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Characterization of hyporheic zone processes of a northern prairie stream

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CHARACTERIZATION OF HYPORHEIC ZONE PROCESSES OF A NORTHERN PRAIRIE STREAM

by

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This thesis, submitted by David B. Rush in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

A hyporheic zone occurs beneath and adjacent to streams where surface water and groundwater mix. This zone is known to be a reservoir for solutes and a habitat for interstitial organisms. Hyporheic zone boundaries in the Tongue River, North Dakota, were investigated through examination of the physicochemical and biological gradients present in the stream channel and bank sediments. The effects of cattle grazing at the streamside interface of the riparian zone were also examined at two locations to determine land use impacts on the hyporheic zone.

Electrical conductivity (EC) and ammonium gradients were observed beneath the stream channel via nests of mini-piezometers (1.27-cm clear polyethylene tube) and wells (2.54-cm PVC). EC and ammonium increased immediately below the stream, then decreased laterally and with depth. Discontinuities in the EC gradient may indicate where metabolic or redox reactions occur under the streambed due to mixing of surface water and groundwater, or conditions in the sediments. Discontinuities in the ammonium gradient may represent a boundary between dissimilatory nitrate reduction to ammonium and a nitrification-denitrification couple, as well as subtle changes in hydraulic gradient. Discontinuities in gradients and zones beneath the stream channel likely fluctuate as subsurface processes shift temporally. Changes in biotic activity could have caused ammonium concentrations in sub-channel water to decrease from spring to summer and then increase from summer to fall at both

sites. Chemical and biological gradients in the Tongue River differ from other studies presumably because of regional differences in geology, climate, and hydrology.

The density and diversity of interstitial meiofauna populations may provide information about the general physical and chemical conditions of streambed sediments. Meiofauna diversity and population size decreased with depth at both study sites. High levels of ammonium and/or ambient reduced conditions in zones beneath the channel could exclude most meiofauna species. Meiofauna population dynamics also may indicate stream reach health.

Cattle grazing in the riparian zone appeared to affect chemical and biological gradients. Ammonium concentrations and EC were elevated at the grazed site (>10 mg/L and 1300 µS/cm, respectively). The lack of riparian vegetation and direct input of cattle waste may have caused higher EC and ammonium at the stream margin of the grazed site. Less dense and diverse populations of meiofauna at the grazed site were likely caused by greater disturbance of the sediments, lack of woody debris and preferred substrate, and more reduced conditions in the channel sediments. Differences in ammonium concentrations in subchannel water between the sites were greater than differences in nitrate concentrations in surface water. This implies that sampling designed to evaluate stream health must consider all sources and reservoirs of pollutants, and cannot solely depend on surface water analysis.

CHAPTER I

INTRODUCTION

Recent advances in hydrology and stream ecology suggest that streams are more than simply surface water drains for a watershed. They dynamically interact with subsurface and lateral zones of a catchment in the down-valley transport of water and solutes. This exchange of surface and subsurface water alters water chemistry through the transformation, storage, metabolism, and release of solutes, which in turn influences the stream channel and adjacent alluvial environments. The environment where stream water and groundwater mix is generally referred to as the hyporheic zone. In addition to solute cycling, the hyporheic zone is a habitat for benthic, phreatic, and subterranean invertebrates such as copepods, nematods, rotifers, and various insect larvae.

Because of its dynamic nature, boundaries of the hyporheic zone have been difficult to determine. Historically, researchers have attempted to define the hyporheic zone on the basis of either processes such as water flow, hyporheic–surface exchange, and solute dynamics, or on population diversity and distribution of invertebrate fauna (Valett et al., 1993). Interdisciplinary studies directly linking these two perspectives are absent in the literature. Mathematical and conceptual models of the hyporheic zone have been developed, but are not well tested (Bencala et al., 1993; Williams, 1993). The modelers conclude that further fundamental research of upper and lower boundary dynamics, water and chemical fluxes, and fauna distributions within the hyporheic zone is necessary (Bencala et al., 1993; Williams, 1993). In addition, few investigations in North America have examined the effects of anthropogenic perturbations on the hyporheic zone.

On the basis of previous research, this study hypothesized that the Tongue River would posses a hyporheic zone that can be delineated by physicochemical and biological gradients. It was presumed that the nature of these gradients would differ from those identified in other studies as a result of variations in regional geology, climate, and hydrology. It was further hypothesized that cattle grazing would affect the structure and boundaries of the hyporheic zone.

Testing these hypotheses was accomplished through characterizing the hyporheic zone and detecting its dynamic boundaries by 1) locating changes or gradients in water chemistry in the sediments beneath and adjacent to the stream, 2) identifying populations of fauna inhabiting the zone, and 3) measuring hydraulic gradients and flow within the zone.

Study Site Locations

The two riparian sites selected for this study are along the Tongue River in the west-central half of Pembina County, North Dakota (Figure 1). The Hinkle Farm (HF) site is approximately 4 km west of the city of Cavalier in the south-central portion of Section 6, Township 161 North, Range 54 West. The Icelandic State Park (ISP) site is approximately 8.5 km west of Cavalier, North Dakota, on the western edge of Section 11, Township 161 North, Range 55 West, within the state park boundary.

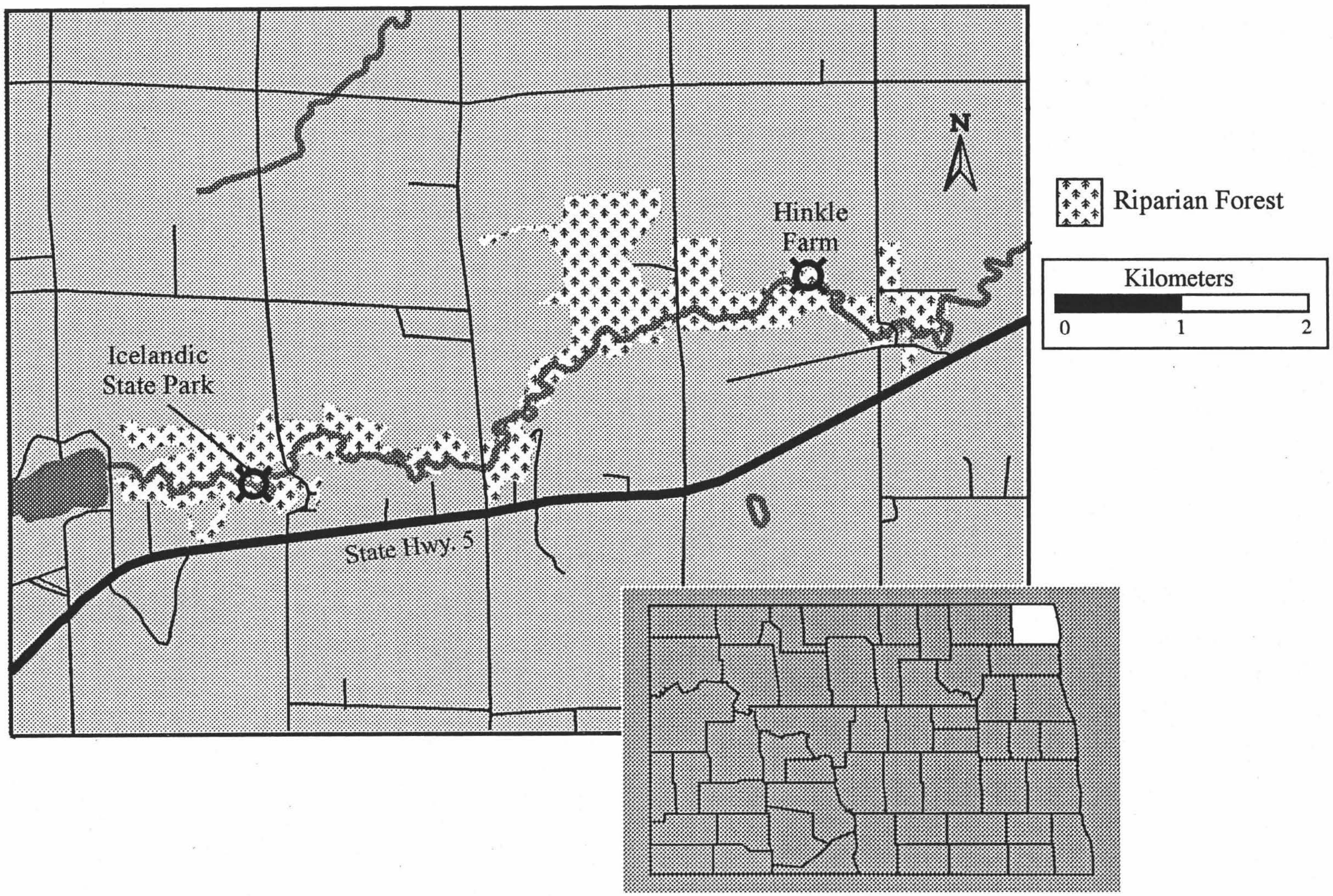

Figure 1. The locations of the study sites in Pembina County, North Dakota. Pembina County is highlighted on the inset of the state of North Dakota.

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Physiographic Setting

Regional Geology

The surficial physiography of the region was formed by glacial and postglacial processes during the Pleistocene Epoch. The last glacial advance of the late Wisconsinan Stage began 26,000 years before present (BP), and persisted until as recently as 9000 years BP (Bluemle, 1991). The most predominant glacial feature in northeastern North Dakota is the lake plain of glacial Lake Agassiz, formed when retreating ice sheets blocked the north-flowing drainage through what is now the Red River Valley (Bluemle, 1991). The damming glacier retreated farther northward in several stages, creating a large glacial meltwater lake that left wave cut scarps and beach ridges (Bluemle, 1991). The beach ridges in Pembina County are located in the west and are nearly continuous from northwest to southeast. The ridges are predominantly fine-grained sands and gravels and may be associated with aeolian dunes.

Regional Climate

Northeast North Dakota ranks as one of the coldest regions in the contiguous United States and because of its central continental location experiences large temperature variations. Average winter high temperatures during 1995 and 1996 when study data were collected were -8 °C, with extremes of 9 °C and -33 °C. The ground is typically snow-covered from December to March, and the frost line reaches depths of 1 to 1.5 m (Thompson and Hetzler, 1977). Summer high temperatures averaged 26 °C with extremes of 38 °C and 3 °C. Average annual precipitation is 50.5 cm (Thompson and Hetzler, 1977), but during the study period was unusually high. Over 30 cm of rain and more than 2 m of snow fell each year of the study, creating flood conditions on the river several times during the project. High and low temperatures and rainfall were recorded by the North Dakota Agricultural Weather Network (NDAWN) at Cavalier, North Dakota (Figures 2 and 3).

Site Geology and Hydrology

Both study sites lie in the alluvial overbank deposits of the Tongue River, mapped as part of the Walsh Formation (Arndt, 1975). The alluvium is mostly sand and silt with some clay and gravel. Borehole sediment analysis for both sites indicates that shale fragments make up much of the sand- and gravel-size sediment (Appendix A). The Pembina Delta underlies the Tongue River upstream from the sites. The delta grades from a coarse, shale-rich sand and gravel in the west to a finer, less shale-rich sand in the east (Arndt, 1975).

The soils at the two study sites belong to the La Prairie and Fairdale Series. The former soils are moderately well drained silty clay loams formed from the alluvium of floodplain terraces, alluvial fans, and abandoned stream channels. The soil has high organic matter, water capacity, and natural fertility, with moderate permeability. The Fairdale soils formed in an environment similar to that for the La Prairie soils, but are better drained with gentler slopes (Thompson and Hetzler, 1977). Both soils are subject to recurrent flooding and quick runoff, and are extremely susceptible to water erosion (Thompson and Hetzler, 1977). The Fairdale silty clay loam is the dominant soil type at the HF site. A combination of the La Prairie–Fairdale silty clay loams is present at the ISP site.

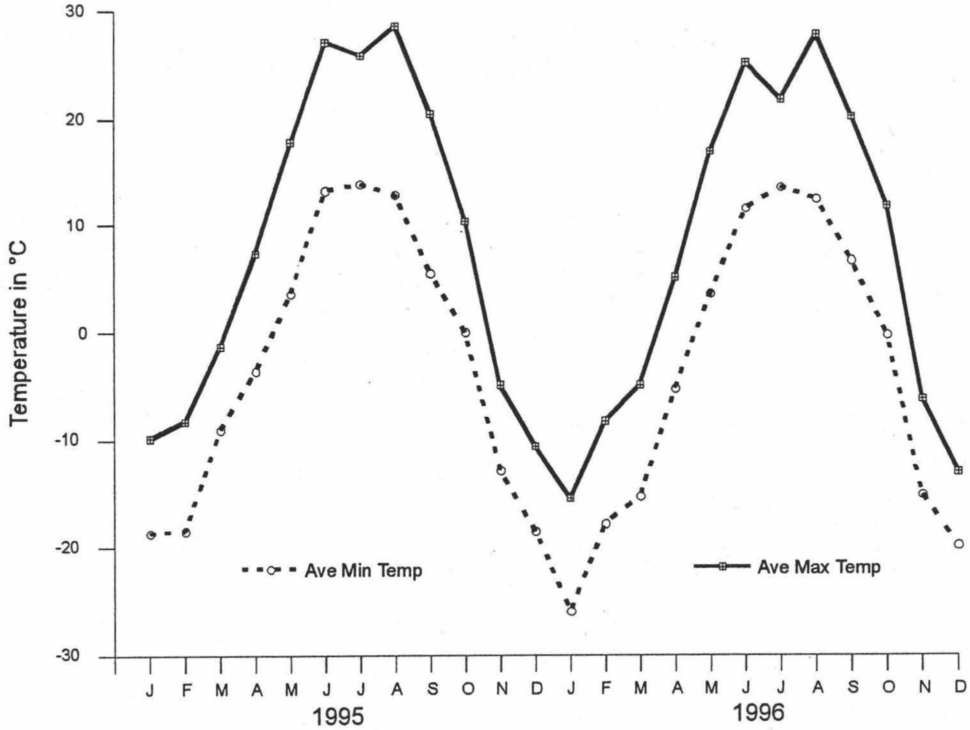


Figure 2. Minimum and maximum average monthly temperatures recorded at Cavalier, North Dakota, in 1995 and 1996 (Data from NDAWN).

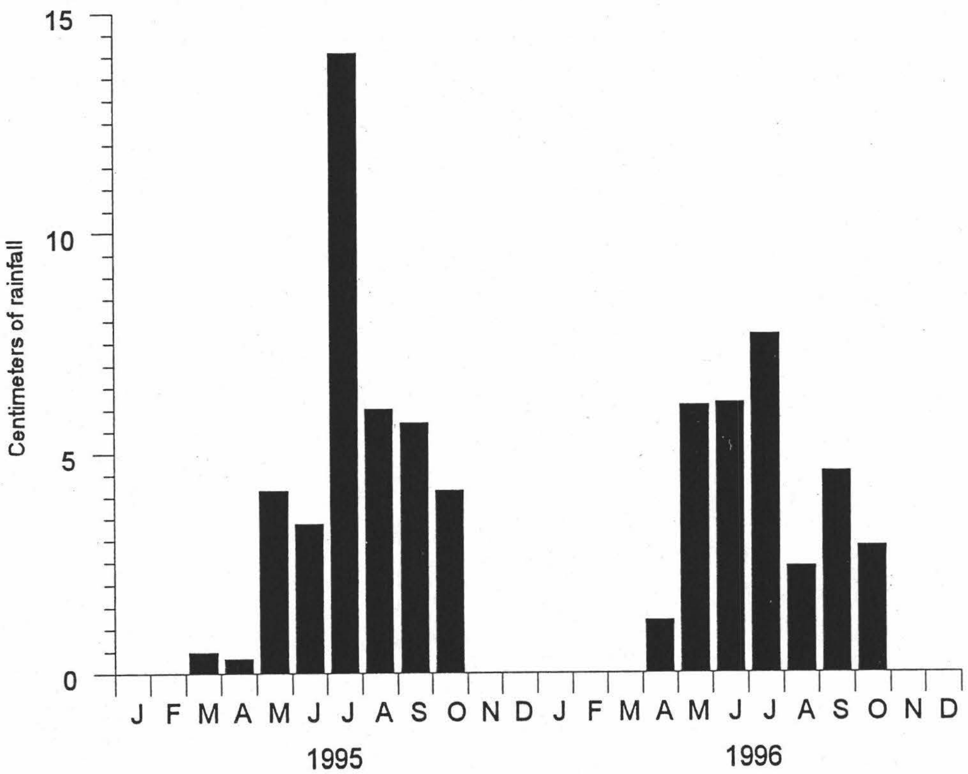


Figure 3. Total monthly rainfall recorded at Cavalier, North Dakota, in 1995 and 1996 (Data from NDAWN).

The headwaters of the Tongue River are at the base of the Pembina Escarpment on the western edge of Cavalier County, North Dakota, approximately 16 km west of the study sites. The river flows 106 km northeast and joins the Pembina River west of Pembina. The reaches of the river studied were classified using Rosgen's (1994) system, resulting in G5/4c- and F6-type reaches at the ISP and HF sites, respectively. Both reaches have a low gradient (less than 0.0004) and high sinuosity, and are moderately to highly entrenched. The basin covers approximately 41,500 ha and has an annual mean discharge of 0.61 m^3/s.

Discharge on the river has been regulated since 1961 by ten upstream retarding basins, the largest of which is Renwick Reservoir 1.45 km upstream from the ISP site. During the 1995 sampling season, a maximum discharge of 9.65 m^3/s was recorded on March 21 and a minimum discharge of 0.088 m^3/s occurred on August 17 (Table 1). Heavy snows from the winter of 1995-96 produced the highest discharge since the dam was completed, 14.8 m^3/s on April 19. The largest recorded pre-dam flow was 334 m^3/s on April 18, 1950. A low flow for 1996 of 0.024 m^3/s was recorded on April 1 (Harkness et al., 1995; 1996).

Site Vegetation

The native vegetation in the county is a mixture of deciduous trees and shrubs, and short- and tall-grass prairie. Prior to settlement, the wooded areas were restricted to the sandy soils of the Pembina Escarpment and Delta, and the riparian zones of rivers and streams. The gently sloping soils of the lake plain were dominated by tall-grass prairie. The riparian vegetation of the Tongue

River, where present, is a mixture of native trees, shrubs, and forbs, with some invasive species (Appendix B).

Table 1. Mean Monthly Discharge in Cubic Meters Per Second for the Tongue River, Recorded at Akra, ND[1]

Month[2]	1995	1996
March	3.4	0.96
April	4.33	7.1
May	1.11	4.07
June	0.25	0.78
July	0.5	0.88
August	0.13	0.23
September	0.24	0.21

[1]Source: Harkness et al. 1995; 1996
[2]Months of open water.

CHAPTER II

BACKGROUND

The hyporheic zone has been conceptually defined as the saturated sediments beneath and adjacent to a stream channel where surface and groundwater interact. This definition is widely accepted by both hydrologists and aquatic ecologists, yet there is little agreement on how the zone should be delineated. Biologists have tended to approach studies of the hyporheic zone from a "population" perspective, investigating communities of interstitial fauna existing within the abiotic habitat of the channel sediments and adjacent alluvium. Hydrologists, on the other hand, have had a "process" perspective, examining the hydrological, geochemical, and biological processes that occur in the saturated stream sediments (Valett et al., 1993). The long history of these two approaches to understanding the hyporheic zone has led to differences in methods of delineation.

Investigations of fluvial interstitial faunal communities were conducted as early as 1927 (Sassuchin et al., 1927), but the impetus for hyporheic studies has been credited to Chappuis (1942) (Williams and Hynes, 1974; Valett et al., 1993). The invertebrates inhabiting the zone, also called meiofauna, are typically 43–1000 µm in length. In the 1950s and 1960s, studies focused on the productivity and faunal assemblages of the shallow benthic layer (Husmann, 1971). By the 1970s and 1980s, the number of hyporheic studies had escalated and the focus began to shift toward linking invertebrate population distributions with physical and chemical parameters of the hyporheic zone (Williams and

Hynes, 1974; Pennak and Ward, 1986) and shift away from the channel benthic layer into the adjacent alluvium (Stanford and Gaufin, 1974; Godbout and Hynes, 1982; Pennak and Ward, 1986). Physical and chemical measures were generally limited to dissolved oxygen (DO), pH, total dissolved solids, temperature, akalinity, and sediment composition. In most of the studies, the hyporheic zone was delineated by the depth of penetration of benthic fauna into the sediments or by a depth used in previous studies. The discovery of discrete populations of meiofauna beneath and laterally away from the channel (e.g., phreatic zone, Danielopol, 1976; Pennak and Ward, 1986) supported Ward's (1989) expansion of the lotic ecosystem to include a vertical dimension, but complicated the use of meiofauna in defining hyporheic boundaries.

Benthic and interstitial fauna have been divided into three vertical distribution categories on the basis of life cycle and habitat preference: 1) stygoxens, 2) stygophiles, 3) stygobites (Gibert et al., 1994). Stygoxens are fauna that exist in surface waters and perhaps the benthic layer, only accidentally occurring in the channel sediments (Gibert et al., 1994). Stygophiles are divided into three subcategories: 1) the occasional hyporheos, which may spend part of its life cycle or find refuge in the hyporheic sediments; 2) the amphibites, whose life cycle requires the use of the hyporheic zone; and 3) the permanent hyporheos, which may spend part or all of their lives in the hyporheic sediments (Gibert et al., 1994). The stygobites are divided into two subcategories: 1) ubiquitous stygobites are widely distributed in many types of groundwater systems, whereas 2) phreatobites are restricted to the phreatic waters of stream systems (Gibert et al., 1994). Separation of fauna by life cycle and habitat preference improves their ability to be used for defining hyporheic boundaries.

However, when habitat preferences overlap, it becomes necessary to further link faunal distributions with physical and chemical processes and characteristics of stream channel sediments.

Williams (1989) examined the relationship of fauna to interstitial chemistry in an attempt to identify upper and lower boundaries of the hyporheic zone. In 4-m transects across two Canadian rivers (Rouge River and Duffin Creek), water and fauna samples were collected every meter to depths of 70–100 cm. Potential boundaries of the hyporheic zone were identified from the nitrate, DO, alkalinity, particulate organic matter (POM), and carbon dioxide data (Williams, 1993). These boundaries or discontinuities in water chemistry were correlated with the distribution patterns of the fauna. A river community was found on the river side of the discontinuity and a groundwater community on the groundwater side (Williams, 1989; 1993). In one river, a benthic community was distinguishable from the hyporheic community, presenting a possible upper boundary to the hyporheic zone (Williams, 1993). The boundaries, however, may be dynamic and difficult to reproduce owing to the high temporal and spatial variability in fauna distribution and abundance (Palmer and Hakenkamp, 1992). From this information and other studies, Williams (1993) developed preliminary seasonal models of the stream system, but cautioned that the models are generalized for streams with deep, porous beds in temperate regions of the Northern Hemisphere. Williams contends that further studies to locate upper and lower boundaries of the hyporheic zone temporally and in a variety of geographies will be essential to improving the models. Results of this study on the Tongue River were compared with Williams' results in Ontario to examine how regional physiographic differences may affect hyporheic boundaries.

Although hyporheic processes do not have as long a history in the literature as population studies, a rapid increase in publications occurred in the late 1980s and early 1990s (Valett et al., 1993). Early studies generally dealt with intergranular flow in relation to fish spawning, benthic habitats, and sedimentation (Schwoerbel, 1961; Breschta and Jackson, 1979; Moring, 1982; Metzler and Smock, 1990). Flow continues to be a major concept in hyporheic studies because it is the driving force behind stream channel development and the mixing and transport of water and solutes.

Overall transport in a stream system is down-gradient, although nutrients tend to cycle between physicochemical and biological reservoirs along the way (nutrient spiraling; sensu Newbold et al., 1981). Exchange between surface and interstitial water was found to have important implications for nutrient storage and metabolism, leading to new theories in stream solute dynamics (Grimm and Fisher, 1984; Triska et al., 1989a, 1989b; Stream Solute Workshop, 1990). Grimm and Fisher (1984) showed that loss of nitrate in surface waters could be due to microbial metabolism in the sediments, a process which uses up oxygen. Replenishment of oxygen in interstitial water was thought to be evidence for surface–interstitial exchange (Grimm and Fisher, 1984). Triska et al. (1989a) took the process one step further with an in situ tracer test to determine the fate of nitrate in the channel and adjacent sediments.

