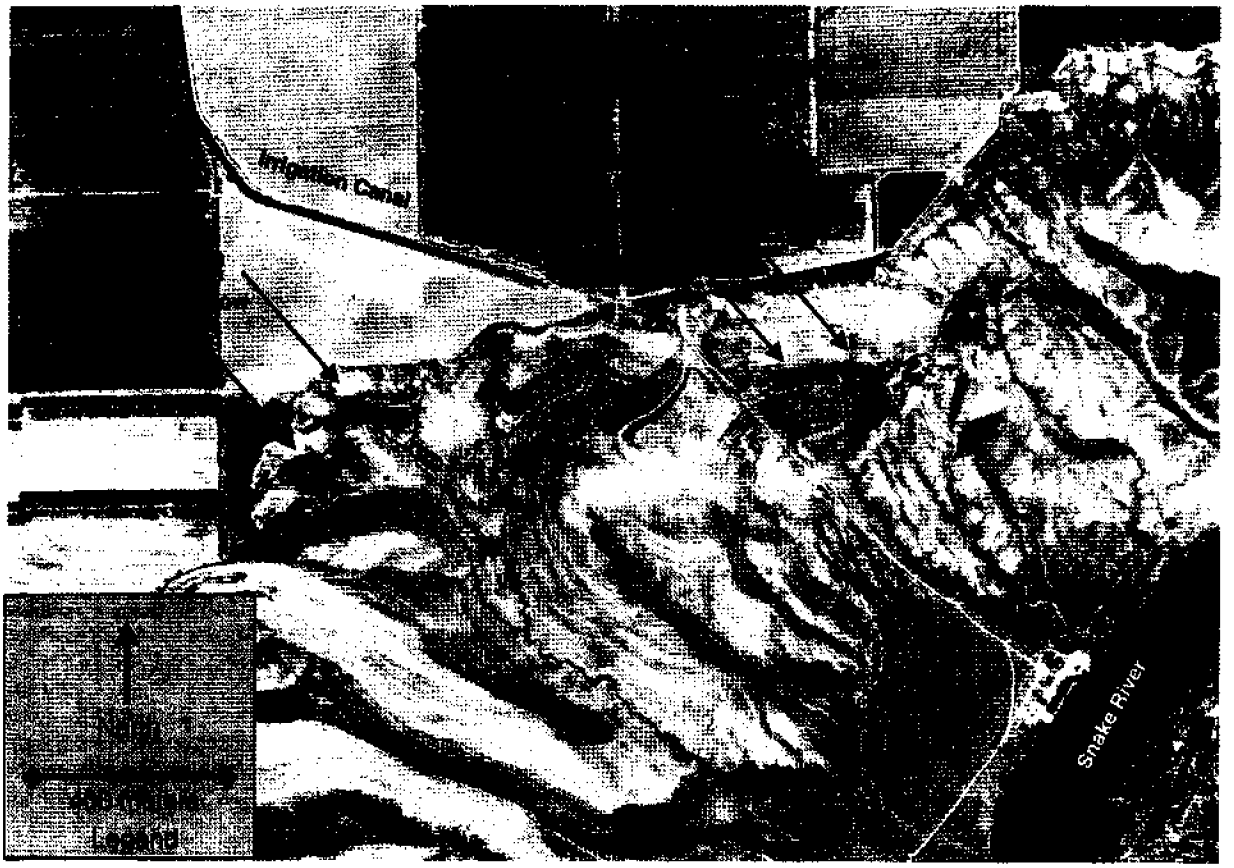

Fig. 1. Infrared air photo of Hagerman sampling area.

Fig. 2. Photographs and geological model of sand aquifer discharge zones.

Fig. 3. Photographs and geological model of basalt aquifer discharge zones.