Chloride and nitrate were injected into Little Lost Man Creek (northern California) over a 17-day period and monitored at downstream stations and wells adjacent to the channel (see Triska et al., 1989b for a detailed description of the injection methods). Ten percent of the injected nitrate lost during the test could not be attributed to dilution, in-channel transport, or metabolism by periphyton

(Triska et al., 1989b). Wells with greater than predicted nitrate concentrations were identified as nitrogen sources to the stream, while those with lower than predicted concentrations acted as nitrogen sinks (Triska et al., 1989b). Chloride was present in all wells after one nominal travel time. Input of chloride exceeded output owing to transient storage, 58 percent of which occurred outside the channel in the interstitial sediments (Triska et al., 1989b). Distribution of the conservative tracer, chloride, was used to define the hyporheic zone where nonconservative nutrients such as nitrate could be stored, metabolized, or released back into the channel. Triska et al. (1989b) concluded that the interactive hyporheic zone contained less than 98 percent but greater than 10 percent channel water, as indicated by the tracer.

The tracer experiments have been repeated at several different locations with varied results. Studies showed that hyporheic flux could account for 40–80 percent of the discharge from a basin, depending on the height of base flow, streambed topography, and sediment characteristics (Castro and Hornberger, 1991; Harvey and Bencala, 1993; Harvey et al., 1996; Morrice et al., 1997). The tracer experiments appear to be less sensitive to hyporheic storage during high base flow, with most of the storage occurring in surface water (Harvey et al., 1996). Further studies using tracers have investigated nutrient fluxes and fates, especially of nitrogen, in the hyporheic zone (Triska et al., 1993a; 1993b) and the contribution of groundwater to surface water systems (Jackman et al., 1997).

Concurrent with the tracer studies, other researchers have investigated the physical and chemical properties of the hyporheic zone. Physical and chemical patterns have been identified in cross section, longitudinally, and with depth (Valett et al., 1990; Hendricks and White, 1991; Duff et al., 1997).

Temperature patterns in the subsurface may indicate zones of upwelling, downwelling, and stream water underflow (White et al., 1987). These studies were not intended to define the boundaries of the zone, but to contribute to the definition.

Although some of the above-discussed studies link "process" and "population" concepts, there remains no single definition of the hyporheic zone that spans disciplines or the spatial and temporal differences in catchments. Authors have continually called for greater interdisciplinary research and focus on cross-system comparisons (Danielopol, 1980; Hynes, 1983; Williams, 1993; White, 1993). Development of conceptual models (Williams, 1993) and mathematical models (Bencala et al., 1993) create a basis for understanding hyporheic structure and function from catchment to catchment. Testing and improving the models in different systems will be necessary before they can be applied. The models also provide a template for evaluating anthropogenic effects on the health and functioning of a stream ecosystem. Several studies in Europe have investigated the use of interstitial fauna populations to evaluate industrial impacts on the Rhone River (Plenet et al., 1992; Notenboom et al., 1994; Gibert et al., 1995; Malard et al., 1996); however few studies have investigated this in North America (Plenet et al., 1992; Ward et al., 1992).

The present study of the Tongue River attempted to expand the knowledge of physical, chemical, and biological patterns at the interface between surface water of the stream and the adjacent groundwater. Comparisons were made with the results of several studies listed above to test proposed conceptual models and improve our understanding of the hyporheic zone.

CHAPTER III

METHODS

Hydrogeological and geochemical parameters of the sediments beneath and adjacent to the Tongue River were monitored from August to October, 1995, and June to September, 1996, to characterize and detect the boundaries of the hyporheic zone. Two sites with similar stream morphologies and sediment characteristics were chosen and instrumented in nearly the same way. A perpendicular transect of piezometers was installed across the stream channel and into the riparian zone. Water level and chemistry data were collected regularly during the two sampling periods to examine spatial and temporal changes in water movement and chemical composition. Slug tests were completed in the stream channel piezometers and several of the riparian piezometers to estimate the hydraulic conductivity of the sediments. The sediment beneath the streambed was cored to examine its composition and stratigraphy. Erosion and deposition of the channel sediment and banks were measured using the piezometer risers as fixed points of reference. In addition to hydrogeological monitoring, biological samples of the streambed sediments were collected to identify populations of meiofauna inhabiting the hyporheic zone.

Groundwater Monitoring Instrumentation

Nests of minipiezometers were installed in the streambed at 0, 1, and 2 m from the stream margin (Figures 4 and 5) following procedures similar to those used by Patch and Padmanabhan (1994). Each nest contained five lengths of

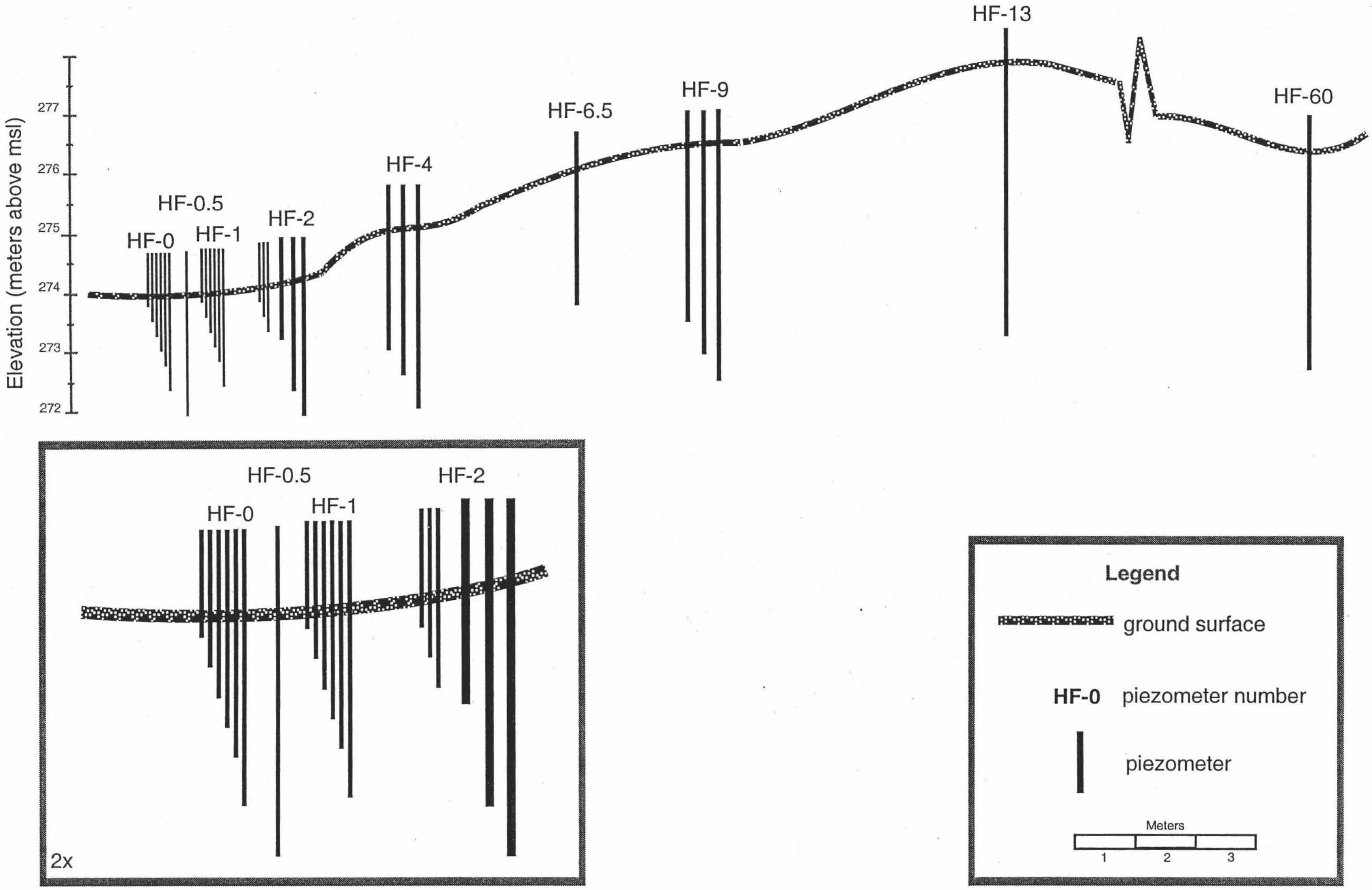


Figure 4. Cross section of the HF site showing the position of piezometer nests in relation to the stream channel and ground surface.

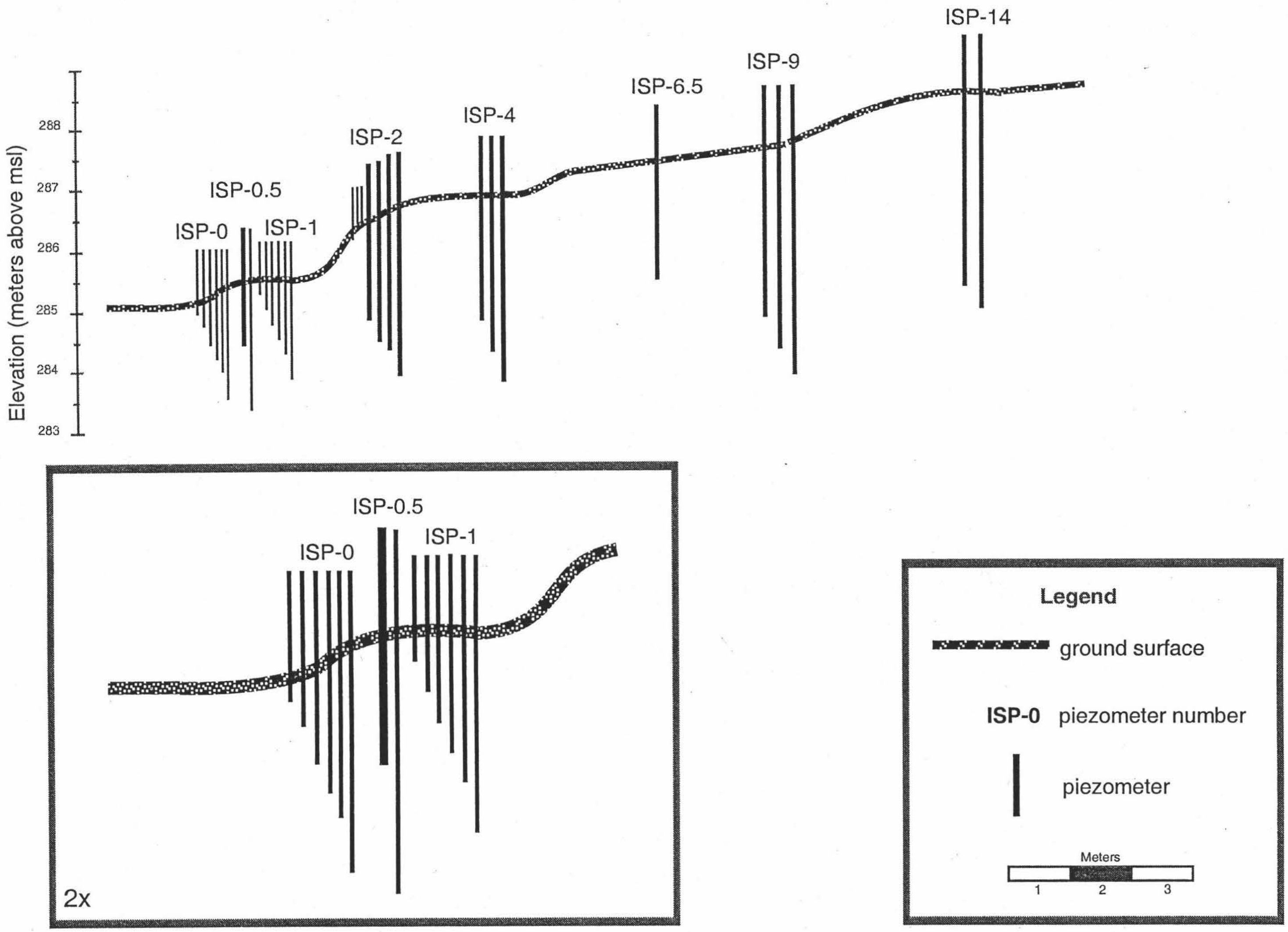


Figure 5. Cross section of the ISP site showing the position of piezometer nests in relation to the stream channel and ground surface.

1.27-cm (outside diameter [OD]) clear polyethylene tube screened at 10, 35, 60, 85, and 110 cm below the streambed. The tubes were heat-sealed at the end, and a 10-cm-long screen was created by drilling each tube with a 0.10-cm-diameter bit (Figure 6). The nests were installed using 3.18-cm (OD) steel pipe with a loose-fitting stainless steel point set in the end (Figure 6). The steel pipe was driven to the deepest screen depth, the tubes were bundled and pushed into the pipe, and the pipe was pulled out around the bundled tubes, allowing the formation to collapse and leaving the stainless steel point in the ground below the nest. It was assumed that the formation completely collapsed around the tubes. The bundle was secured to a stainless steel stake driven into the streambed. Piezometers screened at 1.5 m below the streambed were installed next to each nest in the stream using the method described above with a smaller, 1.90-cm (OD) steel pipe. A single minipiezometer was also installed 0.5 m from the piezometer nest in the center of the channel at a depth of 2.0 m below the streambed. As a result of spring flooding damage in 1996, almost all minipiezometer nests were reinstalled at the beginning of the second sampling season.

Nests of larger piezometers constructed of 2.54-cm (OD), Schedule 20 or 40 PVC were installed at variable distances from the stream margin (Figures 4 and 5; Appendix A). The bottom 10 cm of the piezometers were screened with Schedule 80, 10-slot PVC and capped with a square end cap or nylon drive point (Figure 6). Water table wells were screened across the water table with hacksaw-slotted PVC. Wells were bored using a 5.0-cm auger. Sediment was continuously sampled during drilling; texture, color, moisture content, and appearance were noted. Wells drilled in this manner were sealed with bentonite

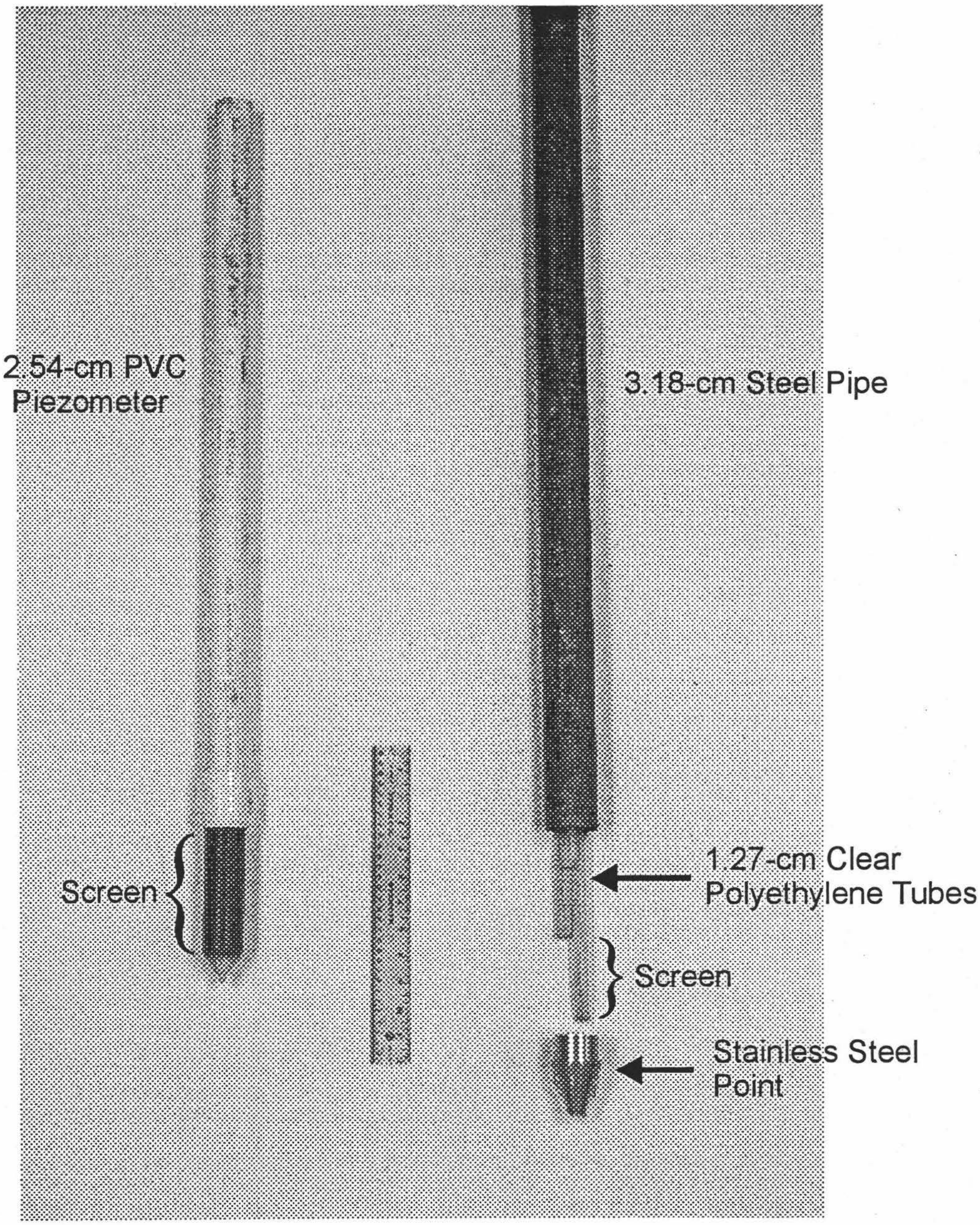


Figure 6 . PVC piezometer and minipiezometers used in study. Minipiezometers are shown in installation casing with stainless steel fall-away point beneath.

and backfilled with cuttings to the surface. In borings with a shallow water table or where the had hole collapsed, casings with nylon drive points were driven to the desired depth and the hole was backfilled. At the stream margin, the 2.54-cm piezometers were screened at 85, 110, and 150 cm below the streambed to complete the sequence left unfinished by the minipiezometers. In the riparian zone, the larger piezometers were screened at 50, 100, and 150 cm below the June 1995 water table. At the HF site, a 5.0-cm, Schedule 40 PVC water table well was installed 32 m from the stream margin. Stainless steel staff gauges were also installed in the streambed near the center of the channel to monitor fluctuations in stream level.

Quality Assurance and Quality Control

The quality assurance goal of this project was to acquire the highest-quality scientific data possible given the limitations of project equipment and funding. Field and laboratory methods followed established protocols for the collection and analyses of water, sediment, and meiofauna samples. Sampling equipment and instruments were operated according to the manufacturer instructions. Meters and probes were calibrated prior to use by the prescribed methods and standard solutions were used where required. Lab blanks, field blanks and replicate samples were used as quality control. Ion balances were calculated for some of the major ion results. Results of the research were peer reviewed prior to publication. Specific quality control procedures are described in Groundwater Monitoring and Meiofauna Sampling sections that follow.

Groundwater Monitoring

Groundwater chemistry and elevation data were recorded every 3 to 4 weeks during the ice-free months. During the second sampling season, Wells HF-9, HF-13, HF-60, ISP-9, and ISP-14 were sampled every 6 to 8 weeks. Hydraulic head elevations were measured in the minipiezometers with a small-diameter Solinst electric water level tape, and a Slope Indicator Co. electric water level indicator was used in the larger piezometers. Measurements were recorded in hundreths of feet from the top of the casing and later converted to metric elevations.

Water samples were pumped from the wells using a Geotech peristaltic pump set at 600 rpm. Minipiezometers were connected directly to the pump with a 0.64-cm polyethylene tube. For the larger piezometers, the polyethylene tube was placed in the well just off the bottom of the screen. Minipiezometers were purged during sampling by continuous pumping through the flow-through cell. All wells were purged dry or for at least 5 minutes with the peristaltic pump prior to sampling. Wells sampled on August 2, 1996, were not purged prior to sampling, because it was thought that purging affected DO measurements. This was later found not to be the case. All field chemistry measurements were made in a sealed, flow-through cell (Figure 7). Samples were analyzed in the field for EC using a Beckman conductivity bridge, pH using a Beckman pH meter and reference electrode, Eh using a Beckman pH/ISE meter and platinum electrode, DO using a Y.S.I. DO meter, and temperature with the pH and DO meters. All instruments were calibrated before each sampling session. The DO meter was calibrated by elevations and pH, Eh, and conductivity meters were calibrated against standard solutions. Values were recorded from the DO meter when the

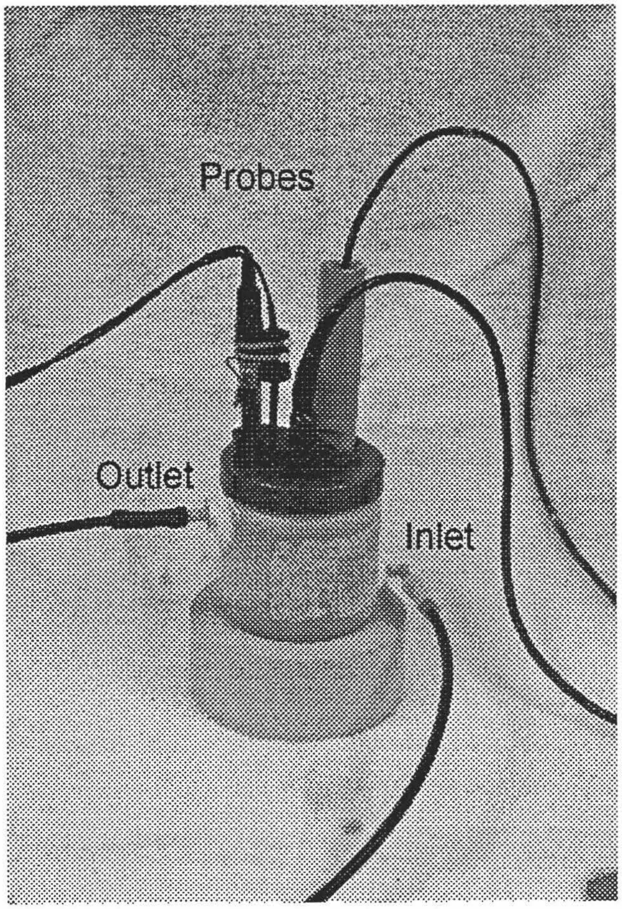


Figure 7. Sealed flow-through cell for field chemistry analysis.

readout was stable for 30 seconds. Values from the other meters were recorded after the DO. Between samples, the polyethylene tube and flow-through cell were triple-rinsed with deionized water.

After field analysis, samples were pumped through a Geotech geofilter using a 0.45-µm cellulose acetate filter paper and collected in 500-mL, high-density polyethylene bottles. All bottles were acid-washed, triple-rinsed with deionized water, and triple-rinsed in the field with formation water before being filled with sample. The bottles were placed on ice and returned to the laboratory for nitrate and ammonium analysis. An Orion™ portable meter with Orion™ NH_4^+ and NO_3^- ion-selective electrodes was used following the procedures described in the meter and probe instruction manuals. The meter and probes were calibrated prior to use with the respective standard solutions. Values were recorded from the meter only when the reading could be reproduced three consecutive times. Lab blanks and field blanks were used for one sample collection to examine equipment and procedure error. Two replicates were sent to the North Dakota Department of Health (NDDH), Chemistry Division, on August 14, 1996. Blank and replicate results were within one standard deviation of the sample results. Ion balances were calculated from the September 1996 major ion analysis results (Table 13 in Appendix E).

Once during the first sampling season and twice during the second, water samples were collected from the stream at both sites and from Wells HF/ISP-0-35, HF/ISP-0-110, HF/ISP-1-35, HF/ISP-1-110, HF-2-35, HF/ISP-2-110, and HF/ISP-9-100 for analysis of major ions. The analyses were conducted at the NDDH using an Orion conductivity meter, a Perkin Elmer ICP atomic emission spectrometer, a Lachat flow injection analyzer, and a Metler autotitrator for akalinity and pH (standard errors for equipment are listed in Table 14 in Appendix E). Samples from August 1995 and July 1996 were filtered to 0.45 µm in the field and shipped on ice. Filtered, unfiltered, and acidified samples were sent on ice to the laboratory for the September 1996 sampling.

To determine the hydraulic conductivity of the hyporheic and riparian sediments, falling-head slug tests were performed with the minipiezometers and some of the riparian piezometers. Rates of falling head in the minipiezometers were measured using a meter stick and stopwatch. The meter stick was placed next to the piezometer, which was then filled with formation water. Times were recorded as the water level reached marked heights on the meter stick. The test was repeated three times, and the average time for each marked height was recorded. This procedure was the same for all minipiezometers. Rates of falling head in the 2.54-cm riparian piezometers were measured with a Terra Systems pressure transducer attached to a Thor datalogger. Transducers were lowered into the piezometers and allowed to stabilize before a slug of deionized water was added. Data were logged until the piezometer had recovered to greater than 90 percent. Hydraulic conductivity was estimated from the time versus falling-head data (Bouwer and Rice, 1976; Bouwer, 1989).

Because the sediment below the streambed could not be described during well installation, cores were taken between 0 and 1 m and 1 and 2 m from the stream margin. A modified Livingston corer was manually pushed to a depth of 0.61–0.92 ms below the streambed. These cores and the samples collected during well drilling were allowed to dry in the laboratory before being analyzed for clay, silt, and sand size fractions. Samples with a visibly low silt and clay content were dry sieved following techniques described in Royse (1970). The remaining samples were analyzed using Perkins' (1977) hydrometer method.

Meiofauna Sampling

Biological samples were collected twice during the study to identify boundaries of the hyporheic zone by examining the fauna populations in the sediments beneath the stream channel. On July 29–30 and October 12, 1996, samples were obtained at low-flow conditions from 25, 50, and 100 cm below the streambed at 0.5, 1.5, and 3 meters from the stream margin (Figure 8). The fauna sampler consisted of a cased sand point attached to a sample bottle with a 0.64-cm tube. The sand point was constructed with 1.91-cm diameter stainless steel pipe with a 3.18-cm-diameter point at the terminus. The screen was 10 cm long with 0.64-cm openings covered with a 1-mm stainless steel wire mesh. Tubing (0.64-cm) was connected to the point using a stopper in the threaded end of the point. The tube was cased with 1.91-cm-diameter steel pipe coupled to the stainless steel sand point. A 3.18-cm-diameter steel pipe was used to case the sand point and attached pipe, covering the screen. The apparatus was then driven into the streambed without contaminating or clogging the screen. At the desired sample depth, the 3.18-cm-diameter steel casing was pulled up 10 cm to expose the screen on the sand point. The 0.64-cm tube was then connected to the sample bottle and to a peristaltic pump. Samples were extracted via the vacuum in the bottle to ensure that organisms were not damaged in the pump.

Before the sample was extracted, 0.5 L of water was removed from the sampler and discarded to clear any contamination that may have occurred during installation. One to 5 L were extracted at each sampling point and depth. The sample was rinsed through a 63-µm sieve and then placed in a 50-mL HDPE

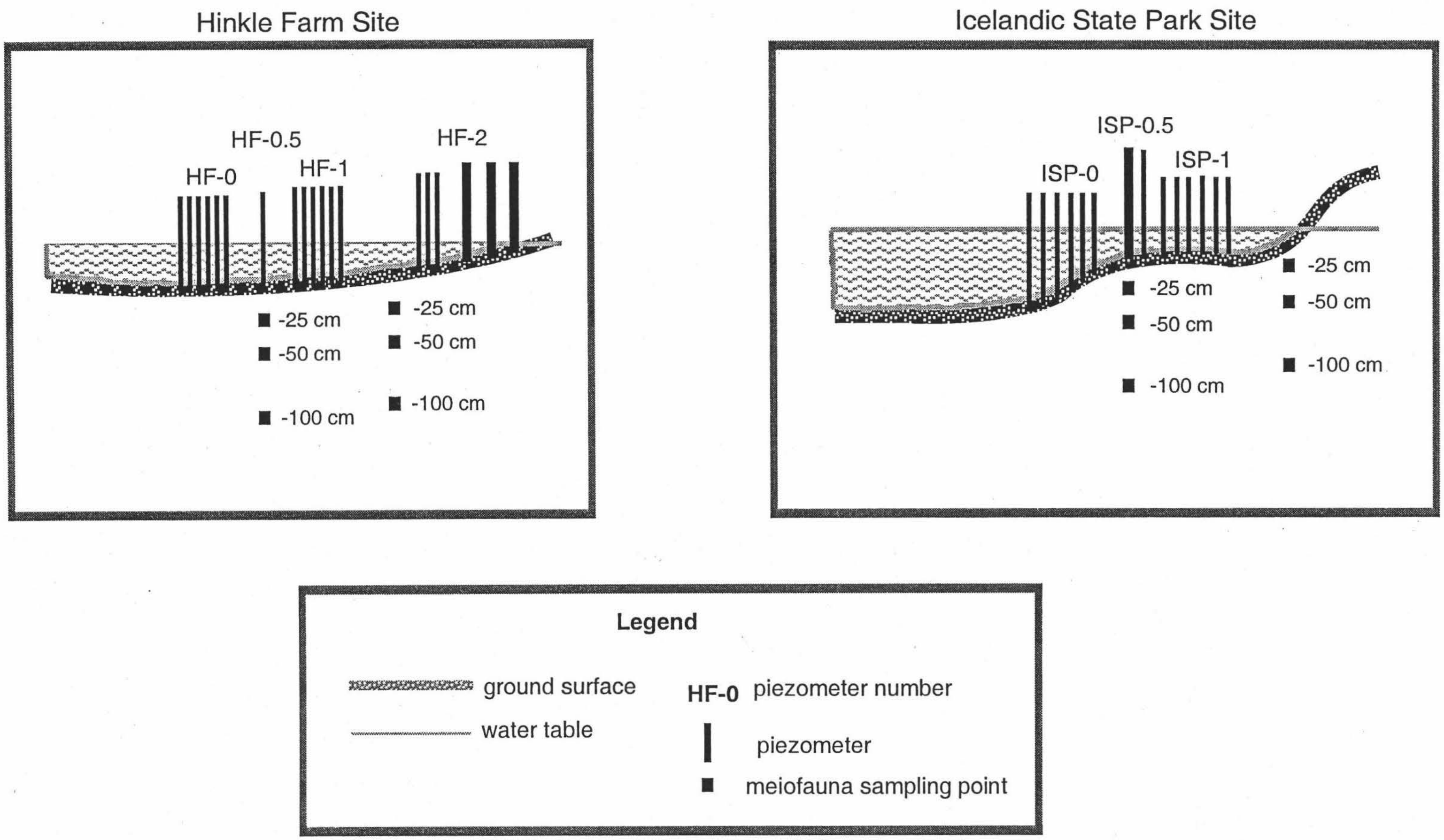


Figure 8. Cross sections of the HF site and ISP site displaying meiofauna sampling locations beneath the channel.

sample bottle. Rose Bengal stain and a 10 percent buffered formalin solution were added to stain and preserve the samples, respectively. In the laboratory, the samples were rinsed and stored in 30–50 percent ethyl alcohol and sorted following a swirl decantation procedure (Appendix C). Procedures for meiofauna separation, storage, mounting, and classification are given in Appendix C.

CHAPTER IV

RESULTS

Sediment Characterization

At both sites, sediments are predominantly sand, with varying percentages of silt and clay (Appendix A). The surface of the streambed is mostly fine-to-medium sand, with some coarser sands and less than 1 percent gravel. At the HF Site, sediments in the channel coarsen slightly with depth, but fine-to-medium sand remains the dominant particle size. Sediments at 30–70 cm below the streambed at ISP are significantly coarser than at the surface, containing 11 to 60 percent gravel. Some gravels are as large as 2–3 cm, indicating periods of high discharge in the past, before the installation of the upstream flood control reservoir. Reduced organic matter is also present in the interbedded sands and gravels; some particles are large enough to be distinguished as wood fragments.

Channel morphology and rates of sedimentation and erosion varied at both sites during the study. Bank instability and periods of flood-stage discharge frequently altered the channel morphology. During the spring flood of 1996, as much as 80 cm of sediment was eroded from HF and 50 cm was deposited at ISP near the stream–riparian interface (Figures 9 and 10).

The near-stream and upland riparian sediments have a composition similar to those of the channel. At HF, medium and fine sands are interbedded with silt and clay layers. Iron oxide staining is present in the sands near the

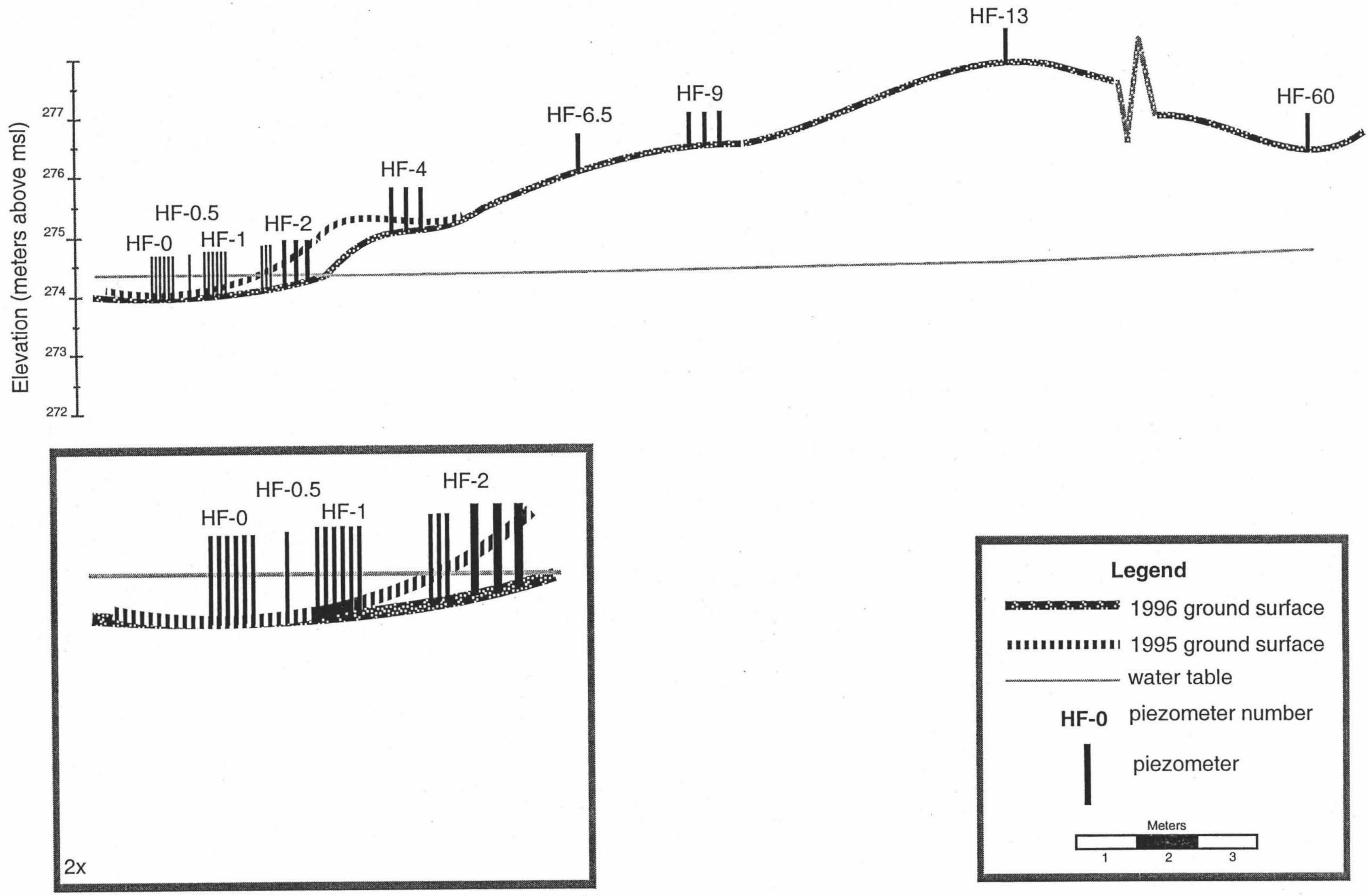


Figure 9. Change in the topographic profile of the channel from 1995 to 1996 at the HF site.

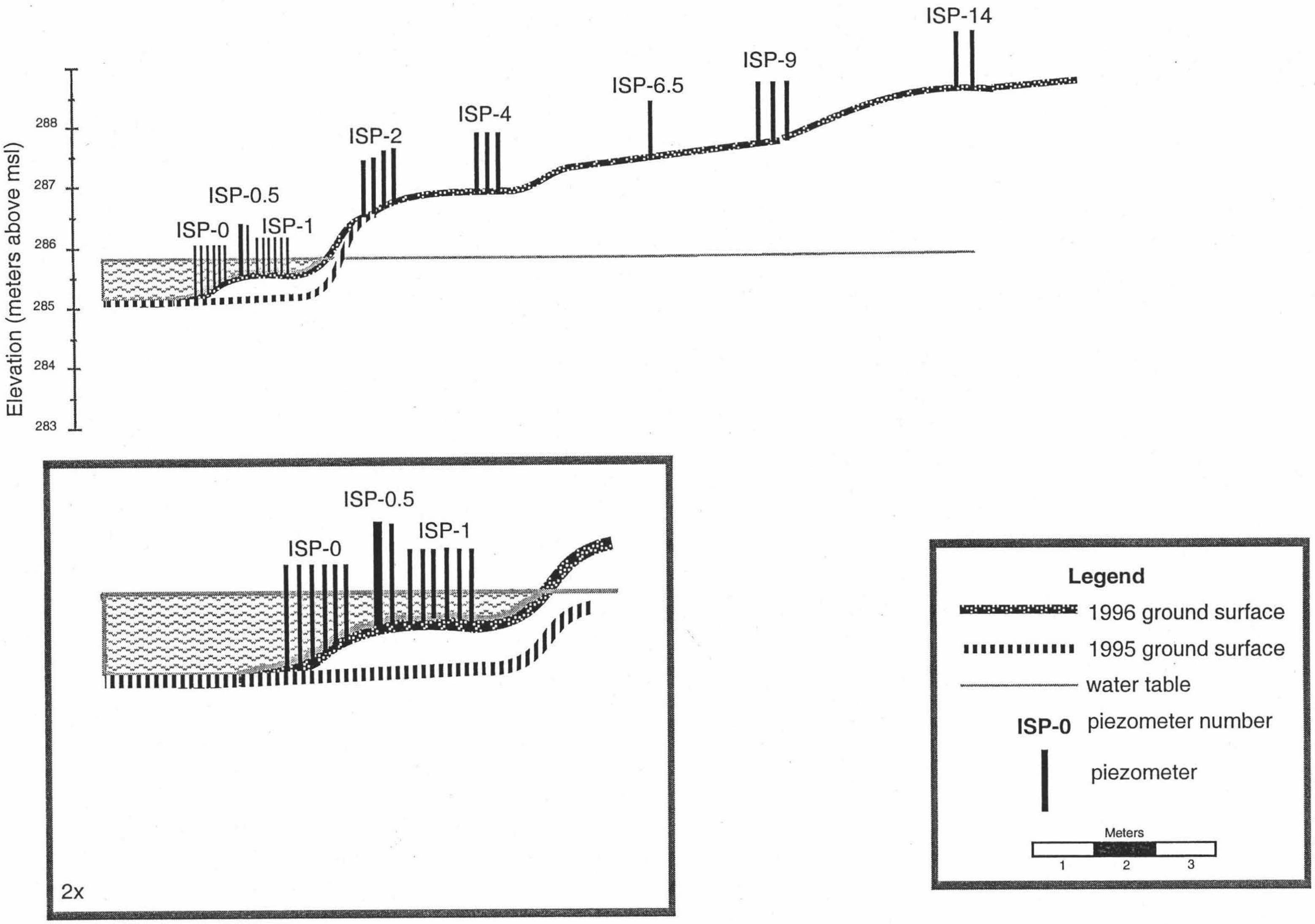


Figure 10. Change in the topographic profile of the channel from 1995 to 1996 at the ISP site.

water table. Below the water table, sands change to gray, with a slight sulfurous smell in the deeper samples. Organic material and shell fragments were found 1 m below the water table in the upland. At ISP, sediments of the upland are predominantly sand with interbedded layers of coarse sand and gravel 1.5–3 m below the surface. Reduced conditions exist just below the water table. Shale is the dominant parent material of most sand and gravel at both sites.

Estimated hydraulic conductivities of the sediments are variable as expected in fluvium (Figures 11 and 12). Conductivities range from 0.09 to 20 m/day, with the sediments beneath the stream channel displaying higher hydraulic conductivities than those in the riparian zone at HF. The highest conductivities occur 85 to 100 cm below the streambed and water table.

Hydrology

Hydrologic conditions on the Tongue River varied throughout the two seasons of data collection (Appendix D). The highest stream discharges occurred both years in April, and the lowest were recorded in August and September (Table 1). Depth of water in the channel as measured on the staff gages did not vary more than 50 cm during the periods of data collection. During the fall of 1995, however, water levels in the channel at HF were below the staff gage, and in the spring of 1996, water levels were above the 2-m high gage.

The water table gradually slopes toward the stream at both sites, indicating gaining stream reaches. At HF, the water table was consistently elevated near Wells HF-13 and HF-60, which are most distant from the stream. The highest elevations in wells from both sites occurred in the early summer and dropped during the following months (Figures 13–16). The water table at both

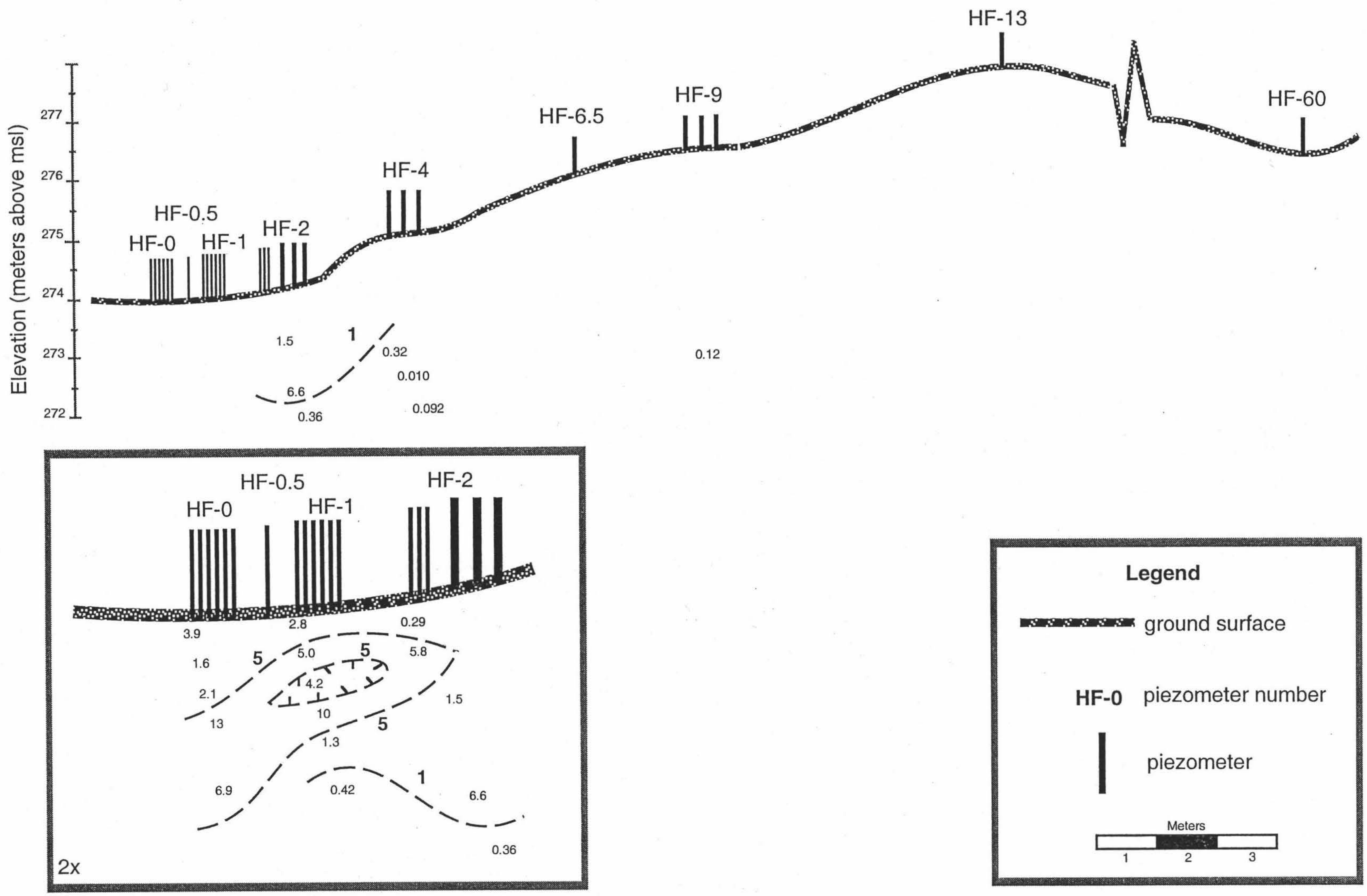


Figure 11. Hydraulic conductivity estimates in m/day at the HF site.

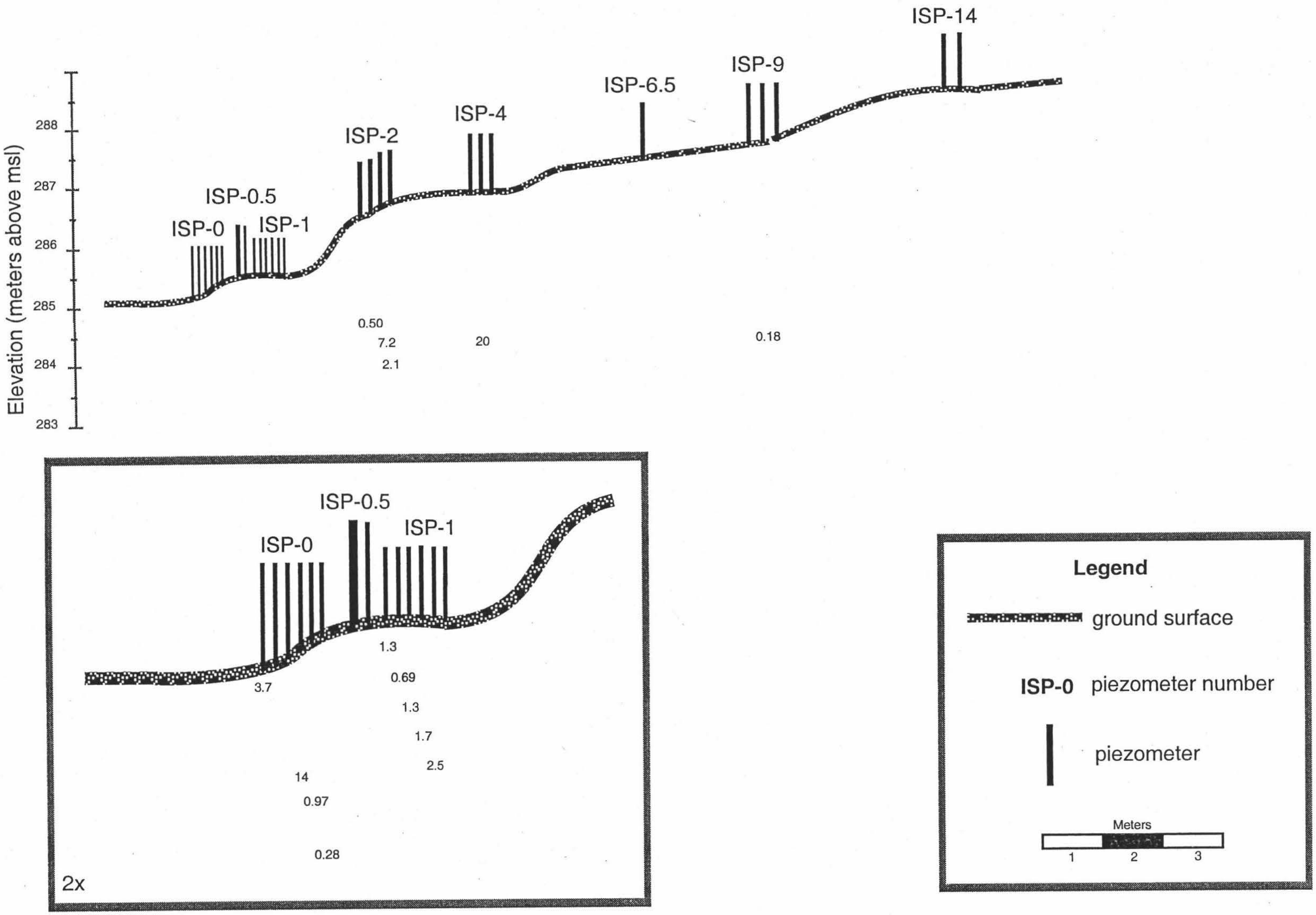


Figure 12. Hydraulic conductivity estimates in m/day at the ISP site.