Table 1. Total coliform bacteria in water from sand and basalt aquifers, wells into sand and basalt formations, the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	bacteria/100 mL water											
Sand aquifer	26c‡	71b	1 598c	410c	16c	102c	70b	9c	8c	136c	35c	625b
Basalt aquifer	58c	228a	360d	1 033b	218b	159b	18b	6c	61b	2 055a	216b	130c
Sand well	39c	71b	21e	125d	7d	231b	2 285a	323b	8c	546b	433b	0d
Basalt well	46c	27b	9e	2e	0c	0d	NS§	NS	0d	0d	4d	1d
Snake River	94b	197a	5 838b	4 525a	2 950a	717a	3 575a	1 392a	1 638a	2 620a	6 500a	6 750a
Irrigation canal	202a	152a	14 013a	5 037a	NW¶	NW	NW	NW	NW	2 390a	5 375a	4 500a

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p < 0.05$), $n = 54$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

Sample Collection

Samples were collected and analyzed for total and fecal coliform bacteria during the second week of each month. Water was collected into sterile 500-mL containers and transported at ambient temperature to the USDA Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. Samples were stored at ambient temperatures and processed for microbial testing within 24 h of collection (Greenberg et al., 1992). Samples were collected and analyzed for total and fecal coliform bacteria, NO_3, NH_4, PO_4–P, and total P. Subsamples tested for nutrients were stored at 4°C prior to testing (Greenberg et al., 1992).

Coliform and Nutrient Analysis

Total coliform and fecal coliform bacteria were analyzed using the membrane filter technique (Greenberg et al., 1992). Preliminary water samples from test runs taken 1 to 3 d prior to each test were analyzed to determine each dilution before bacteria were counted. One milliliter of water was diluted in 99 mL of sterile distilled phosphate-buffered water (Greenberg et al., 1992). One hundred milliliters of final dilution of each sample was vacuum-filtered through a sterile 0.45-μm filter and placed on Em Endo medium (Difco Laboratories, Detroit, MI) to determine total coliform bacteria. Similarly, FC medium was used to determine fecal coliform bacteria. Total coliform bacteria were incubated at 39.5 ± 0.02°C for 24 h. Fecal coliform bacteria were incubated at 44.5 ± 0.02°C for 24 h. Nitrate and ammonium were determined using a Lachat autoanalyzer (Lachat Quickchem Systems, Milwaukee, WI) using methods described by Keeney and Nelson (1982). Phosphate and total P were determined using methods described by Olsen and Sommers (1982).

Statistical Analyses

All dependent variables were tested for normal distribution. Number of total and fecal coliform bacteria were transformed using logarithms to achieve normal distributions. Data were then analyzed using general linear model (GLM) procedures for a repeated measures design with Statistical Analysis Systems (SAS Institute, 1996). Statistical comparisons were made of total and fecal coliform bacteria, NH_4, NO_3, total P, and PO_4 in water by aquifer type (Snedecor and Cochran, 1980; Kirk, 1982). In all analyses, residuals were equally distributed with constant variances. Differences reported were significant at $p < 0.05$, as determined by the least squares means test. Total and fecal coliform bacteria are reported in untransformed numbers.

RESULTS

The number of TC and FC bacteria were always higher in Snake River and irrigation canal water than in ground water from either aquifer (Tables 1 and 2). Most months, the numbers of TC and FC bacteria did not differ between Snake River and irrigation canal water. The number of TC bacteria in ground water discharging from the basalt were higher than from the sand aquifer in August, October, November, December, March, April, and May, while TC numbers were higher in the sand aquifer in September and June. Numbers of TC bacteria in ground water flowing from the basalt and sand aquifer did not differ in July, January, and February. Numbers of FC bacteria were higher in ground water flowing from the basalt than from the

Table 2. Fecal coliform bacteria in water from sand and basalt aquifers, wells into sand and basalt formations in the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	bacteria/100 mL water											
Sand aquifer	722b‡	329c	113a	1a	1a	0a	0b	0b	0b	0b	0c	0b
Basalt aquifer	13d	3d	0d	1a	0b	0a	0b	1a	0b	0b	1b	0b
Sand well	79c	0e	0d	1a	0b	0a	0b	0b	0b	0b	0c	0b
Basalt well	8d	1d	1c	0b	0b	0a	NS§	NS	0b	0b	0c	8a
Snake River	1812a	1225a	0d	1a	0b	0a	5a	3a	1a	9a	7a	3a
Irrigation canal	3000a	888b	13b	1a	NW¶	NW	NW	NW	NW	9a	8a	2a

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p < 0.05$), $n = 54$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