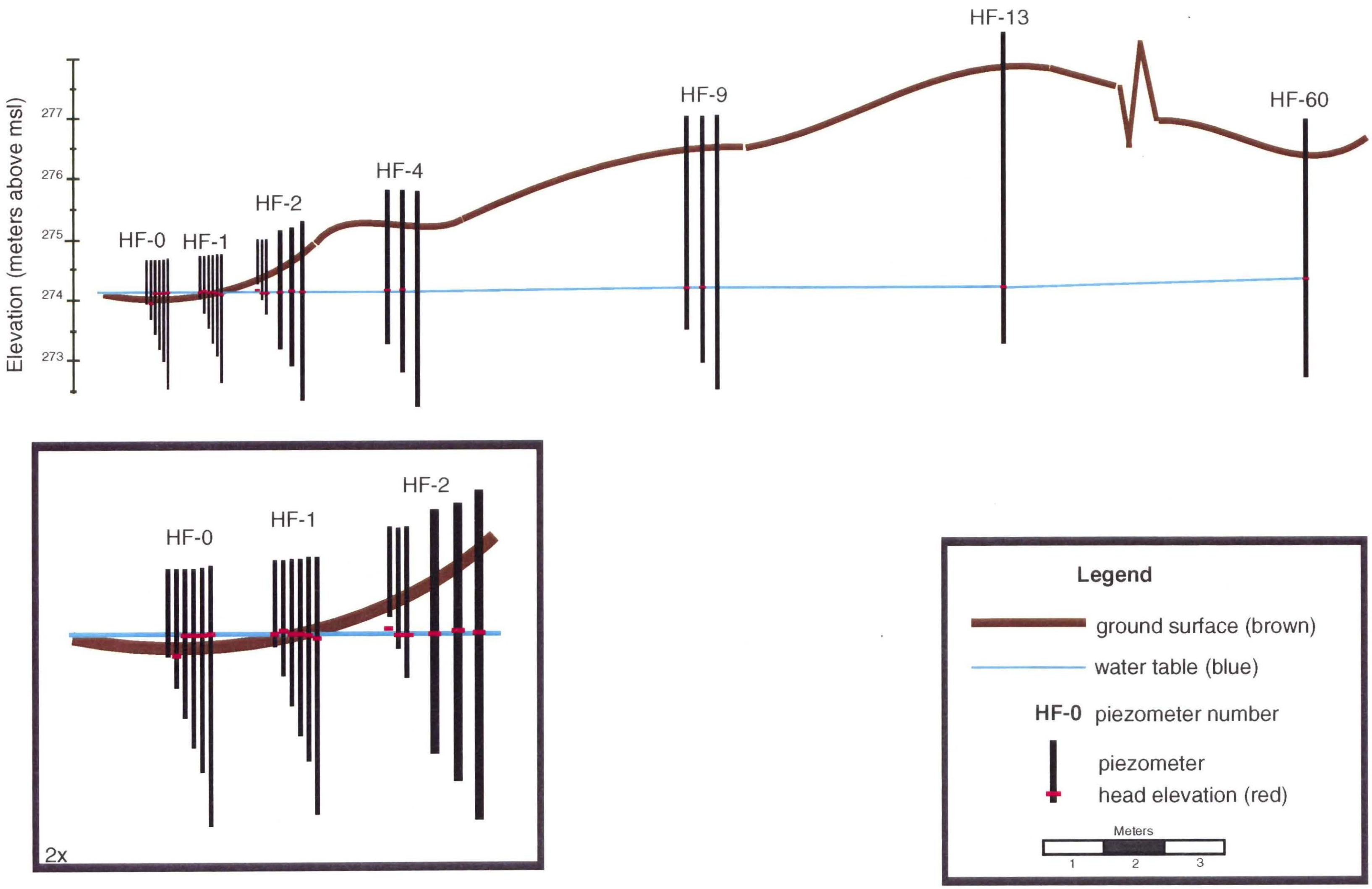


Figure 13. Water table and piezometric head elevations at the HF site, 23 September 1995.

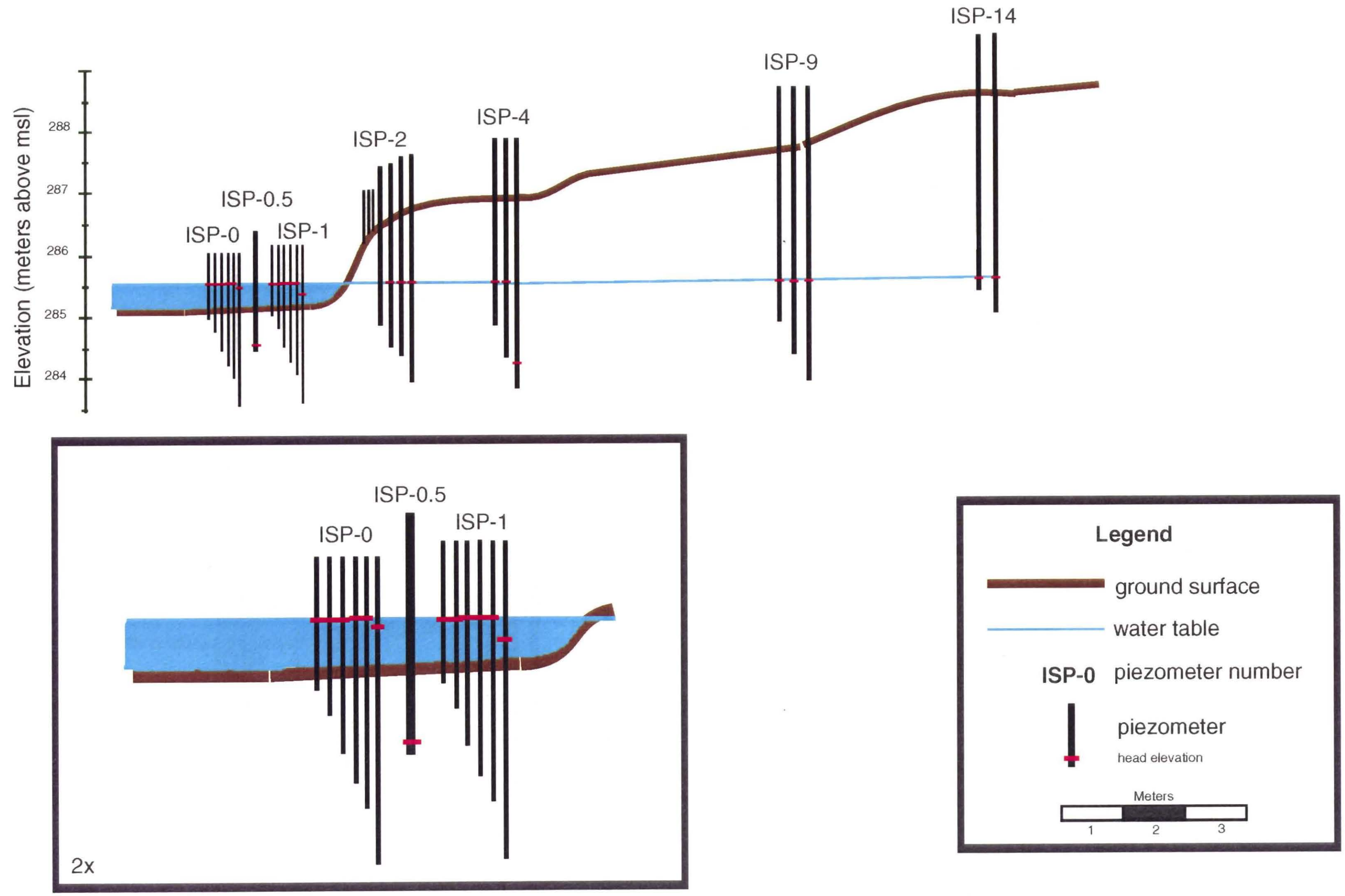


Figure 14. Water table and piezometric head elevations at the ISP site, 23 September 1995.

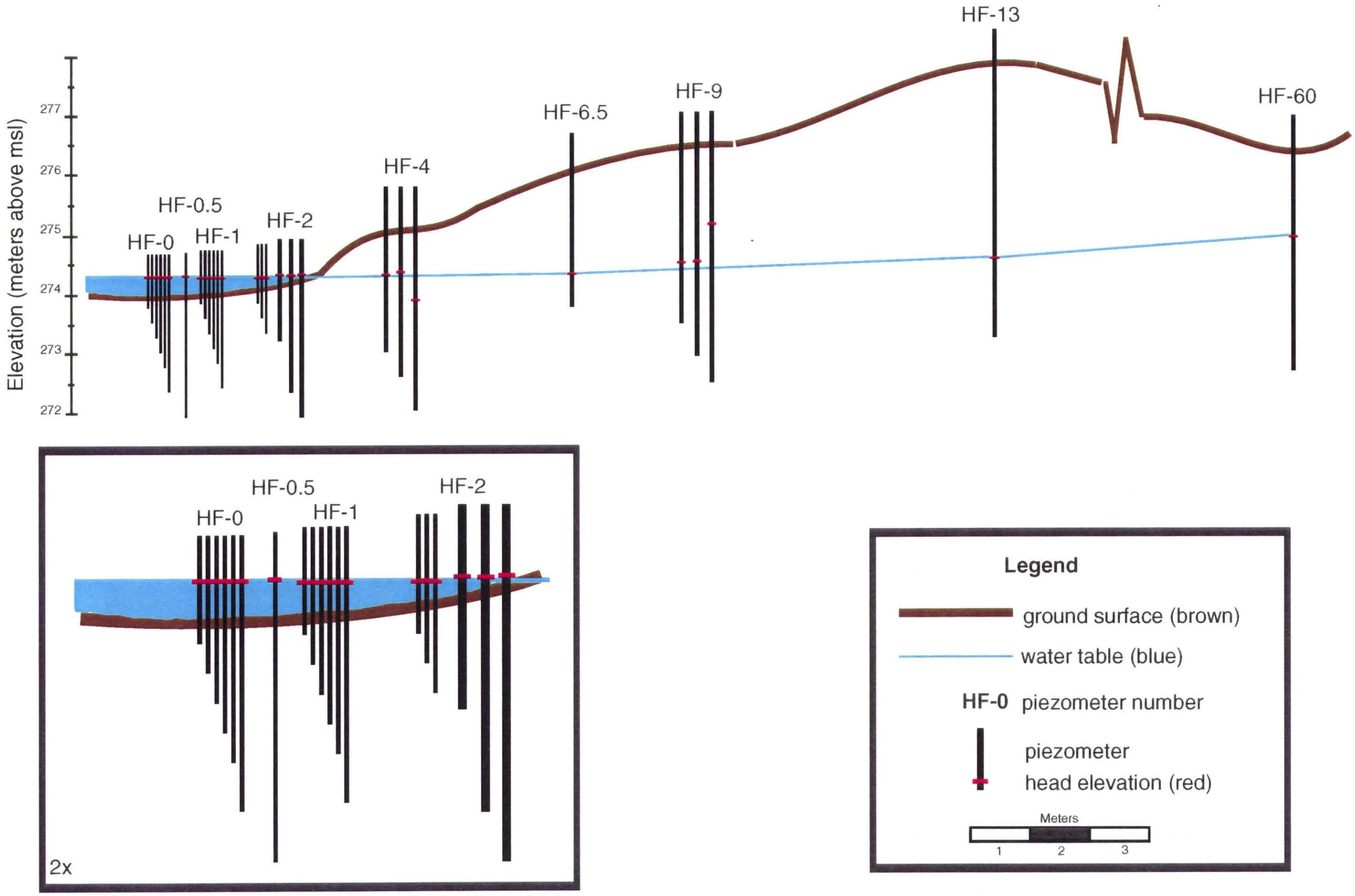


Figure 15. Water table and piezometric head elevations at the HF site, 6 June 1996.

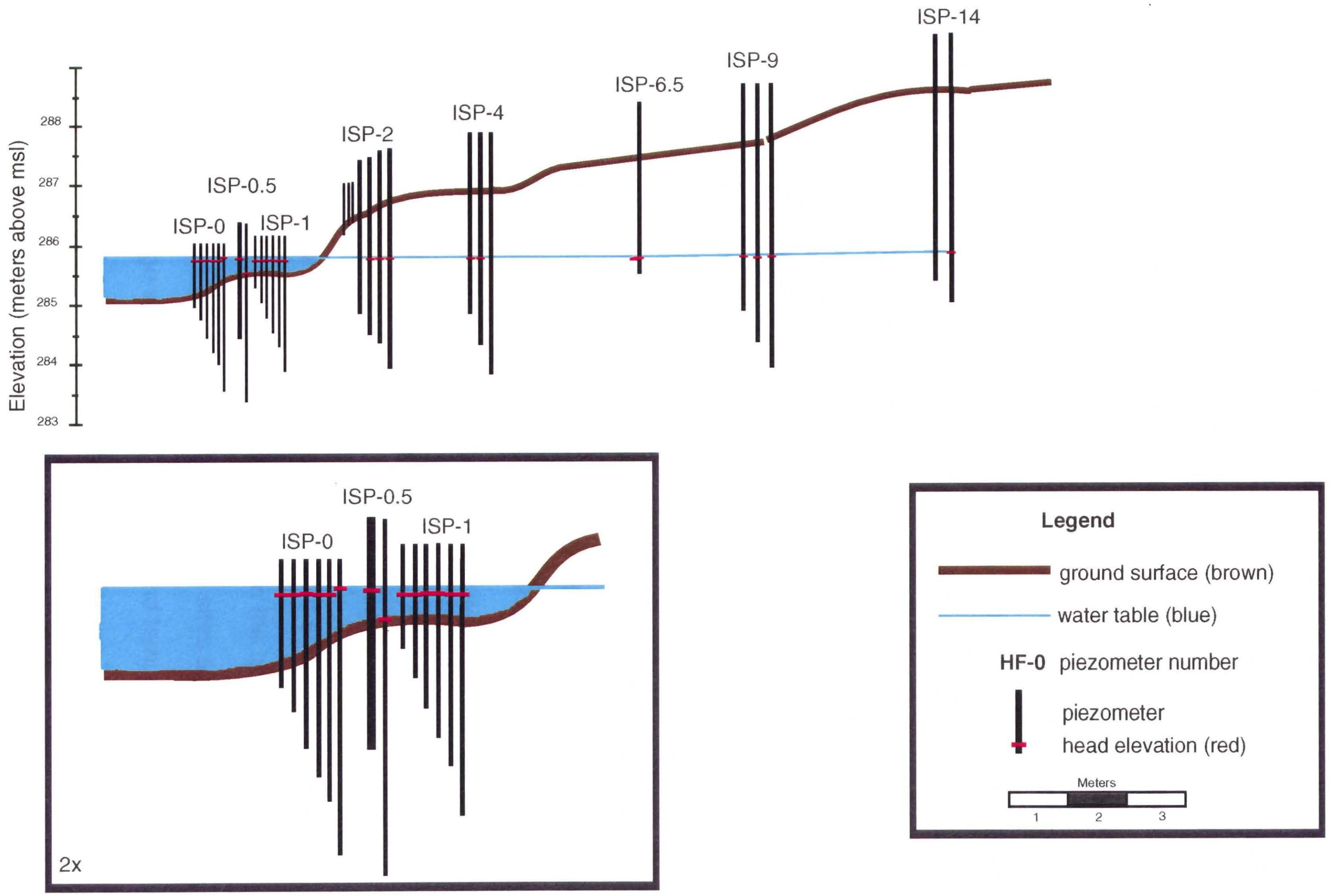


Figure 16. Water table and piezometric head elevations at the ISP site, 6 June 1996.

sites responded to changes in stream level and did not vary more than 1 m in elevation between wells and from site to site (Appendix D). The average lateral hydraulic gradient ranged from 0.018 in the spring/early summer to 0.010 in the late summer/fall for HF. At the ISP site, the average hydraulic gradient was 0.0039 and varied only 0.0004 between seasons. Consistent vertical hydraulic gradients were not recorded for any of the nested piezometers. Distinct upward or downward gradients were not apparent in any of the nested minipiezometers. Generally, the water level in the channel piezometers corresponded to changes in stream stage (Appendix D).

Geochemistry

Water samples were collected from both sites in August, September, and October of 1995 and June, July, August, and September of 1996. Not all wells and piezometers were sampled at each event. Analyses of the samples showed variation in the chemistry of stream water, groundwater in the adjacent riparian zone, and a possible mixing zone (Table 12 in Appendix E). Both spatial and temporal variations in the concentrations of chemical parameters existed within and between sites. Major and minor ion analyses were performed for select wells from each site three times during the study (Table 13 in Appendix E).

Surface Water

Chemical characteristics of the surface water and deep riparian groundwater were not noticeably different between the two sites (Table 2). Surface water characteristics varied little between sites and sample dates (Table 3). The average values for DO, EC, pH, and temperature were less than 6 percent different between sites. The average Eh was 7 percent different between sites, as much as 20 mV higher at ISP. Eh was

Table 2. Selected Surface Water and Riparian Groundwater Chemistry Results

Sample Location	Sample date	Dissolved Oxygen, mg/L	Electrical Conductivity, µS/cm	Temp, °C	pH	Na^+, mg/L	NO_3^- mg/L N	NH_4^+, mg/L
HF-Surface	8/28/95	7.11	627	20.7	7.98	32	0.592	0
ISP-Surface	8/27/95	5.94	632	19.3	7.05	34.2	0.576	0
HF-Surface	7/08/96	6.68	658	18.8	8.35	26.3	0.062	0
ISP-Surface	7/09/96	6	652	20.5	8.55	29.4	0.063	0
HF-9 (-100 cm)[1]	8/28/95	0.68	886	13	7.34	7.8	0	0
ISP-9 (-100 cm)	8/27/95	0.57	563	13.2	6.9	3.1	0	0.188
HF-9 (-100 cm)	7/08/96	NA	627	9.8	6.9	6.2	0.086	0
ISP-9 (-100 cm)	7/09/96	0.94	589	10.6	6.75	0	0	0

[1]Wells were located 9m from the stream–riparian interface and screened at 100 cm below the June 1995 water table.

Table 3. Average Value, Average Deviation, and Percent Difference of Averages Between Sites for Select Water Quality Parameters Measured in Surface Water

Site[1]	Dissolved Oxygen, mg/L	Electrical Conductivity, μS/cm	pH	Temp., °C	NO_3^- mg/L	NH_4 mg/L	Eh, mV
HF Site	7.64 ± 0.76	442 ± 69	7.72 ± 0.41	17.3 ± 4.0	0.12 ± 0.13	0.005 ± 0.007	281 ± 97
ISP Site	7.26 ± 1.35	465 ± 67	7.48 ± 0.60	17.6 ± 3.6	0.11 ± 0.13	0.021 ± 0.030	302 ± 75
Percent Difference	5	5	3	2	14	307	7

[1]n = 7 for both sites.

highest in the spring and decreased throughout the summer at both sites. Ammonium showed the greatest variation between sites and sampling events. The majority of samples contained no ammonium; however, low concentrations were present on two dates at each location. The average concentration at ISP was 4 times higher than that of HF (Table 3). Nitrate concentrations in the channel water varied with no apparent trend. The average nitrate concentration at HF was nearly 14 percent higher than levels at ISP (Table 3). Relative to federal drinking water standards, concentrations were very low. Nitrate tended to be highest in July and September and lowest in June and October (Table 12 in Appendix E).

Groundwater

Wells 4 or more meters from the stream channel were assumed to be sampling riparian groundwater. The wells at both sites located 9 m from the channel and 100 cm below the June 1995 water table were used to compare the chemical characteristics of groundwater between sites (Table 4). As with surface water, the DO, pH, and water temperature were less than 6 percent different between sites. DO concentrations in the groundwater wells were below 2 mg/L, indicating an oxygen-depleted and potentially reduced environment. Eh measured in the wells ranged from 90 to 257 mV at HF and 65 to 200 mV at ISP. Some wells also displayed high levels of dissolved iron and manganese; concentrations ranged from 3.2 to 30.2 mg/L and 0.96 to 3.9 mg/L, respectively (Table 13 in Appendix E). Although DO was nearly absent from the groundwater, levels of nitrate were present in wells for some sample dates. Levels of nitrate tended to be highest in the early summer, but absent from groundwater by mid-summer. Higher-than-average nitrate levels were observed on June 6, 1996 and July 9, 1996, at ISP (Table 12 in Appendix E),

Table 4. Average Value, Average Deviation, and Percent Difference of Averages Between Sites for Select Water Quality Parameters Measured in Wells 9 m from the Stream Margin

Site[1]	Dissolved Oxygen, mg/L	Electrical Conductivity, μScm	pH	Temp., °C	NO_3^- mg/L	NH_4, mg/L	Eh, mV
HF Site	0.67 ± 0.16	483 ± 70	7.10 ± 0.15	10.4 ± 1.0	0.025 ± 0.030	0.198 ± 0.14	245 ± 12
ISP Site	0.71 ± 0.12	349 ± 35	6.99 ± 0.14	10.9 ± 0.9	0.014 ± 0.018	0.075 ± 0.03	135 ± 5
Percent Difference	5	38	1	5	82	165	81

[1]n = 5 for both sites.

Table 5. Cation and Anion Concentrations in mg/L from Select Riparian Groundwater Wells at Both Sites (data from North Dakota Department of Health).

Sample Location	Date Collected	Fe^{2+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-1}	N^2	SO_4^{2-}	Cl^-	F^-	SiO_2
HF-9-100	8/28/95	3.90	1.93	121	33.4	7.8	1.9	526	<0.02	—	—	—	—
ISP-9-100	8/27/95	6.06	1.68	85.2	23.0	3.1	1.0	391	<0.02	—	—	—	—
HF-9-100	7/8/96	3.17	0.959	76.7	19.9	6.2	3.2	339	0.86	—	—	—	—
ISP-9-100	7/9/96	11.5	2.08	92.7	24.1	<0.1	1.1	400	0.12	—	—	—	—
HF-9-100	9/15/96	9.63	2.10	144	38.6	4.6	3.0	505	0.02	55	<3.0	0.31	37.3
ISP-9-100	9/16/96	12.3	1.87	95.8	25.2	<0.1	1.2	391	<0.02	9	<3.0	0.24	36.7

[1]CO_3^{2-} and OH^- were below detection limits of 1 mg/L.

[2]NO3 + NO_2 as N.