Table 3. Total nitrate concentrations in water from sand and basalt aquifers, wells into sand and basalt formations, the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	mg NO_3/liter water											
Sand aquifer	7.0a‡	6.9a	6.3a	6.8a	7.1a	7.1a	7.1a	7.1a	7.0a	6.9a	6.7a	6.5b
Basalt aquifer	4.7b	4.4b	4.58ab	4.4b	4.3b	4.4b	4.2b	4.3b	4.1b	4.1b	4.2b	4.1b
Sand well	4.1b	4.7b	5.3a	6.0a	7.4a	7.7a	8.5a	9.1a	8.9a	8.7a	7.8a	9.1a
Basalt well	4.4b	3.9b	3.7b	3.9b	3.9b	3.9b	NS§	NS	5.1b	3.8b	3.7b	8.1a
Snake River	0.9c	1.1c	1.4c	1.5c	1.6c	1.6c	1.3c	1.5c	1.1c	0.6c	0.9c	5.3b
Irrigation canal	0.9c	1.3c	1.5c	1.5c	NW¶	NW	NW	NW	NW	0.6c	0.93c	6.3b

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$), $n = 27$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

sand aquifer in July, August, and September, while FC numbers were higher in the sand aquifer in February and May. Numbers of FC bacteria in ground water flowing from the basalt and sand aquifer did not differ in October, December, January, March, April, and June. Numbers of TC bacteria were higher in ground water taken from the sand well than from the basalt well in October, November, December, January, March, April, and May while TC numbers were higher in the basalt well only in June. Numbers of FC bacteria were higher in ground water taken from the basalt well than from the sand well in August, September, and June while FC numbers were higher in the sand aquifer only in July.

The NO_3 concentration was usually higher in water flowing from the sand aquifer and in the perched water table in the sand aquifer than in water flowing from the basalt aquifer or in the perched water table in the basalt aquifer (Table 3). Concentrations of NH_4 did not consistently differ between the basalt and sand perched water tables or water flowing from sand or basalt aquifers (Table 4). Concentrations of both NO_3 and NH_4 in sand and basalt water tables and in water flowing from both aquifers were higher than NO_3 and NH_4 concentrations in canal or river water. Concentrations of NO_3 and NH_4 did not differ in the water in the irrigation canal and the Snake River. There was no difference between concentrations of total P in water flowing from basalt and sand aquifers except in June, when water flowing from the basalt aquifer had an extremely high concentration (Table 5). Concentrations of total P did not consistently differ between basalt and sand perched water tables. There was no difference between total P concentration in canal water and the Snake River except in August 1999, when river water had an extremely high total P concentration. The PO_4 concentration was usually higher in water flowing from the basalt aquifer than the water flowing from sand aquifer (Table 6). The PO_4 concentration did not consistently differ between canal water and the Snake River water.

DISCUSSION

Fecal colifom bacteria are bacteria that originate from intestinal tracts of homothermic animals. Their presence indicates fecal contamination of water. Total and fecal coliform bacteria are sensitive and commonly used indicators of bacterial pathogen contamination of natural waters. Their presence implies the potential presence of microorganisms that are pathogenic to humans. Fecal coliform bacteria have a strong correlation with fecal contamination of water from warm-blooded animals. If 1 fecal coliform per 100 mL of water is detected, the water is considered unsafe to ingest (Greenberg et al., 1992; USEPA, 1998). We found one or more coliform bacteria per 100 mL water in more than 50% of the samples in water that flowed from sand and basalt aquifers, indicating that this ground water is not safe for human consumption.

Table 4. Ammonium concentrations in water from sand and basalt aquifers, wells into sand and basalt formations, the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	mg NH_4/liter water											
Sand aquifer	0.45a‡	0.45a	0.01b	0.03b	0.04b	0.03a	0.30a	0.03a	0.01b	0.01b	0.06b	0.06b
Basalt aquifer	0.10b	0.30b	0.11a	0.04a	0.03b	0.03a	0.30a	0.04a	0.01b	0.01b	0.01b	0.01b
Sand well	0.02c	0.66a	0.00c	0.00c	0.02b	0.05a	0.27a	0.00b	0.00b	0.00b	0.00b	0.00b
Basalt well	0.05bc	0.36b	0.05b	0.00c	0.05b	0.03a	NS§	NS	0.00b	0.00b	0.02b	0.00b
Snake River	0.00d	0.15c	0.00c	0.00c	0.08a	0.00b	0.015a	0.02b	0.04a	0.041a	0.12a	0.01a
Irrigation canal	0.00d	0.02d	0.02c	0.00c	NW¶	NW	NW	NW	NW	0.06a	0.16a	0.15a