No_3^- + NO_2

but average nitrate levels were over 80 percent higher at HF. Ammonium was seasonally present in the groundwater. In the summer months, it was absent from all wells except HF-4 nest and ISP-4 nest, but was detected in the deep riparian wells at both sites in September (Table 12 in Appendix E). The average ammonium concentration in groundwater at HF was over 1.5 times greater than at ISP.

The minipiezometers and wells screened beneath and directly adjacent to the stream channel were likely sampling a mixing zone or potential hyporheic zone. Water beneath the channel was generally reduced and contained large concentrations of iron, manganese, and other dissolved ions (Table 13 in Appendix E, Wells HF/ISP 0-2). Oxygen-depleted conditions were present beneath the streambed (-10 cm), where DO concentrations decreased to less than 1 mg/L. Despite the steep oxygen gradient, concentrations did not consistently decrease with depth or distance from the channel (Figure 17). Oxygen levels were lower in wells and piezometers under the stream channel than in surface water or groundwater. Eh also displayed an irregular distribution and was generally lower in the hyporheic zone than in surface water or groundwater. The lowest Eh measurements were recorded at the stream–riparian interface between 60 and 100 cm beneath the streambed (Figures 18 and 19). Subsurface temperatures were cooler than the channel water, but warmer than the deeper riparian groundwater (Appendix E). Fluctuations in temperature between sample dates decreased with depth and distance from the channel.

Gradients were present for EC and ammonium and, to a lesser extent, nitrate, between surface water, hyporheic water, and groundwater. At both sites,

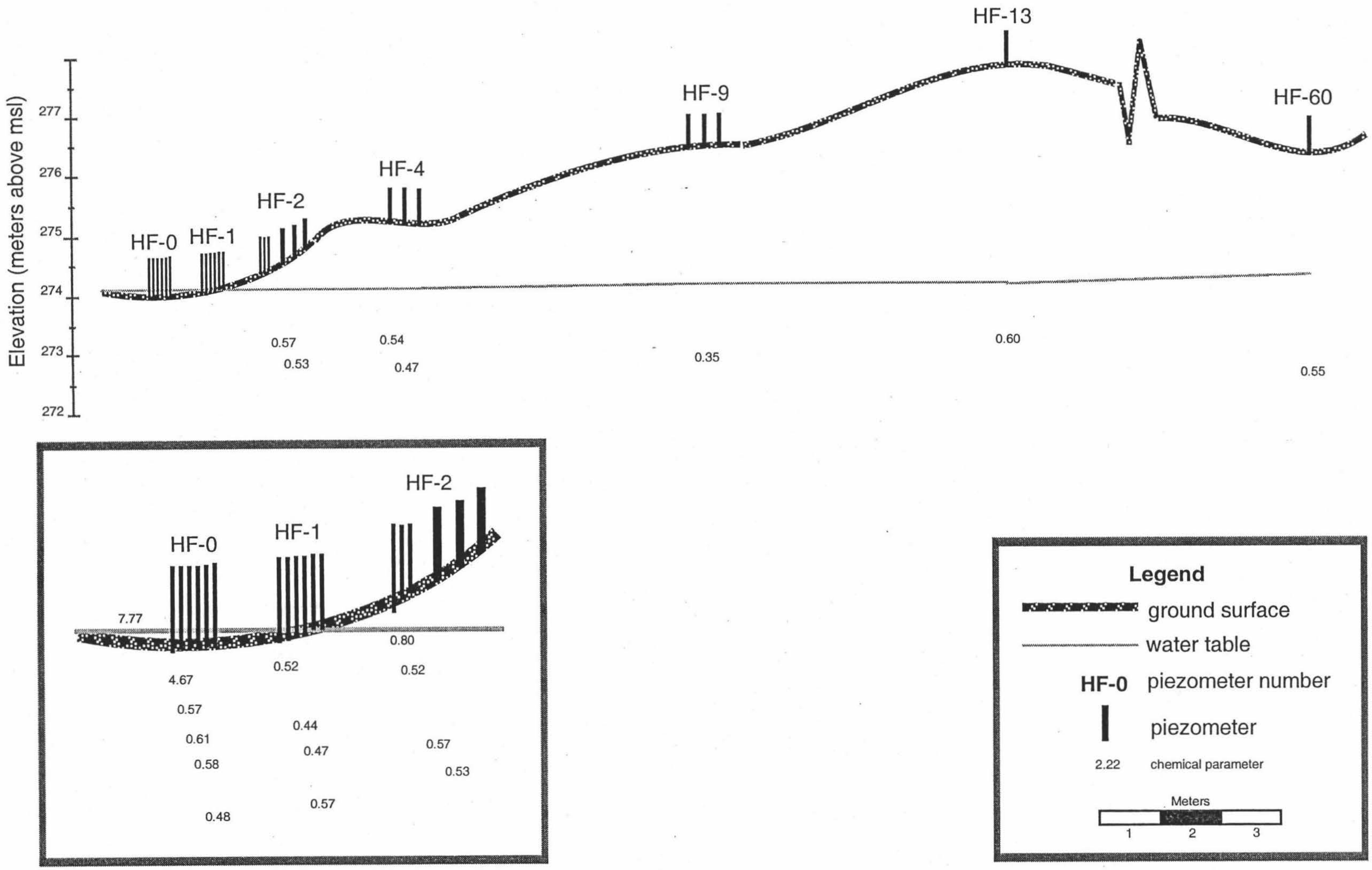


Figure 16. Dissolved oxygen concentrations in mg/L at the HF Site, 24 September 1995.

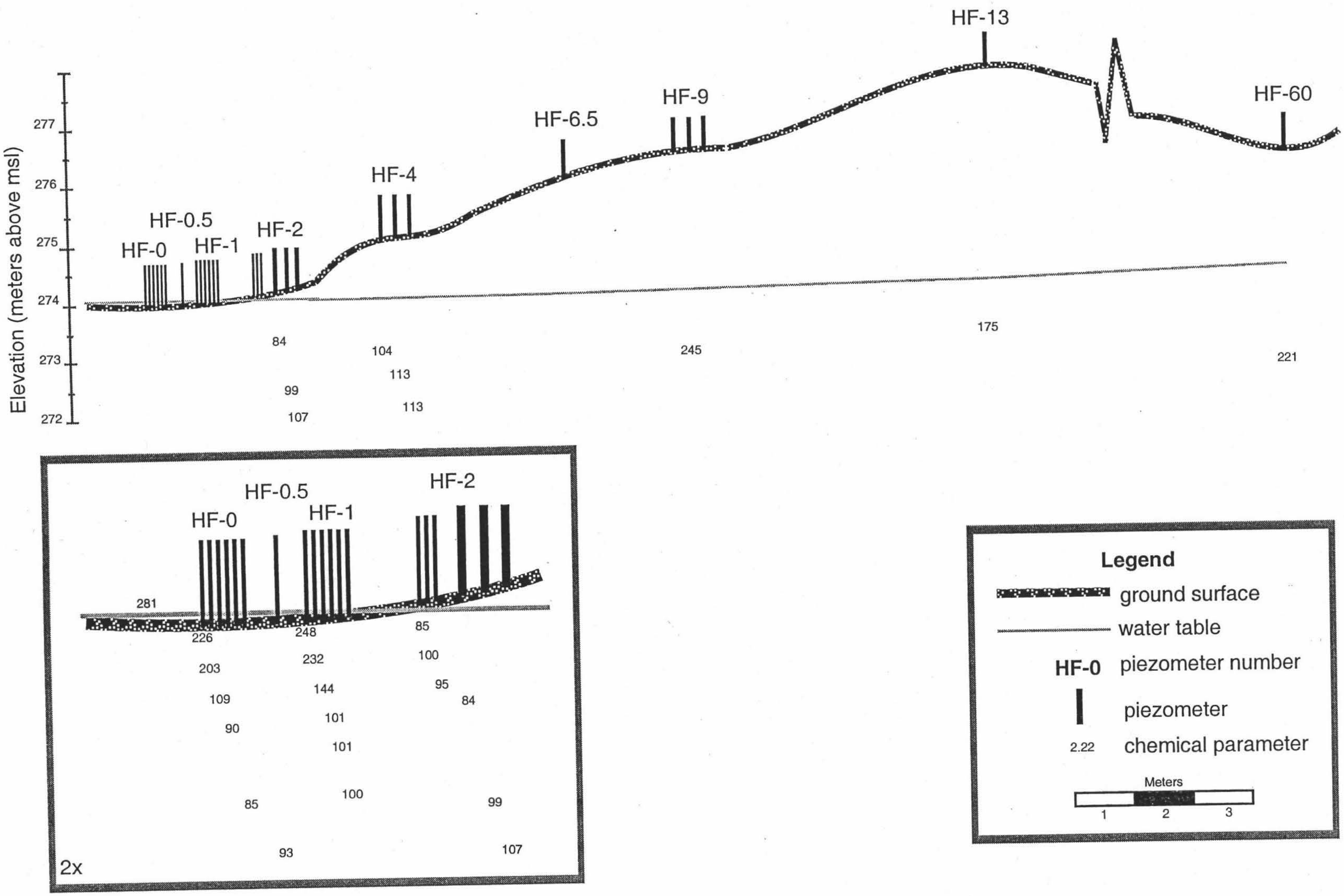


Figure 18. Average Eh in mV at the HF site for all sample collection dates (error = +/- 20 mV).

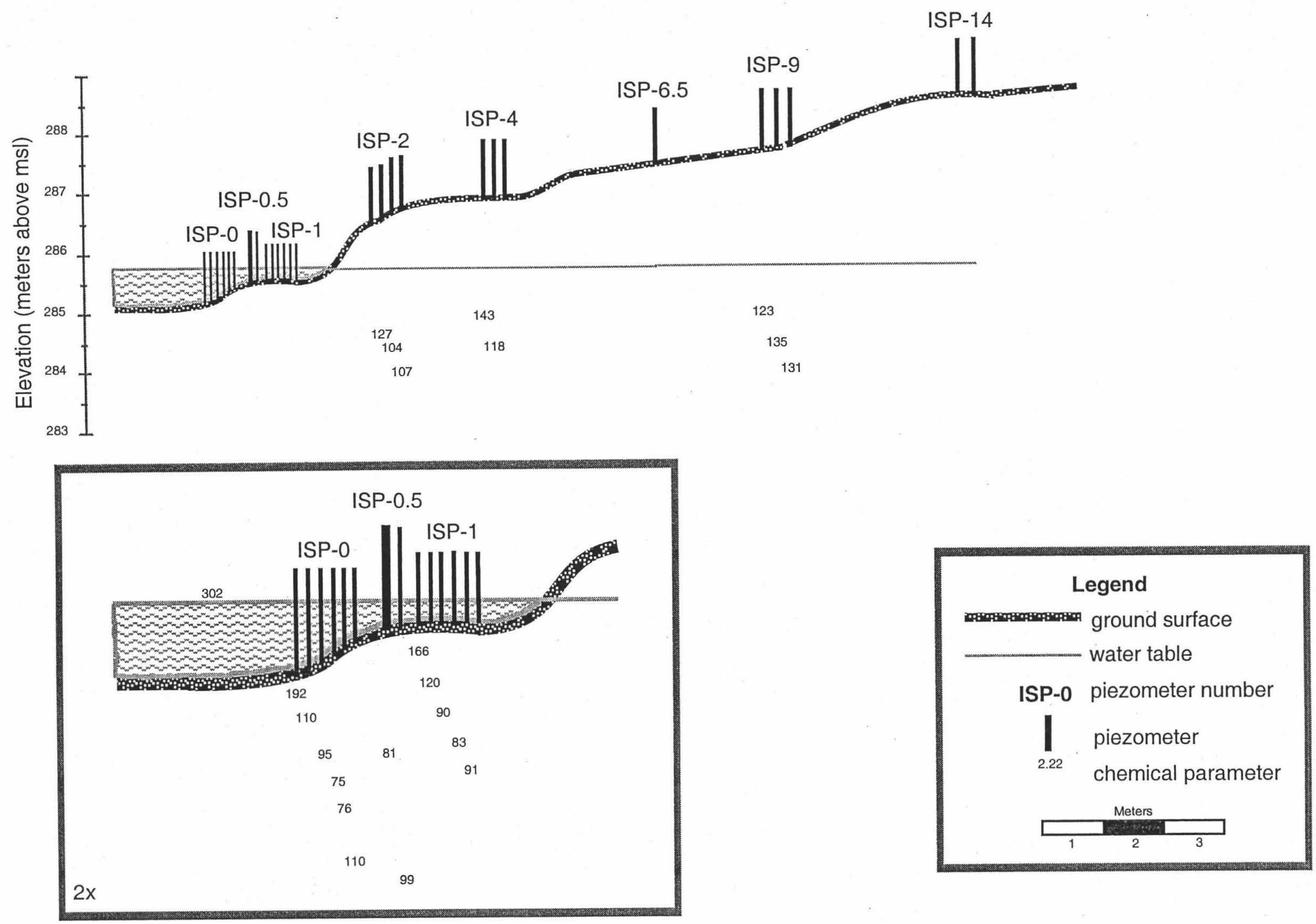


Figure 19. Average Eh in mV at the ISP site from all sample collection dates (error = +/- 20 mV).

EC increased 10 cm below the streambed, then decreased laterally into the riparian zone and with depth (Figures 20 and 21). Graphs of EC data for a single date at both sites display a marked increase 10 cm below the streambed that gradually decreases at a depth of 50 to 150 cm (Figures 22a and b). This trend was consistent at both sites for all sampling events. The depth of the EC gradient and lateral extent into the riparian zone varied throughout the summer. Conductivities at the HF site were 300 to 800 μS/cm higher than at ISP, with a peak EC of 1300 μS/cm on August 28, 1995. The highest conductivity readings at HF occurred near the stream–riparian interface, 10 to 35 cm below the streambed. Elevated concentrations of Ca^{2+}, Mg^{2+}, and Na^{+} were present at 35 cm beneath the channel near the stream-riparian interface and, with the exception of Ca^{2+}, were consistently higher at the HF site than at the ISP site (Figure 23). This trend was present in other hyporheic wells for all sampling events where more complete ion analyses were conducted (Table 13 in Appendix E).

The distribution of ammonium in the hyporheic zone was similar to EC patterns, but at greater depth. Between 55 and 100 cm below the streambed, ammonium levels increased in nests HF-0 through HF-2. From -110 to -150 cm, concentrations decreased to levels similar to those found in deeper groundwater, represented by Well Nest HF-4 (Figure 24). Ammonium concentrations were consistently elevated 10 to 35 cm below the channel in Well Nest HF-2, reaching levels in excess of 16 mg/L (Table 12 in Appendix E). High concentrations of ammonium were also present in Well Nest HF-1 during the 1995 sampling season. Ammonium was present in very few samples from ISP.

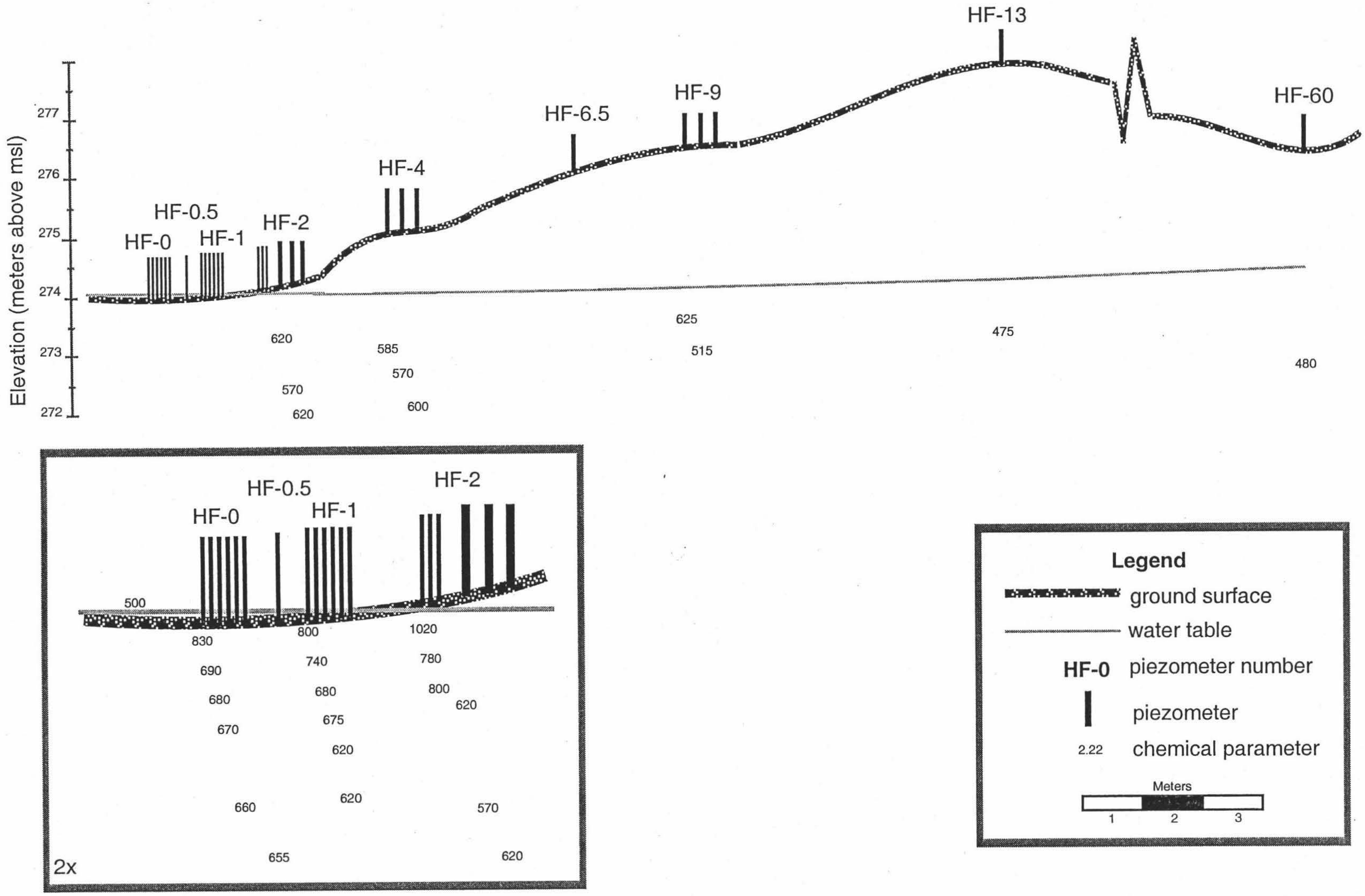


Figure 20. Electrical conductivities in μS/cm at the HF site, 15 September 1996.

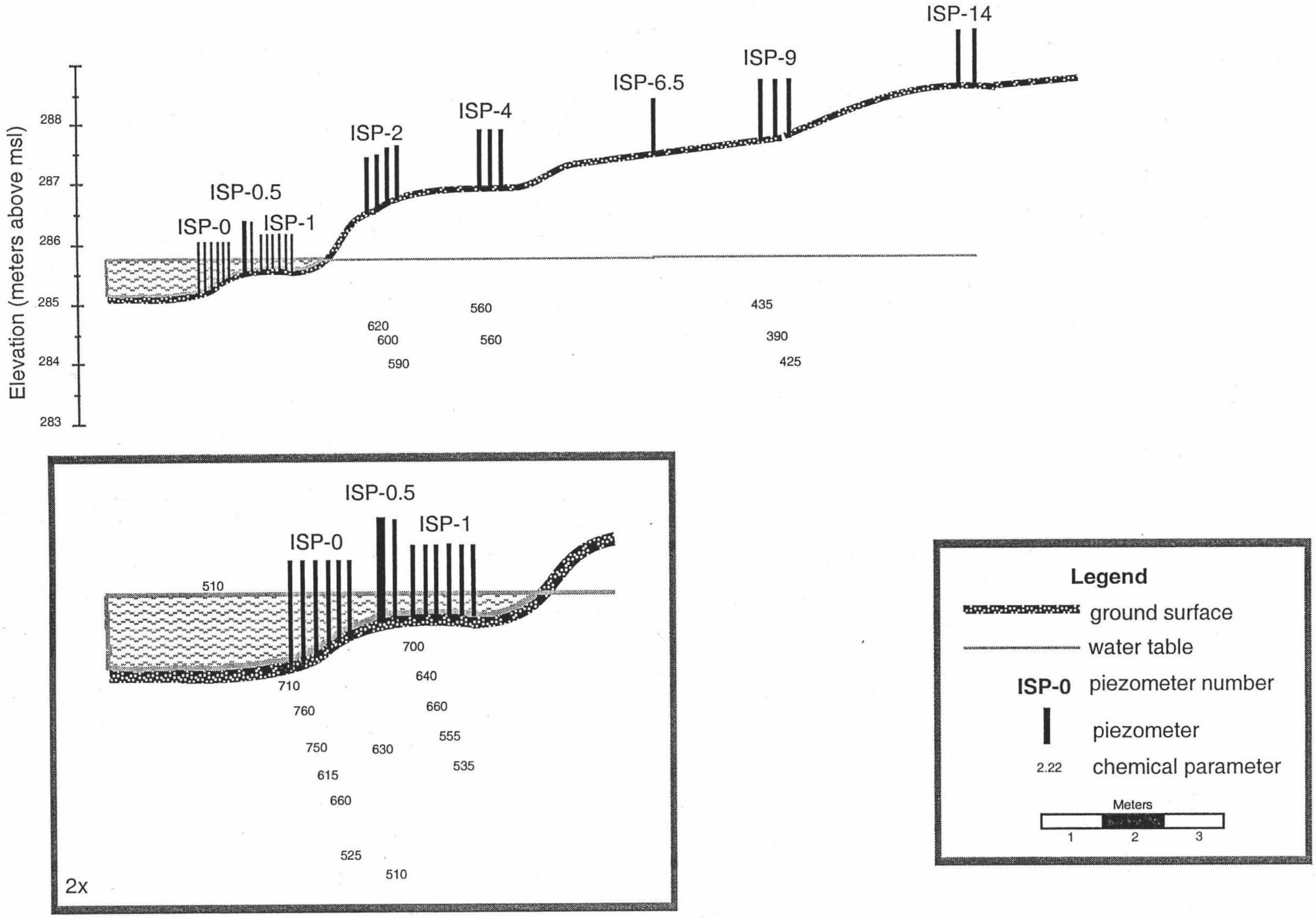
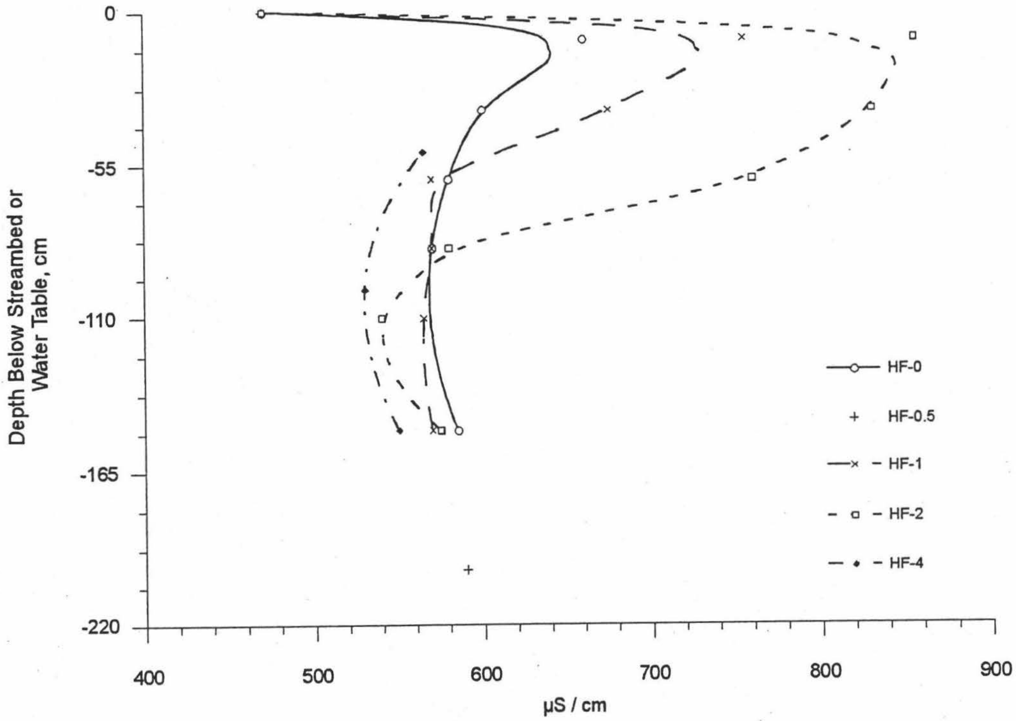


Figure 21. Electrical conductivities in μS/cm at the ISP site, 14 September 1996.

a) Hinkle Farm 8/2/96



b) Icelandic State Park 8/1/96

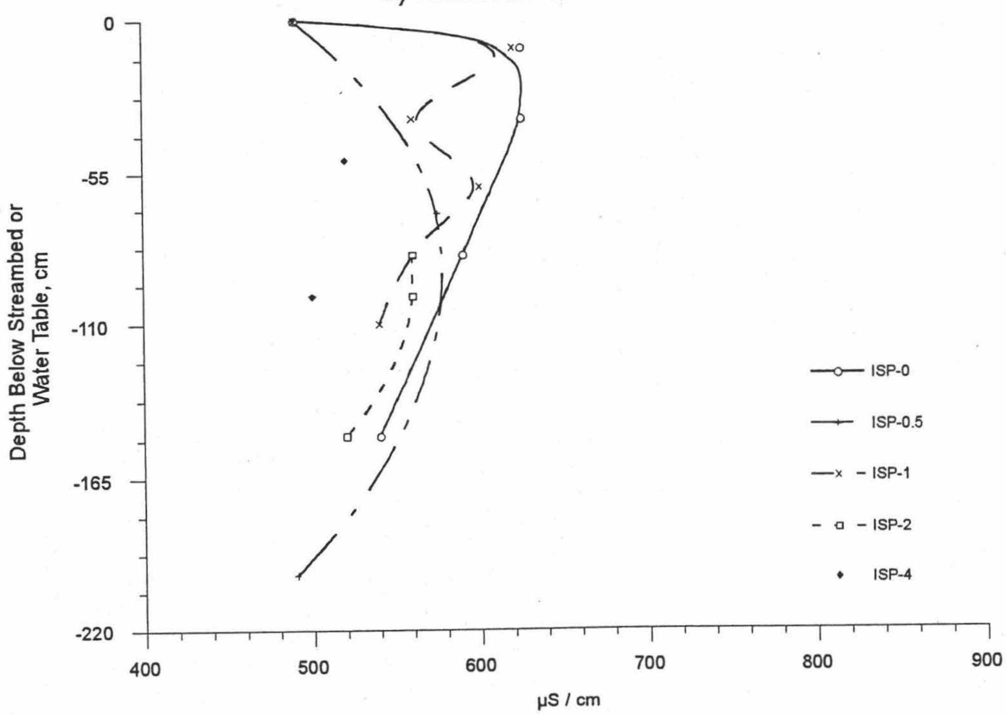


Figure 22 a and b. Electrical conductivity beneath the channel at both sites.