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$), $n = 27$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

Table 5. Total phosphorus concentrations in water from sand and basalt aquifers, wells into sand and basalt formations, the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	mg total P/liter water											
Sand aquifer	1.6a‡	3.2c	5.1b	2.1a	3.2a	1.6b	1.1b	1.5b	1.0a	1.2ab	2.0a	1.3d
Basalt aquifer	1.9a	2.7c	5.5b	1.5a	2.0b	1.6b	2.2a	1.5b	1.0a	1.1b	1.5ab	7.2a
Sand well	1.9a	11.5a	7.6a	3.0a	2.8a	1.8ab	2.4a	1.4b	1.0a	1.2b	1.2b	2.0c
Basalt well	1.4a	2.3c	3.2c	2.0a	2.0b	1.4b	NS§	NS	1.0a	1.4a	1.3b	2.2c
Snake River	1.6a	9.2a	2.8c	1.9a	2.3ab	2.2a	2.4a	2.5a	1.2a	1.0b	1.7ab	2.1c
Irrigation canal	1.2a	4.2b	2.6c	1.7a	NW¶	NW	NW	NW	NW	0.9b	1.5ab	4.3b

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$), $n = 27$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

The concentrations of TC and FC in ground water were generally, but not always, higher in the faster-flowing basalt aquifer than the sand aquifer, indicating that the slower flow in and finer grain size of the sand aquifer generally filter more TC and FC bacteria. Ground water flowing through the basalt aquifer flows through faults and fissures and does not contact as much rock or sediment surface area as water flowing through fine-grained sand. Water flowing through the basalt aquifer is moving in a matter of days while water is flowing through the sand aquifer is moving in a matter of 21 mo. Bacteria flowing through the basalt aquifer have drastically less time and opportunity to contact and adhere to sediment or rock. Fecal coliform bacteria were found in fewer ground water samples than river water samples, showing that the ground water is safer for human consumption than surface water.

Nitrate concentrations in water flowing from the sand aquifer and in the perched water table in the sand aquifer were usually higher than in water flowing from the basalt aquifer or perched water table in the basalt aquifer. Concentrations of NO_3–N ranged from a low of 4.1 mg NO_3–N/L in the basalt aquifer to a high of 9.1 mg NO_3–N/L in water from the sand well. The higher NO_3–N concentrations in the sand aquifer could mean that negatively charged NO_3–N was previously deposited in this aquifer, adhering to the positively charged sand grains, and then was flushed out during the sampling period. Water flowing from the basalt aquifer contained NO_3–N concentrations well below the 10 mg NO_3–N/L drinking water limit. Water flowing from the sand aquifer contained higher NO_3 concentrations and some samples approached 10 mg NO_3–N/L. Wells in this area should be monitored at regular intervals to determine if NO_3–N concentrations in ground water are increasing.

Input of N to the Snake River ecosystem may have important effects on eutrophication and ultimately fish survival and species composition as well function and stability of ecosystems. Nitrate concentrations in ground water in southern Idaho agricultural regions are often above background (Rupert, 1996; Rupert et al., 1996; Plummer et al., 2000). Nitrogen fertilizer applications as inorganic and animal manure in southern Idaho range from 8 to more than 20 Mg/km^2 and historically are among the highest in the United States (Battaglin and Goolsby, 1994; Wood and Low, 1988; Rupert, 1997). Phosphate concentrations were higher in water flowing from the basalt aquifer than the sand aquifer. The shoestring basalt in Layer 3 contains high concentrations of hydroxyapatite [$Ca_5(PO_4)(OH)$], which is one of the minerals mined for phosphorus fertilizer. Total P and PO_4 concentrations are not extremely high in water flowing from basalt or sand aquifers and should not alter concentrations in the Snake River system.

Agricultural operations need to be aware of the potential for the spread of disease-causing microorganisms to farm workers when handling and applying solid and or liquid waste. Diseases associated with enteric bacteria range from bacteria that cause mild to life-threatening

Table 6. Phosphate concentrations in water from sand and basalt aquifers, wells into sand and basalt formations, the Snake River, and Bell Rapids Irrigation Canal.