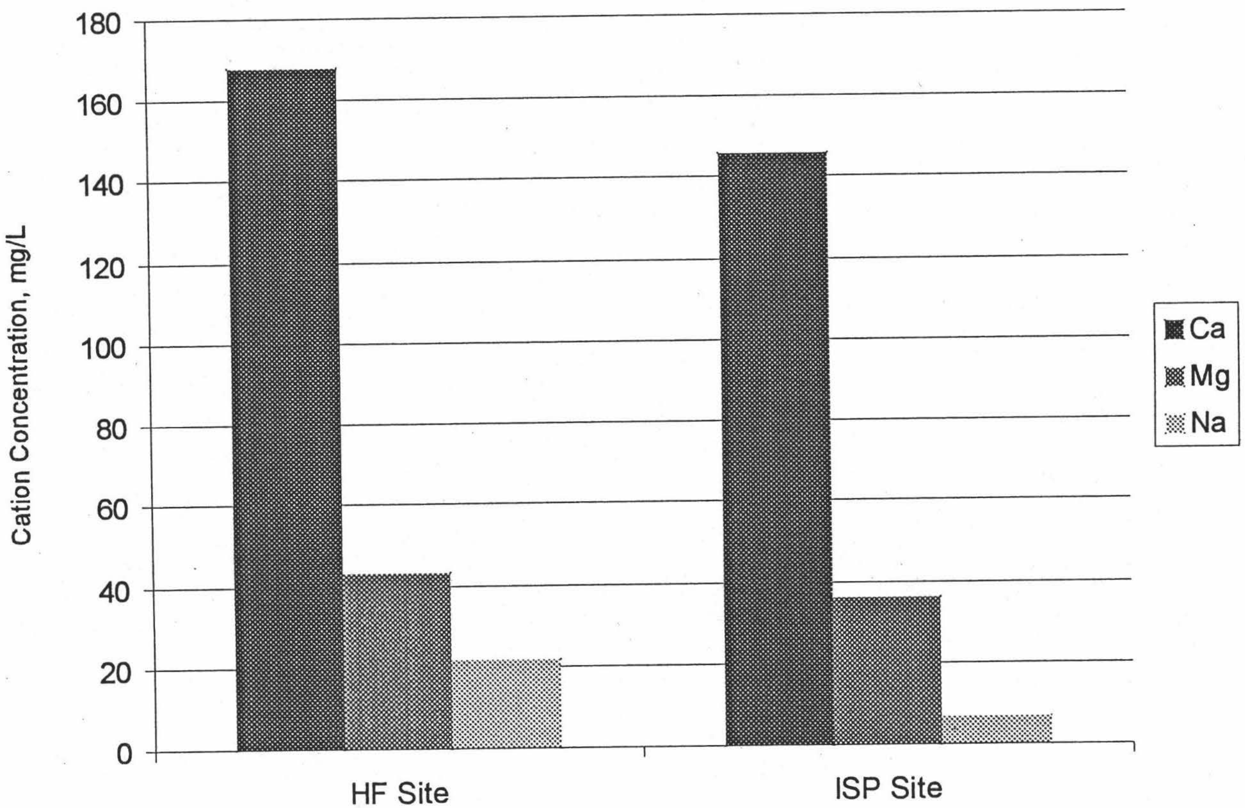


Figure 22. Select cation concentrations from both sites on 9/15/00, (data from NDDH).

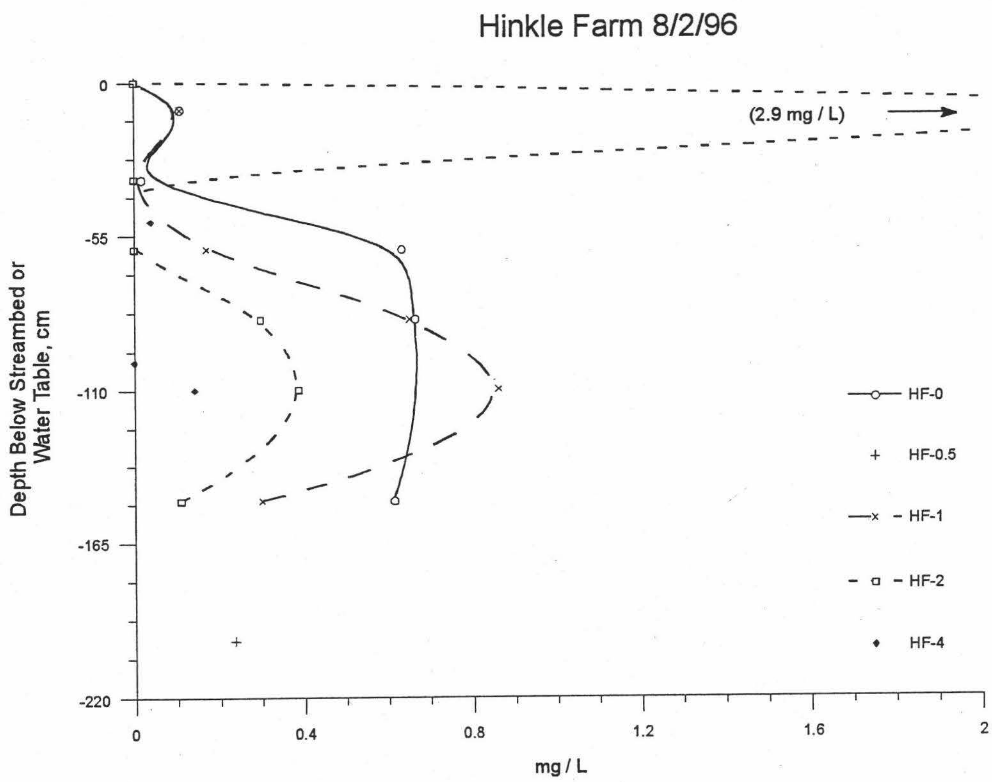


Figure 24. Ammonium concentrations beneath the channel at the Hinkle Farm Site.

Seasonal variations were observed in ammonium concentrations at both sites. When ammonium levels from Well Nests HF-1 and ISP-1 were plotted against time, results show concentrations decreasing from spring to summer and increasing from summer to fall (Figures 25a and b). It is also apparent in these plots that overall ammonium levels were higher at HF than at ISP.

Nitrate levels were also elevated at HF in comparison to ISP. Nitrate levels decreased at HF in the fall of 1995, but did not change more than 0.1 mg/L-N during the 1996 season. In contrast, nitrate at ISP was generally present in low levels or absent (Table 12 in Appendix E).

Meiofauna

Invertebrates were found at both sites on the two collection dates (Tables 6 and 7). Distribution of the meiofauna varied both spatially and temporally, with some patterns of distribution evident at both sites. Generally, the number of individuals at the HF site decreased from the channel center (0.5 m) to the stream bank (1.5 m) and below 50 cm under the channel. The diversity and total number of individuals collected increased from the summer to fall at the 0.5 m location, but decreased at the 1.5 meter location. Organisms were found at the 100-cm depth in the fall, but not in spring.

At ISP, the diversity and number of invertebrates collected was greater at the 1.5-m station for both sample dates. Fauna diversity increased by three groups from summer to fall at the 1.5-m location. On both dates, the greatest concentration of fauna was at the 50-cm depth, 1.5-m from the center of the channel. The number of individuals did not change significantly between sample collection dates, but were distributed deeper (100 cm) in the sediments.

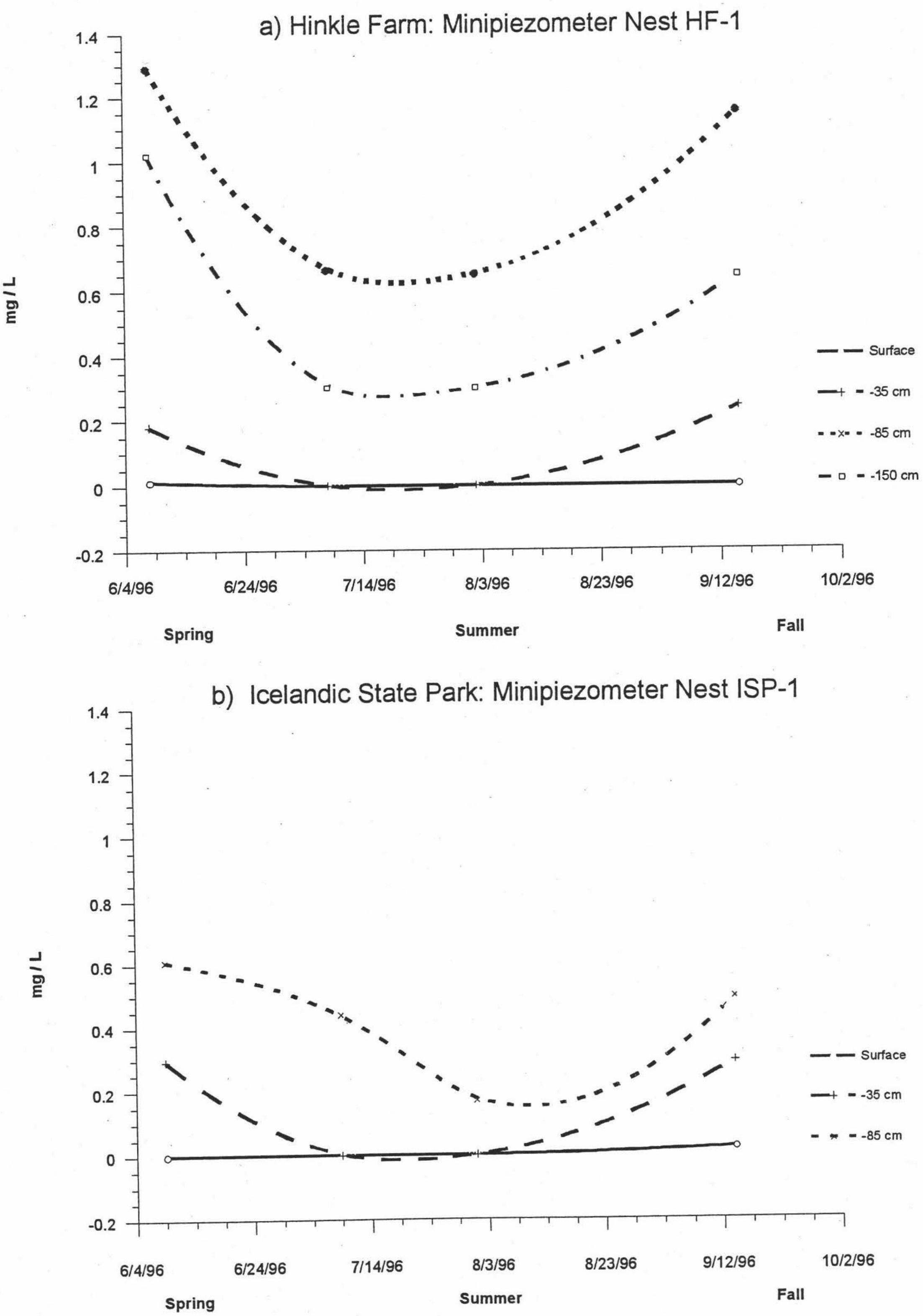


Figure 25 a and b. Ammonium concentration in minipiezometer nests 1 meter from the stream margin plotted over time.

Table 6. Results of Meiofauna Collections at the HF Site

Depth Below Streambed	0.5-m Collection Location[1]		1.5-m Collection Location[1]	
	Number of Individuals	Fauna Group Name	Number of Individuals	Fauna Group Name
		July 30, 1996, Sample		
25 cm	1	Copepoda	None	
50 cm	7	Nematoda	1	Nematoda
			1	Turbellaria
100 cm	None		none	
Total	8	2 Groups	2	2 Groups
		October 12, 1996, Sample		
25 cm	7	Diptera	1	Diptera
	3	Nematoda		
	1	Trichoptera		
	2	Copepoda (1 as nauplii)		
50 cm	5	Nematoda		
	1	Hydracarina		
	1	Diptera		
100 cm	1	Nematoda		
	1	Rotifera		
Total	22	6 Groups	1	1 Group

[1]Distance is measured from piezometer Well Nest HF-0 toward the stream bank.

Table 7. Results of Neiofauna Collections at ISP Site

Depth Below Streambed	0.5-m Collection Location[1] Number of Individuals	0.5-m Collection Location[1] Fauna Group Name	1.5-m Collection Location[1] Number of Individuals	1.5-m Collection Location[1] Fauna Group Name
		July 29, 1996, Sample		
25 cm	2	Turbellaria		
		Copepoda (as nauplii)	6	Turbellaria
50 cm	1	Copepoda (as nauplii)	32	Turbellaria
	3	Nematoda	14	Nematoda
	1	Diptera	5	Oligochaeta
			1	Copepoda (as nauplii)
100 cm	None			
Total	8	3 Groups	55	4 Groups
		October 13, 1996, Sample		
25 cm	2	Diptera		
	1	Cladocera	4	Rotifera
			4	Diptera
			4	Copepoda (as nauplii)
			1	Turbellaria
			1	Ostracoda
50 cm	None		28	Turballaria
			3	Nematoda
			2	Rotifera
100 cm	5	Rotifera	1	Cladocera
	5	Copepoda (as nauplii)		
	1	Cladocera		
Total	11	3 Groups	49	

[1]Distance is measured from piezometer Well Nest ISP-0 toward the stream bank

The diversity and total number of organisms collected were greater at the ISP site than the HF site. Four groups, Cladocera, Oligochaeta, Turbellaria, and Ostracoda, were found only at ISP. Turbellaria was the most common group at ISP, with over 67 specimens collected. Copepoda, Nematoda, Diptera, and Rotifera were common to both sites. Trichoptera and Hydracarina were unique to HF. Nematoda was the dominant group collected at HF.

Most of meiofauna collected were identified only to phylum, class, order, or other broad grouping because of the expertise and time required for further classification. However, several groups of specimens were classified to lower taxonomic levels. The results of this work help document the various invertebrate distributions in the Northern Great Plains.

The adult copepoda found in the study were identified as *Eucyclops prionophorus* (Kiefer), belonging to the order Cyclopoida, family Cyclopidae. *Eucyclops sp.* is a common freshwater copepod distributed throughout North America (Reid, 1997). Many of the copepoda collected were in the nauplii stage, especially in the fall. At this life stage, identification beyond phylum, and possibly order, requires considerable expertise. The cladocera collected were identified as *Bosmina longirostris* (O. F. Mueller) of the order Anomopoda, family Bosminidae. This "water flea" is common to freshwaters throughout the world. It should be noted that Cladocera is no longer a taxonomic term, but is still used to refer to this group of invertebrates (Dodson and Frey, 1991). Several of the Rotifera that were in good condition for microscopic inspection were classified as *Polyarthra sp.*, belonging to the order Ploimida, family Synchaetidae. This family possesses unique feather-shaped appendages or paddles (Wallace and Snell, 1991). The majority of the diptera found at both sites are thought to belong to the family Chironomidae, the largest and most diverse (161 genera) of the flies and midges, if not of all aquatic insects (Hilsenhoff, 1991).

CHAPTER V

DISCUSSION

Physical Characterization

Interaction between surface water and groundwater occurs beneath and adjacent to the channel in the hyporheic zone along the entire course of a stream. The morphology and channel characteristics of the stream, convective forces of surface water flow, and groundwater gradients control the interaction (Harvey and Bencala, 1993; Morrice et al., 1997). Spatial and temporal variations of these factors affect the structure and function of the hyporheic zone. Therefore, the biological reactions (those that are catalyzed by or occur only because of biological activity) and chemical reactions occurring in the hyporheic zone will differ between seasons, watersheds, and reaches within a watershed.

Rapid sedimentation and erosion observed on the Tongue River between 1995 and 1996 (Figures 9 and 10), may have influenced chemical conditions of the hyporheic zone by changing the depth of surface water penetration into the channel sediments and adding or removing POM and bacteria. Rapid burial and subsequent decay of POM could produce a reduced environment that would be conducive to the production and storage of nutrients such as ammonium. It is also possible that the scouring of sediment would expose previously reduced zones to oxygen-rich waters and perhaps release nutrients into the water column in both dissolved and suspended forms. Scouring would also displace populations of interstitial invertebrates, creating unfavorable conditions for long-term colonization. Changes in channel morphology affect the depth of water in the channel and the height of the wetted perimeter up the bank. These changes can influence populations of periphyton living on the stream bottom and vegetation growing along the stream margin.

Horizontal and vertical gradients control the rates and points of surface water–groundwater exchange. Gradients are influenced by stream morphology and sediment hydraulic conductivity. Previous studies have recorded vertical hydraulic gradients as high as 60 cm at the heads of riffles, transitions from riffle to pool, near in-stream structures (beaver dams), and from groundwater seeps (White et al., 1987; White, 1990; Harvey and Bencala, 1993; Jackman et al., 1997). Consistent vertical gradients were not apparent at either site on the Tongue River (Appendix D). The lack of variation between head elevations in nested minipiezometers may be due to the low stream and groundwater gradients.

Variations occurred in head elevations between sampling dates, suggesting that even the deepest in-stream piezometers rapidly responded to stream discharge fluctuations. These rapid fluctuations in stream discharge and corresponding piezometeric head beneath the stream channel may have had an effect on the structure and function of the hyporheic zone. Lateral gradients between the riparian upland and the channel were generally less than 0.02. Greater stability in the water table at the ISP site may have been influenced by the presence of riparian vegetation. The vegetation would increase evapotransporation, possibly decreasing the amount of infiltrated rainwater that reached the water table. In the spring, gradients between the stream and upland piezometers were steeper than during the other seasons, indicating some lateral contribution of groundwater to the channel. It is likely that the most important gradient in terms of stream water–groundwater interaction may have been longitudinal in the downstream direction.

Heterogeneity of fluvial channel sediments can influence the stream water–groundwater interaction. The interbedded silt, sand, and gravel of the Tongue River affect flow paths and the residence time of water in the sediments, thus creating variability in estimated hydraulic conductivity measurements. The subsequent variability has implications for chemical concentrations and reactions in the sediments.

DO concentrations beneath the streambed could be useful in identifying flux of surface water into the sediments. For example, on September 24, 1995, the DO concentration in piezometer Well Nest HF-0, 35 cm below the streambed, was 4.67 mg/L (Figure 17). This DO concentration was higher than those of adjacent piezometers indicating that a greater percentage of oxygen-rich surface water was exchanged at this location. One month later, the water level in the river had risen, and the point of greatest surface water exchange was now below piezometer Well Nest HF-1. These rapid variations in DO concentration were also observed at ISP (Table I2 in Appendix E), indicating that surface water exchange with the sediments may be in a constant state of flux.

In contrast, longer flow paths and zones of lower hydraulic conductivity increase the residence time of water within the sediments. Longer residence time without the influx of oxygenated surface water, but with bacteria and organic material, encourages the progression of reduction reactions (Drever 1988; Korom, 1992). For example, 10 cm below the streambed in Well Nest HF-2, the hydraulic conductivity was 0.29 m/day (Figure 11). The Eh (Figure 18) at that depth was consistently the lowest on average for this site. At a pH of 7, denitrification is thought to occur at an Eh of 500–700 mV; ammonia is the stable nitrogen species at an Eh below 300 mV (Drever, 1988). For these reasons, reduced zones may support greater metabolism or storage of nutrients. Shorter flow paths and zones of high hydraulic conductivity may not allow for complete metabolism of nitrogen, but would be prime habitat for interstitial organisms because of the rapid influx of oxygen and dissolved solutes (Strayer, 1994).

Hyporheic Boundaries

Physicochemical Gradients

Gradients by which hyporheic boundaries could be identified were not evident in most of the chemical parameters measured in this study. Temperature has been used in previous studies as an indicator of surface water–groundwater exchange (White et al., 1987). However, consistent temperature gradients were not observed at either site in this study, possibly as a result of warming during sample collection. Temperature may be useful for mapping general areas of stream water downwelling or groundwater upwelling, but not for identifying hyporheic boundaries. DO decreased from surface to subsurface waters, but a steep gradient or discontinuity could not be identified between groundwater and possible hyporheic water. Similar conclusions can be drawn from Eh measurements.

Nitrate showed no distribution pattern or gradient, and was absent from many of the collected samples. It is likely that the presence of cattle in the riparian upland was responsible for the higher nitrate concentrations observed in the surface and hyporheic water at HF. When cattle graze in the riparian zone, they selectively eat the choice vegetation, leaving only sparsely distributed nonpalatable plants, such as at HF (Appendix B). Well-vegetated riparian zones act as filters, removing nutrients from surface runoff and shallow groundwater (Schlosser and Karr, 1981; Peterjohn and Correll, 1984; Pinay and Decamps, 1988). Nutrients are taken up by the plants and utilized before they reach the stream. The absence of stream channel vegetation from HF, which would also use nitrogen compounds, may also have contributed to increased nitrate in surface water.

The presence of nitrate in groundwater at HF was likely influenced by cattle manure and lack of riparian vegetation, but it is possible that nitrate was derived from oxidized ammonium. During sampling, oxygen could have been introduced to water through the filtration and bottling process before preservative was added. This may explain the presence of nitrate in the groundwater when DO levels were below 1 mg/L.

Seasonal variations in nitrate concentrations could be attributed to natural processes. Nitrate levels in surface waters tend to be elevated in the spring because of spring meltwater and rains carrying nitrogen from the uplands. Levels decrease in the summer when plants, algae, and bacteria are actively using the nitrogen. Nitrate levels increase in the fall when plants and algae die or go dormant and allochthanous material is contributed to the stream. The lack of nitrate in piezometers beneath the channel and groundwater wells may be due to losses through denitrification or conversion to ammonium. During spring floods, high water levels in the stream reverse the gradient, causing nitrogen-rich surface water to move deeper into the sediments. Throughout the summer, nitrate is used by bacteria in the sediments and converted to nitrogen gas through denitrification or to ammonium through nitrate reduction. These nitrate patterns have potential implications for understanding nutrient cycling, but are not indicative of surface water–groundwater boundaries.

Of the parameters measured in this study, only EC and ammonium display any significant gradients that could be interpreted as discontinuities or boundaries. These discontinuities are not true divisions, but rather represent sharp gradients between zones with different physical and chemical properties. Because water in the hyporheic zone is thought to be a variable mixture of the surface and groundwater interacting with sediments beneath the channel, physical or chemical discontinuities may be indicative of the hyporheic zone.

The mixing of water with differing physical and chemical properties, as well as interaction with the sediments, would be expected to promote geochemical, biological, and reduction–oxidation reactions. Many of these reactions produce ions that are stable for some period of time in the relatively reduced subchannel water. For example, the reduction of iron oxides produces stable Fe^{2+} ions in solution. A more important process may be heterotrophic denitrification, through which a considerable amount of bicarbonate is produced in reactions such as $5C + 4NO_3^- + 2H_2O = 2N_2 + 4HCO_3^- + CO_2$. Because bicarbonate ions contribute to the EC of natural waters (McPherson, 1995), EC may serve as an approximate indicator of the zone where metabolic or reduction–oxidation reactions are occurring under the streambed.

The conspicuous gradient in EC beneath the HF site (Figure 22a) probably indicates surface water and groundwater mixing or reactions caused by the conditions in the sediments. At 100 cm below the channel, results from all the piezometer nests converge toward a narrow EC range similar to that of riparian groundwater. The magnitude of this change increases in nests of piezometers closer to the stream bank. This pattern may be caused by changes in the water level, which expose or inundate sediments at the stream margin, leading to extreme fluctuations in the redox state. Shifting redox conditions would produce periods of ion immobility, causing a buildup of solutes and/or precipitates (e.g., iron oxide staining of the sediments). Additional solute contributions at the stream bank–water interface may come from riparian runoff or shallow through-flow. Evaporation from the capillary effect at the water's edge also may contribute to higher EC in piezometers by concentrating salts (ions) in the water (Figure 23).

Similar gradients are present at ISP, but are not as pronounced. Differences in EC gradients between HF and ISP may be due to the presence of cattle, which will be discussed in a later section. Chemical gradients have also been documented in upwelling zones of the Rhone River in France (Dole-Olivier et al., 1994).

An indication of the extent of the chemically active zone beneath the channel was achieved by superimposing the gradients on a cross section of the site. Dashed lines in cross sections of the HF site indicate where the steepest gradients or discontinuities in EC occur (Figures 26 and 27). Above the discontinuity, where EC is elevated, is likely where surface water and groundwater are mixing, creating conditions ideal for more ions to be dissolved in the water. However, it is unclear what percentages of water in the mixing zone are surface water and groundwater. EC below the lines is similar to that of the groundwater 9 m into the adjacent riparian zone.

Seasonal variations were also observed in the position of the discontinuity. In spring (Figure 26), the EC discontinuity was deep, possibly owing to the

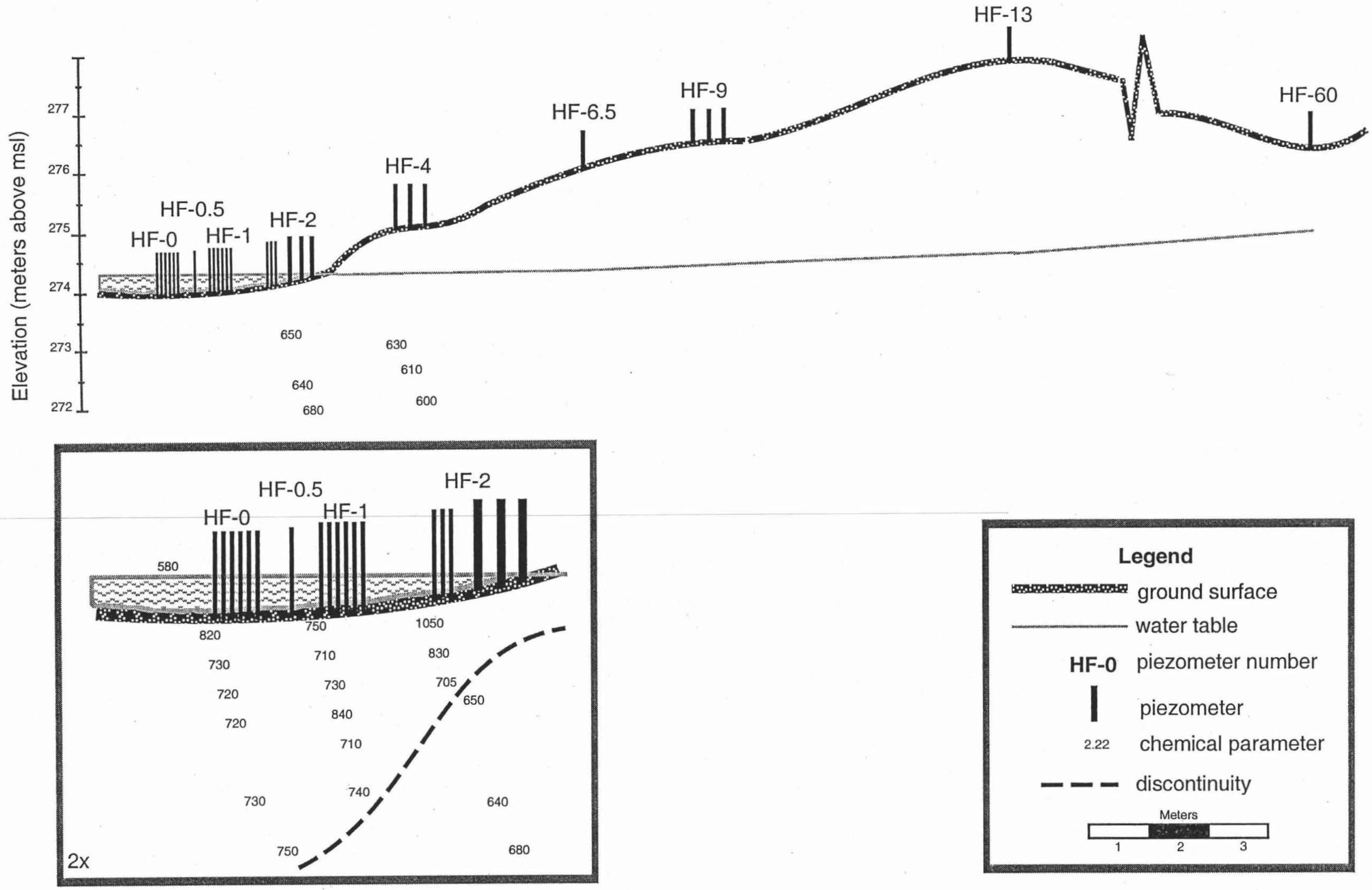


Figure 26. Cross section of the HF site showing a discontinuity in the EC gradient on 8 June 1996. Data are displayed in $\mu S/cm$.

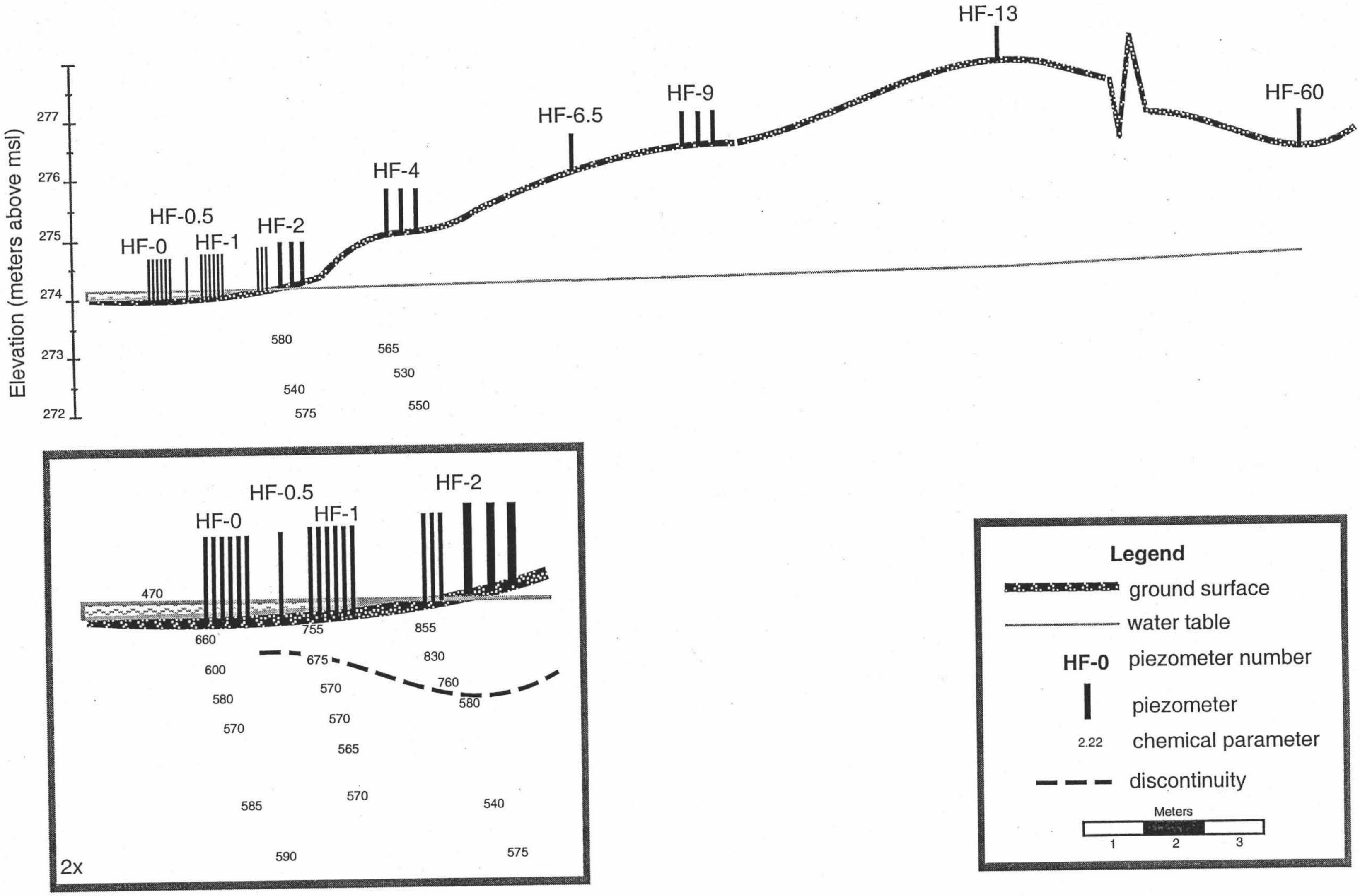


Figure 27. Cross section of the HF site showing the discontinuity in the EC gradient on 2 August 1996. Data are displayed in µS/cm.

downward hydraulic gradient created by high spring discharges. By summer, (Figure 27) the steep EC gradient was shallower in the streambed sediments and more pronounced.

Gradients similar to those for EC were observed for ammonium concentrations in the subsurface at HF, but occurred at a greater depth. Ammonium levels were elevated between 55 and 165 cm beneath the streambed for the in-stream and marginal minipiezometer nests (Figure 24). The unusually high concentration of ammonium recorded at -10 cm probably represents a microenvironment caused by burial of cattle manure. At depths where ammonium concentrations are elevated, the environment creates a reservoir for ammonium. Above -55 cm, it is likely that conditions do not create a stable environment for ammonium.

The distribution of ammonium concentrations at HF indicate that two different processes may be at work in the channel sediments. Where the ammonium concentrations are elevated, dissimilatory nitrate reduction to ammonium (DNRA), or ammonification, may be the favored process. DNRA can be a significant process in highly reduced conditions where organic carbon is not a limiting factor (Tiedje et al., 1982). At HF, organic matter is incorporated into the channel sediments and the conditions below -60 cm are very reduced, both of which favor DNRA. These conditions also exist in the microenvironment at -10 cm near the stream margin. Because little or no ammonium or nitrate nitrogen occurs in the shallow subsurface sediments, it is possible that the dominant process above -60 cm is heterotrophic denitrification. Above -60 cm, the conditions are not as reduced and samples generally had higher bicarbonate levels, which may be indicative of denitrification. Triska and Duff (1997) suggested that coupled nitrification and denitrification processes had the potential to oxidize ammonium from the deeper sediments and denitrify nitrate in the shallow subchannel sediments of the Shingobee River, Minnesota. Subchannel DO concentrations were higher in the Shingobee River study than those measured in the sediments beneath the Tongue River, which may limit DNRA in the latter system.

Discontinuities in the ammonium gradients delineate zones under the channel at HF (Figures 28 and 29). The location of these steep gradients varies seasonally. In the spring (Figure 28), the area of high ammonium is larger and extends farther into the sediments under the stream bank. By late summer (Figure 29), the zone of elevated ammonium is less extensive. It is possible that riparian vegetation affects the ammonium distribution by using nitrogen through the growing season. Subtle seasonal fluctuations in vertical and longitudinal hydraulic gradients may also be responsible for the variations. High spring discharges may push the discontinuity toward the sediments under the bank and increase the extent of the zone. In the late summer and fall, groundwater contributes to the channel, possibly causing the high-ammonium zone to shrink or shift farther under the center of the channel. The discontinuity lines most likely represent not only the boundary between DNRA and the nitrification–denitrification couple, but also indicate subtle changes in hydraulic gradient beneath and adjacent to the stream channel.

The significance of the EC and ammonium discontinuities is that they have nearly the same shape and approximate locations in channel sediments. Although this does not establish an exact lower boundary for the

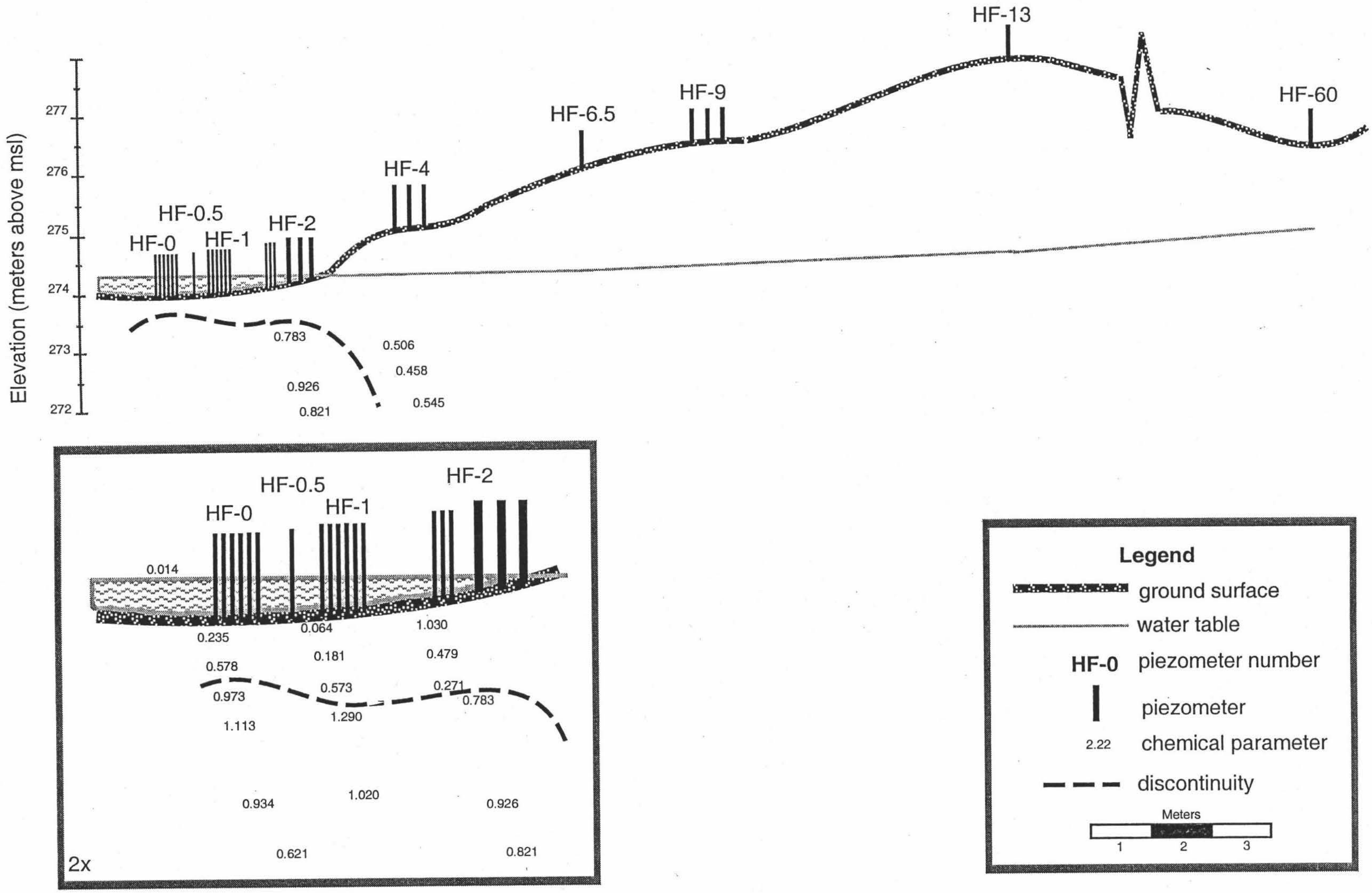


Figure 28. Cross section of the HF site showing the discontinuity in the ammonium gradient on 8 June 1996. Data are displayed in mg/L NH_3.

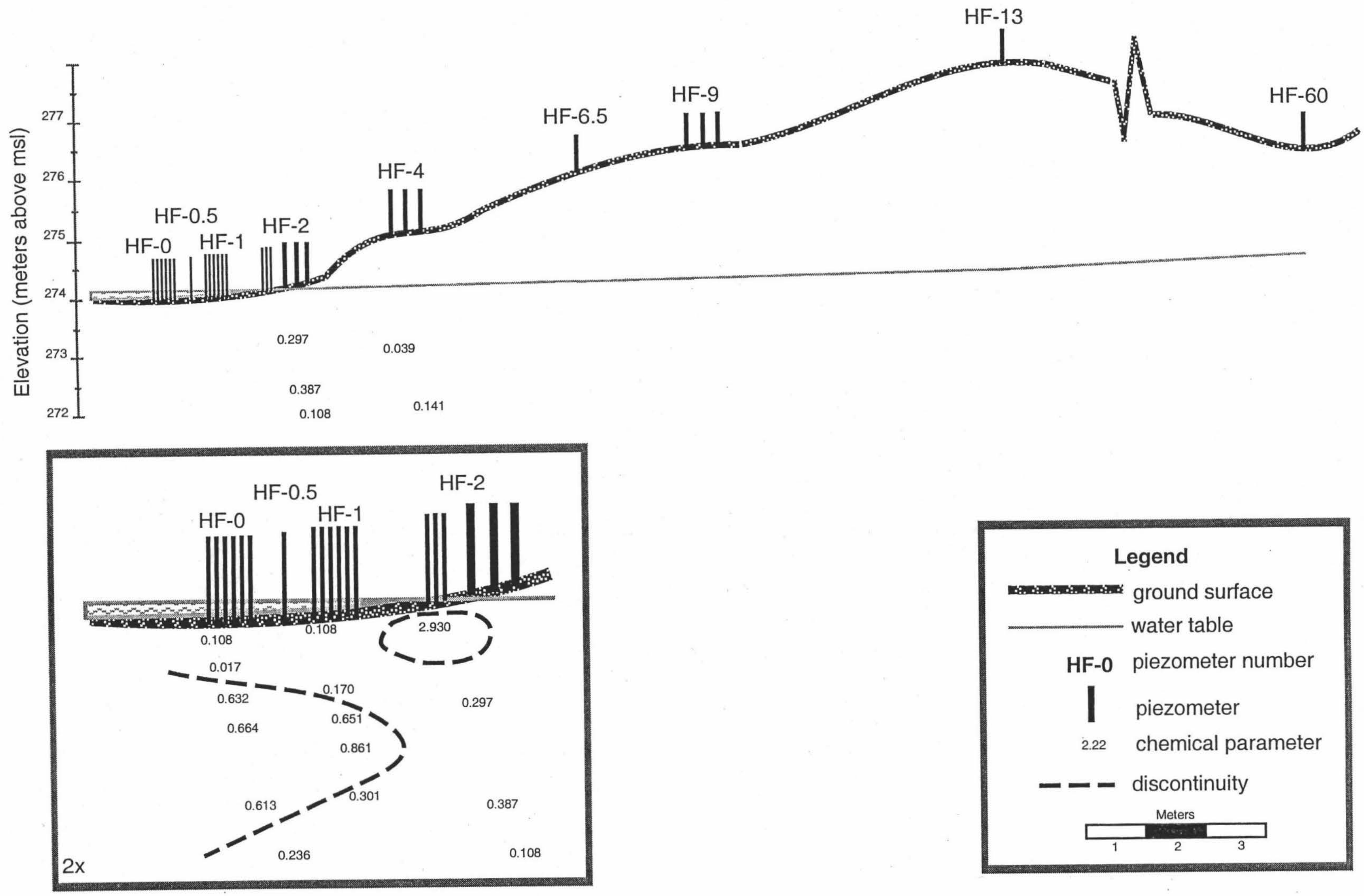


Figure 29. Cross section of the HF site showing the discontinuity in the ammonium gradient on 2 August 1996. Data are displayed in mg/L as NH_3.

hyporheic–groundwater interface, it does support the existence of gradients or boundaries that can be tracked spatially and temporally.

Gradients and zones beneath the stream channel may fluctuate as subsurface processes shift daily, seasonally, or annually. An example of this can be found in fluctuations of ammonium concentrations in subchannel sediments. At both HF and ISP, the ammonium concentrations measured in the subchannel waters decreased from spring to summer and then increased from summer to fall (Table 12 in Appendix E). Ammonium concentrations drop as much as 0.6 mg/L over a 4-month period. Overall concentrations are lower at the ISP site, but the same phenomenon occurs. Similar behavior was observed in the surface water ammonium from the Shingobee River, Minnesota (Figure 30) (Duff et al., 1997). Changes in biotic activity due to temperature fluctuations have been suggested as a cause of the seasonal cycling in ammonium concentrations (Duff et al., 1997).