Treatment†	1999 July	August	September	October	November	December	2000 January	February	March	April	May	June
	mg PO_4/liter water											
Sand aquifer	0.1b‡	0.5c	1.0a	0.1a	0.2b	0.2a	0.2b	0.2b	0.2a	0.1ab	0.0b	0.1c
Basalt aquifer	0.4a	0.3c	0.8a	0.2a	0.2b	0.3a	0.3b	0.4b	0.2a	0.2a	0.1a	1.2a
Sand well	0.4a	1.7a	0.6ab	0.2a	0.5ab	2.3a	0.3b	0.2b	0.0b	0.0ab	0.0b	0.3c
Basalt well	0.4a	0.2c	0.4b	0.4a	0.5ab	0.4a	NS§	NS	0.0b	0.1ab	0.0b	0.5b
Snake River	0.3a	2.9a	0.5b	0.5a	0.7a	0.6a	0.7a	0.8a	0.0b	0.0b	0.0b	0.5b
Irrigation canal	0.2ab	0.8ab	0.5b	0.5a	NW¶	NW	NW	NW	NW	0.2a	0.0b	1.3a

† Water flowing from the basalt aquifer was applied to the soil approximately 7 d prior to outflow and collection while water flowing from the sand aquifer was applied to soil approximately 630 d prior to outflow and collection.
‡ In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$), $n = 27$.
§ NS = not sampled.
¶ NW = no water in the irrigation canal.

gastroenteritis, hepatitis, skin infections, wound infections, conjunctivitis, respiratory infections, and generalized infections (Moe, 1997). We suggest a more intense sampling of ground water in areas where recharge is a result of irrigated agriculture.

REFERENCES

Bailey, R.G. 1998. Ecoregions of North America. USDA For. Serv., Washington, DC.

Battaglin, W.A., and D.A. Goolsby. 1994. Spatial data in geographic information system format on agricultural chemical use, land use and cropping practices in the United States. Water-Resour. Investigations Rep. 94-4176. U.S. Geol. Survey, Denver, CO.

Bonnichsen, B., and R.M. Breckenridge. 1982. Cenozoic geology of Idaho. Idaho Bull. 26. Idaho Geol. Survey, Moscow, ID.

Collett, R.A. 1980. Soil survey of Ada County area. USDA Soil Conserv. Serv., Washington, DC.

Cooper, S.R., and G.S. Brush. 1993. A 2,500-year history of anoxia and eutrophication in Chesapeake Bay. Estuaries 16:617–626.

David, M.B., and L.E. Gentry. 2000. Anthropogenic inputs of nitrogen and phosphorus and riverine export for Illinois, USA. J. Environ. Qual. 29:494–508.

Davis, S.M. 1991. Growth, decomposition and nutrient retention of *Cladium jamaicense* Cranz. and *Typha domingenis* Pers. in the Florida Everglades. Aquat. Bot. 40:203–224.

Edwards, A.C., H. Twist, and G.A. Codd. 2000. Assessing the impact of terrestrially derived phosphorus on flowing water systems. J. Environ. Qual. 29:117–124.

Entry, J.A. 1999. Influence of nitrogen on atrazine and 2,4 dichlorophenoxyacetic acid mineralization in blackwater and redwater forested wetland soils. Biol. Fertil. Soils 29:348–353.

Entry, J.A. 2000. Influence of nitrogen on cellulose and lignin mineralization in blackwater and redwater forested wetland soils. Biol. Fertil. Soils. 31:436–440.

Entry, J.A., K. Cromack, Jr., R.G. Kelsey, and N.E. Martin. 1992. The response of Douglas-fir to *Armillaria ostoyae* infection after thinning or thinning plus fertilization. Phytopathology 81:682–689.

Farmer, C.N. 1999. A hydrostratigraphic model for perched aquifer systems located near the Hagerman Fossil Beds National Monument, Idaho. M.S. thesis. Univ. of Idaho, Moscow, ID.

Greenberg, A.F., L.S. Clescerl, and A.D. Eaton. 1992. Standard methods for the examination of water and wastewater. 18th ed. Am. Public Health Assoc., Washington, DC.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—Inorganic forms. p. 643–698. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kirk, R.E. 1982. Experimental design: Procedures for the behavioral sciences. 2nd ed. Brooks Cole Publishing Co., Belmont, CA.

Koch, M.S., and K.R. Reddy. 1992. Distribution of soil and plant nutrients along a trophic gradient in the Florida Everglades. Soil. Sci. Soc. Am. J. 56:1492–1499.

Lebo, M.E., and J.H. Sharp. 1993. Distribution of phosphorus along the Delaware, an urbanized coastal plain estuary. Estuaries 16: 290–301.

Mallin, M.A., J.M. Burkholder, M.R. McIver, G.C. Shank, H.B. Glascow, Jr., B.W. Touchette, and J. Springer. 1997. Comparative effects of poultry and swine waste lagoon spills on the quality of receiving waters. J. Environ. Qual. 26:1622–1631.

Mawdsley, J.L., R.D. Bardgett, R.D. Merrry, B.F. Pain, and M.K. Theodorou. 1995. Pathogens in livestock waste, their potential for movement through soil and environmental pollution. Appl. Soil Ecol. 2:1–15.

Moe, C.L. 1997. Waterborne transmission of infectious agents. p. 136–152. *In* C.J. Hurst et al. (ed.) Manual of environmental microbiology. Am. Soc. of Microbiol. Press, Washington, DC.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Plummer, L.N., M.G. Rupert, E. Busenberg, and P. Schlosser. 2000. Age of irrigation water in ground water from the Eastern Snake River Plain Aquifer, south-central Idaho. Ground Water 38:264–283.

Rupert, M.G. 1996. Major sources of nitrogen input and loss in the upper Snake River Basin, Idaho and western Wyoming. Water-Resour. Investigations Rep. 96-4008. U.S. Geol. Survey, Denver, CO.

Rupert, M.G. 1997. Nitrate (NO_2 + NO_3–N) in ground water of the upper Snake River Basin, Idaho and western Wyoming. 1991–1995. Water-Resour. Investigations Rep. 97-4174. U.S. Geol. Survey, Denver, CO.

Rupert, M.G., M.J.A. Stone, and D.S. Ott. 1996. National Water Quality Assessment Program. Nitrate and pesticide in ground water, Blaine, Cassis, Lincoln and Minidoka counties, south central Idaho. Fact Sheet FS 246-95. U.S. Geol. Survey, Denver, CO.

Saddler, J.L. 1997. Sedimentology and stratigraphy of Pleistocene Tuana gravel at Hagerman Fossil Beds National Monument, Idaho. M.S. thesis. Idaho State Univ., Pocatello.

SAS Institute. 1996. SAS user's guide: Statistics. Version 6.03 ed. SAS Inst., Cary, NC.

Sharpley, A., B. Foy, and P. Withers. 2000. Practical and inovative measures for the control of agricultural phosphorus losses to water: An overview. J. Environ. Qual. 29:1–9.

Snedecor, W.G., and W.G. Cochran. 1980. Statistical methods. 7th ed. Iowa State Univ. Press, Ames.

Stevenson, J.C., L.W. Staver, and K.W. Staver. 1993. Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. Estuaries 16:346–361.

USEPA. 1998. Environmental impacts of animal feeding operations. Preliminary data summary. Feedlots point source category study. USEPA Office of Water, Washington, DC.

Vector, E. 1994. Geophysical investigation of the Fossil Gulch canalat the Hagerman fossil Beds National Monument. Rep. 94-5020. Vector Eng., Carson City, NV.

Vitousek, P.M., J.D. Aber, R.W. Horwarth, G.E. Likens, P.M. Matson, D.W. Schindler, W.H. Schlessinger, and D.G. Tilman. 1997. Human alteration of the global nitrogen cycle: Sources and consequences. Ecol. Applic. 7:737–750.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation and nitrogen-management impacts on nitrate leaching under potato. J. Environ. Qual. 29:251–261.

Ward, M.H., S.D. Mark, K.P. Kantor, D.D. Weisenburger, A. Correa-Villasenor, and S.H. Zahm. 1996. Drinking water nitrate and the risk of non-Hodgkin's lymphoma. Epidemiology 7:465–471.

Waterman, P.G., and S. Mole. 1989. Extrinsic factors influencing production of secondary metabolites in plants. p. 108–138. *In* E.A. Bernays (ed.) Insect–plant interactions. CRC Press, Boca Raton, FL.

Wood, W.W., and W.H. Low. 1988. Solute geochemistry of the Snake River Plain regional aquifer system. Idaho and eastern Oregon. Professional Paper 1408-D. U.S. Geol. Survey, Reston, VA.