In addition to temporal variations, regional differences exist in the physical and chemical parameters that may display discontinuities beneath the stream channel. Williams (1993) identified discontinuities in nitrate, oxygen, and organic matter in Duffin Creek, Ontario (Figure 31). In contrast, this study found discontinuities in EC and ammonium. The shape and extent of the discontinuties found in Duffin Creek were also different from those identified in the Tongue River. These types of regional differences in the chemistry within and beneath the stream are likely the result of differing physical attributes of the channel such as sediment size, composition and deposition rates, lateral and longitudinal gradients, and types and density of vegetation (including adjacent riparian

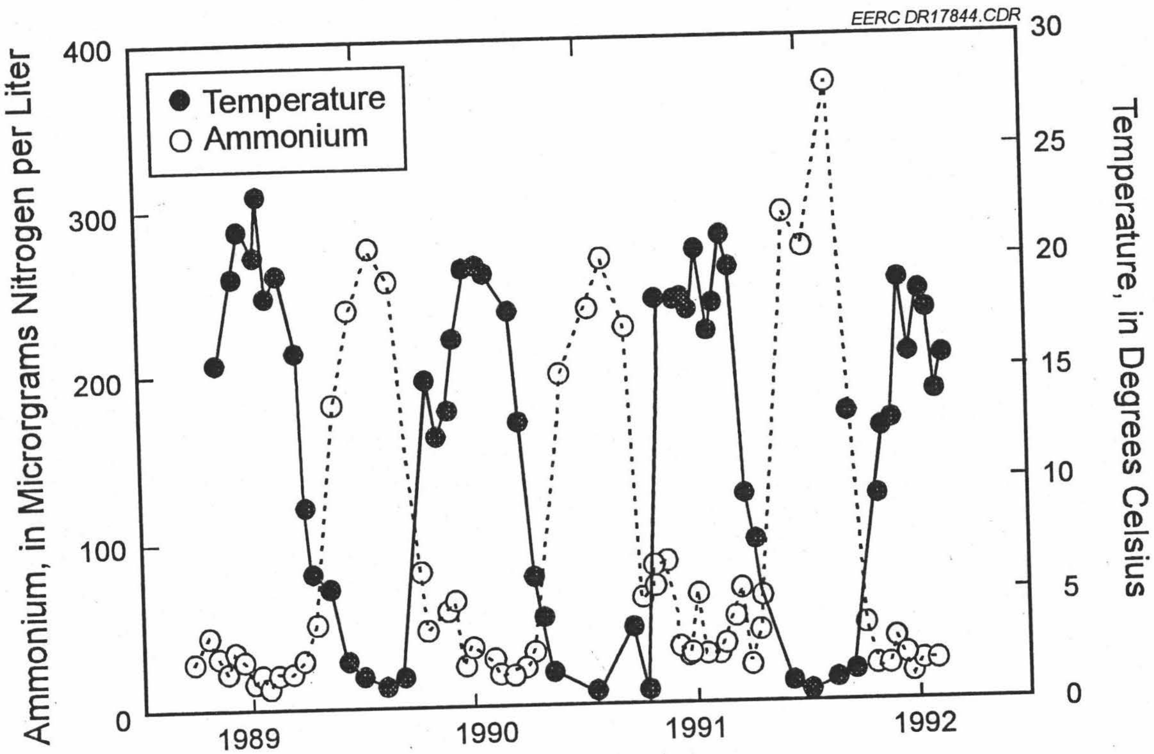


Figure 30. Temperature and ammonium concentrations in the upper Shingobee River, Minnesota, (from Duff et al., 1997).

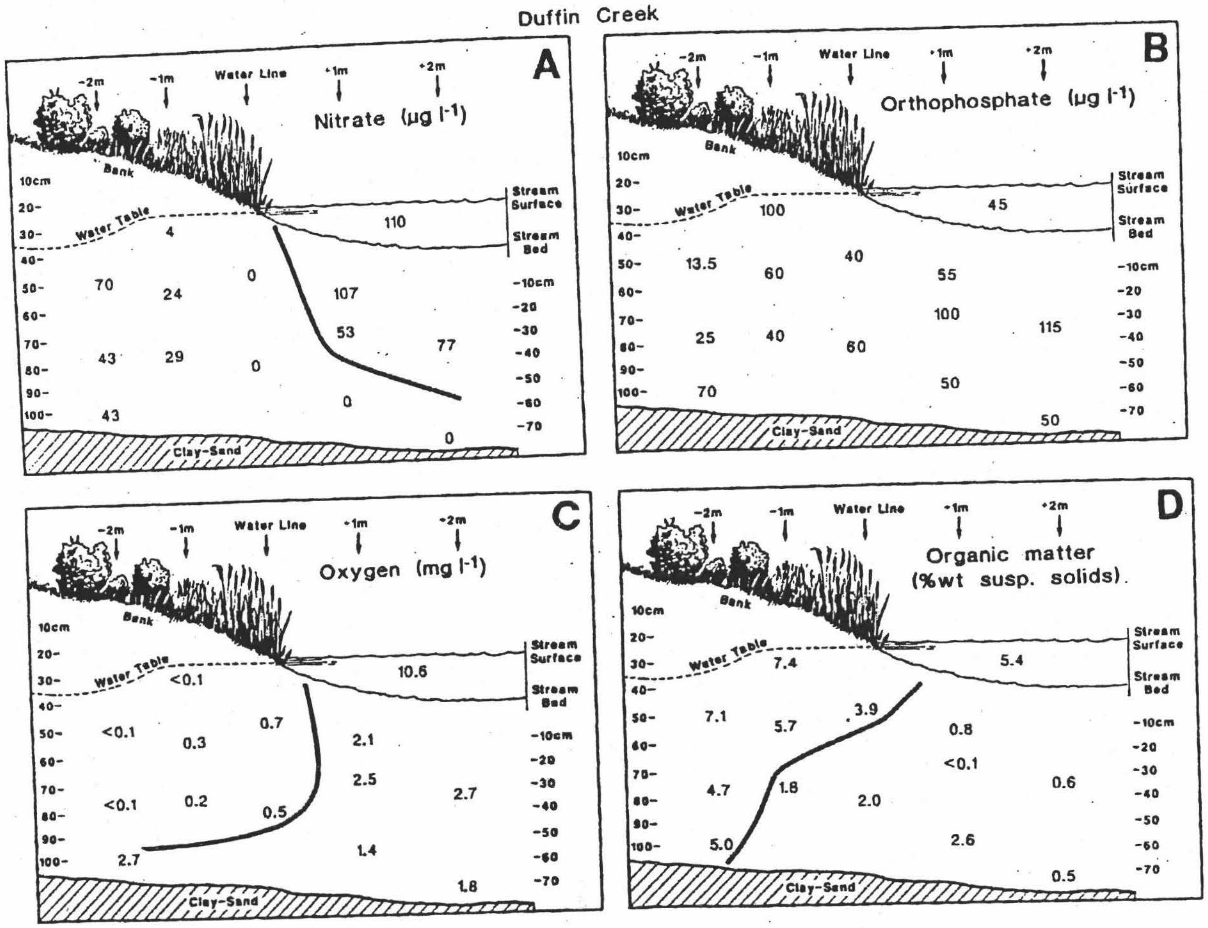


Figure 31. An example of the parameters measured by Williams (1993) showing areas of discontinuity (black line) (from Williams, 1993).

vegetation). This provides additional evidence that physical factors exert a significant influence on the structure and function of the hyporheic zone.

Fauna Gradients

Results of the meiofauna collections show distributions that may correspond to the chemical discontinuities identified in the sediments beneath and adjacent to the stream channel. However, it must be noted that meiofauna populations in the sediments are thought to be controlled by a variety of factors such as redox conditions, available interstitial space, and supply of organic matter (Strayer, 1994). This makes meiofauna presence or absence difficult to attribute to, or correlate with, one or two parameters. The density and diversity of these invertebrates may provide clues about general physical and chemical characteristics of water in the streambed sediments.

Few or no meiofauna 100 cm beneath the stream channel suggests that conditions are not optimal for organisms at that depth or present a barrier to migration. At HF, few meiofauna are found below 50 cm from any depth at the 1.5-m sampling point. Below 55 cm in piezometer Well Nests HF-0 and HF-1, and 10 cm below the streambed in Well Nest HF-2, ammonium is elevated above levels in the stream water and riparian groundwater (Figure 24). It is possible that the high levels of ammonium or simply the ambient reduced conditions in these zones are inhospitable to most meiofauna species. Many meiofauna species require DO levels above those found in the sediments beneath the Tongue River. In contrast, the near absence of ammonium in the sediments at ISP may account for the greater numbers and diversity of meiofauna populations at all depths beneath the channel.

When compared to the conditions in the bed sediments and adjacent riparian influences, meiofauna population density and diversity may reflect the functioning condition or health of the stream reach. As in the example above, higher levels of ammonium at the HF site may be the cause of the low density of invertebrates in certain subchannel zones. Cattle grazing in the riparian zone, and their effects on riparian vegetation and additional contribution of nitrogen to the stream, may affect not only nutrient cycling in the stream, but the distribution of benthic fauna. At ISP, cattle are absent from the vegetated riparian zone, ammonium levels are lower, and meiofauna populations are more diverse and numerous, all indicators of a healthy stream reach. Caution should be taken in using meiofauna populations as a measure of stream health because more factors (e.g., sediment size) affect population differences between sites than just the overall health of the stream reach.

Influence of Cattle in the Riparian Zone

Degradation of water quality from cattle grazing was more evident in the chemistry of the hyporheic zone than in the surface channel water or deep riparian groundwater. Cation concentrations and EC were considerably elevated at the grazed site (HF) within the hyporheic zone. Where vegetation was absent, the sediments may have been exposed to increased evaporation and accumulation of leached salts. Direct input of cattle wastes to the channel may also have contributed some salts. These factors, combined with decreased hyporheic flushing due to high rates of sedimentation, could account for the elevated EC and cation concentrations. Further investigation would be necessary to directly link increased leaching of salts from the soils due to cattle waste and the lack of riparian vegetation.

Elevated ammonium concentrations in the hyporheic zone at HF could be directly attributed to the presence of cattle, lack of riparian vegetation, and increased sedimentation, which may exacerbate the problem. Cattle linger at the stream margin and excrete waste when drinking or crossing the stream. Further waste and nutrients are contributed by runoff from the nearly bare slopes of the riparian zone. Trampling and high rates of sediment deposition cause rapid burial and covering of the nitrogenous waste. The highly reduced conditions in the hyporheic zone, 10 to 35 cm below the streambed, appear to be favorable for the retention of the nitrogen in the waste as ammonium.

If, in fact, a significant portion of nitrogen from cattle waste is retained within the porewater of the streambed as ammonium, then impacts to water quality from cattle may not be detected using current sampling and analysis regimes for measuring stream health. Most stream sampling protocols recommend sampling and analyzing surface water for nitrate. The difference in stream water nitrate levels between the ISP and HF sites on 2 August 1996 is 0.02 mg/L N. The relatively small difference in nitrate levels between the sites would suggest that cattle are not greatly impacting water quality at the HF site. However, peak ammonium concentrations from beneath the stream channel on 2 August 1996 display an order of magnitude difference between sites (Table 12 in Appendix E). This result suggests that cattle may be having a greater impact on subchannel water at HF than on surface water or riparian groundwater. The implication of this result is that sampling regimes designed to evaluate stream health must consider all sources and reservoirs of pollutants.

CHAPTER VI

CONCLUSION

As hypothesized, the Tongue River likely possesses a hyporheic zone as evidenced by differences between surface water and groundwater chemistry. However, identifying consistent boundaries between surface water, hyporheic water, and groundwater in the sediments beneath the stream channel is impractical because of the spatial and temporal variability of physical, chemical, and biological parameters selected as boundary indicators. Cross-watershed comparisons and the establishment of universal indicators of hyporheic boundaries are not easily accomplished due to expected regional differences in geology, climate, and hydrology that influence the nature of physicochemical and biological gradients. Numerous processes and conditions in the water or sediment can independently or collectively affect the variability of physical, chemical, and biological parameters, making it difficult to attribute observed patterns only to the mixing of surface water and groundwater. Adjacent land uses and degradation of riparian vegetation were also found to have an effect on physical and chemical parameters, therefore influencing the structure and boundaries of a hyporheic or mixing zone. For these reasons, none of the physical, chemical, or biological parameters measured in this study clearly defined a mixing zone. However, many of these parameters could be used to indicate conditions or processes occurring in the stream or riparian sediments, or provide an indication of the health of the stream reach.

Hydraulic conductivity measurements, for example, do not necessarily indicate interaction between surface water and groundwater, or hyporheic boundaries. At both sites of this study, points of high hydraulic conductivity exist (> 10 m/day) but low DO levels and sparse meiofauna populations suggest the points may be isolated from the stream by low permeability sediments. Based on these results, determining the average hydraulic conductivities for fluvial sediments could allow for catchment-scale quantification of groundwater/surface water interaction (Morrice et al., 1997), but would not be sufficiently detailed for determining location and boundaries of the hyporheic zone within a single reach. Future work to measure fluxes of stream water into the channel and riparian sediments should use tracer-dilution methods similar to Jackman et al. (1997) on the Shingobee River.

Several of the chemical parameters measured in this study, such as nitrate and DO, would not make good single-event sampling indicators of mixing zones because of the variability in distribution and absence of a pattern or gradient beneath the channel. Nitrate and DO concentrations in the Tongue River also differed from those of other streams (Williams, 1993), suggesting that processes affecting these parameters may vary significantly between watersheds and regions. At the reach scale, DO may be useful in measuring the surface water into the sediment, which, based on the seasonal changes in DO observed in this study, appears to be in a constant state of flux.

Electrical conductivity and ammonium displayed gradients with distinct discontinuities beneath the streambed, but the discontinuities could not be directly linked to surface water and groundwater boundaries. The discontinuities more likely indicate boundaries between reaction zones or chemically distinct zones in the channel sediments that might be tracked spatially and temporally. Temporal solute cycles controlled by reactions in the channel sediments may be able to be tracked by examining fluctuations in discontinuities of chemical gradients. This may lead to a better understanding and perhaps predictability of the location and extent of the hyporheic zone. Further research will be necessary to better determine the processes controlling EC and nitrate cycling in the hyporheic zone and to examine the occurrence of EC and ammonium gradients in stream systems.

Examining the chemistry of shallow subchannel water may also have implications for evaluating impacts to streams. By sampling only surface water and riparian groundwater qualities, evidence of nitrogen loading on the stream system may be overlooked. Results from this and other studies suggest that conditions beneath the stream channel have important implications for the retention of nitrogen (Duff et al., 1997; Triska et al., 1990). Sampling regimes intended to evaluate the health of stream should include water samples from directly beneath and adjacent to the channel. Additional studies should be conducted to determine the processes that affect nitrogen storage in channel sediments and the seasonal and spatial variability that can be expected.

Cattle grazing in the riparian zone appears to have both a direct and indirect effect on the health and functioning of the hyporheic zone. In a direct way, cattle wading in the stream channel disturb the sediment, which may limit meiofauna colonization, release stored nutrients into the stream, and lead to more rapid burial of POM. Indirectly, the cattle affect the stream by compacting riparian soils and decreasing the density and diversity of riparian vegetation. Healthy riparian vegetation filters nutrients from runoff and shallow groundwater flow, retains sediments on the banks, and provides cooling shade for the stream. Future stream system and nutrient studies should examine the extent to which human influences, such as cattle grazing, impact the hyporheic zone.

Numerous factors that control the distribution of meiofauna in the channel sediments make it impractical at this time to use these invertebrates as indicators of boundaries between surface water and groundwater. It is possible that their distributions could be useful in identifying some physical and chemical characteristics of the streambed sediments. However, the best use of the fauna may be as indicators of overall stream health. This may be especially important in consideration of the role that channel sediments play in the cycling of solutes. Before meiofauna can be efficiently used as bio-indicators, more needs to be understood about their regional distribution and the factors that influence their distribution in the sediments under and adjacent to streams.

APPENDIX A

SOIL BOREHOLE LOGS AND WELL COMPLETION REPORTS

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: variable
Well Number: HF-0-mini nest		Screened Interval: variable
Date Drilled: 18 May 1995		Riser Height: 1.60
Drilling Method:		Elev. Casing Top: variable
Logged By:		Elev. Ground Surface: 273.94
Depth	**Sample Description**	**Well Design**
See log for Borehole HF-0.5		Casing: 1.27-cm polyethylene tubes Depths: 0-0.10 0-0.35 0-0.60 0-0.85 0-1.00 0-1.50 Screen: Perforated poylethylene tube, 0.10m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth:
Well Number: Borehole HF-0.5		Screened Interval:
Date Drilled: 12 October 1996		Riser Height:
Drilling Method: Modified Livingston corer		Elev. Casing Top:
Logged By: D. Rush		Elev. Ground Surface:
Depth	**Sample Description**	**Well Design**
0 - 0.15	0.29% gravel, 7.8% coarse sand, 39% medium sand, 50% fine sand, 0% silt, 4.6% clay.	
0.15 - 0.30	0.31% gravel, 39% coarse sand, 18% medium sand, 29% fine sand, 6.8% silt, 5.3% clay.	
0.30 - 0.46	1.0% gravel, 26% coarse sand 30% medium sand, 31% fine sand, 5.5% silt, 5.3% clay.	
0.46 - 0.61	0.31% gravel, 18% coarse sand 29% medium sand, 44% fine sand, 1.7% silt, 5.3% clay.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.10
Well Number: HF-0.5-2.0		Screened Interval: 2.00 - 2.10
Date Drilled: 29 May 1996		Riser Height: 1.18
Drilling Method:		Elev. Casing Top: 275.28
Logged By:		Elev. Ground Surface: 274.10
Depth	**Sample Description**	**Well Design**
See log for Borehole HF-0.5		Casing: 1.27-cm polyethylene tube Depths: 0-2.00 Screen: Perforated polyethylene tube, 0.10m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: variable
Well Number: HF-1-mini nest		Screened Interval: variable
Date Drilled: 18 May 1995		Riser Height: 1.38
Drilling Method:		Elev. Casing Top: variable
Logged By:		Elev. Ground Surface: 274.29
Depth	**Sample Description**	**Well Design**
See logs for Boreholes HF-0.5 and HF-1.5		Casing: 1.27-cm polyethylene tubes Depths: 0-0.10 0-0.35 0-0.60 0-0.85 0-1.00 0-1.50 Screen: Perforated polyethylene tube, 0.10m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth:
Well Number: Borehole HF-1.5		Screened Interval:
Date Drilled: 12 October 1996		Riser Height:
Drilling Method: Modified Livingston corer		Elev. Casing Top:
Logged By: D. Rush		Elev. Ground Surface:
Depth	**Sample Description**	**Well Design**
0 - 0.15	4.1% gravel, 31% coarse sand 26% medium sand, 29% fine sand, 2.1% silt, 7.5% clay.	
0.15 - 0.30	0.68% gravel, 5.4% coarse sand, 17% medium sand, 60% fine sand, 12% silt, 5.3% clay.	
0.30 - 0.46	0.18% gravel, 3.2% coarse sand, 17% medium sand, 69% fine sand, 3.3% silt, 6.4% clay.	
0.46 - 0.61	0.18% gravel, 7.0% coarse sand, 18% medium sand, 66% fine sand, 4.4% silt, 6.4% clay.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: variable
Well Number: HF-2-mini nest		Screened Interval: variable
Date Drilled: 20 June 1995		Riser Height: 0.81 (support pole)
Drilling Method: Hand auger		Elev. Casing Top: variable
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 274.8
Depth	**Sample Description**	**Well Design**
0-0.30	Loose loamy sand. Very low moisture. Cattle disturbance, no vegetation.	Casing: 1.27-cm polyethylene tubes
0.30-0.71	Moist grey silty sand.	Depths: 0-0.10 0-0.35 0-0.60
0.71-0.81	Grey sand mottled with green and black clay. Very moist. Small oxide grains present. Slight sulfur odor.	
0.81-0.91	Saturated black, silty sand. Reduced organics and small brown soil particles present. Hole collapsed.	Screen: Perforated polyethylene tube, 0.10m length
	End of boring	Well Type: Mini-piezometers
		Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 1.48
Well Number: HF-2-85		Screened Interval: 1.38 - 1.48
Date Drilled: 20 June 1995		Riser Height: 0.24
Drilling Method: Hand auger		Elev. Casing Top: 274.98
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 274.73
Depth	**Sample Description**	**Well Design**
See logs for Borehole HF-1.5 and HF-2-mini nest.		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.38 Elevation: 274.73 - 273.35 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.38 - 1.48 Elevation: 273.35 - 273.25 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 1.77
Well Number: HF-2-110		Screened Interval: 1.67 - 1.77
Date Drilled: 20 June 1995		Riser Height: 0.39
Drilling Method: Hand auger		Elev. Casing Top: 275.12
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 274.72
Depth	**Sample Description**	**Well Design**
See logs for Borehole HF-1.5 and HF-2-mini nest.		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.67 Elevation: 274.72 - 273.05 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.67 - 1.77 Elevation: 273.05 - 272.95 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.20
Well Number: HF-2-1.5		Screened Interval: 2.10 - 2.20
Date Drilled: 20 June 1995		Riser Height: 0.41
Drilling Method: Hand auger		Elev. Casing Top: 275.08
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 274.66
Depth	**Sample Description**	**Well Design**
See logs for Borehole HF-1.5 and HF-2-mini nest.		Casing: 2.54-cm ID, sch 40 pvc Depth: 0.0 - 2.10 Elevation: 274.66 - 272.56 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.10 - 2.20 Elevation: 272.56 - 272.46 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 1.95
Well Number: HF-4-50		Screened Interval: 1.85 - 1.95
Date Drilled: 20 June 1995		Riser Height: 0.36
Drilling Method: Hand auger		Elev. Casing Top: 275.61
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 275.26
Depth	**Sample Description**	**Well Design**
See log for HF-6.5-WT		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.85 Elevation: 275.26 - 273.41 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.85 - 1.95 Elevation: 273.41 - 273.31 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.36
Well Number: HF-4-100		Screened Interval: 2.26 - 2.36
Date Drilled: 20 June 1995		Riser Height: 0.60
Drilling Method: Hand auger		Elev. Casing Top: 275.81
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 275.21
Depth	**Sample Description**	**Well Design**
	See log for HF-6.5-WT	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.26 Elevation: 275.21 - 272.95 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.26 - 2.36 Elevation: 272.95 - 272.85 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.97
Well Number: HF-4-1.5		Screened Interval: 2.87 - 2.97
Date Drilled: 20 June 1995		Riser Height: 0.51
Drilling Method: Hand auger		Elev. Casing Top: 275.76
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 275.25
Depth	**Sample Description**	**Well Design**
See log for HF-6.5-WT		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.87 Elevation: 275.25 - 272.38 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.87 - 2.97 Elevation: 272.38 - 272.28 Well Type: Naturally developed Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.23
Well Number: HF-6.5-WT		Screened Interval: 2.13 - 2.23
Date Drilled: 14 May 1996		Riser Height: 0.82
Drilling Method: Hand auger		Elev. Casing Top: 276.88
Logged By: D.Rush		Elev. Ground Surface: 276.05
Depth	**Sample Description**	**Well Design**
0-0.46	Loamy, gritty, brown sand with organic fragments and some clay.	Casing: 2.54-cm ID, sch 20 pvc
0.46-0.61	Fine brown sand with few organic fragments. Nearly saturated.	Depth: 0.0 - 1.05 Elevation: 276.05 - 275.00
0.61-0.91	Fine sand with reduced black organics and root fragments. Saturated.	Screen: Hacksaw-slotted, 2.54-cm ID pvc
0.91-1.14	Fine to medium brown sand with some silt and clay. Some root fragments.	Depth: 1.05 - 2.23 Elevation: 275.00 - 273.83
1.14-1.37	Medium to coarse sand. Mottled with black and iron oxide streaks.	Well Type: Naturally developed
1.37-1.59	Medium to fine, grey sand with some silt and clay. Black streaks and oxide stains present.	Annular Fill: Collapsed formation and cuttings
1.59-1.75	Fine to medium grey sand with reduced organic particles.	
1.75-2.01	Fine, grey, loamy sand with some clay and silt. Organic fragments.	
2.01-2.53	Hole collapsed.	
	End of Boring	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 2.90
Well Number: HF-9-50		Screened Interval: 2.80 - 2.90
Date Drilled: 20 June 1995		Riser Height: 0.43
Drilling Method: Power auger and driven		Elev. Casing Top: 276.88
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 276.45
Depth	**Sample Description**	**Well Design**
	See log for HF-6.5-WT and HF-13-12	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.80 Elevation: 276.45 - 273.65 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.80 - 2.90 Elevation: 273.65 - 273.55 Well Type: Naturally developed Annular Seal: Bentonite chips Depth: 1.52 - 1.98 Elevation: 274.93 - 274.47 Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 3.40
Well Number: HF-9-100		Screened Interval: 3.30 - 3.40
Date Drilled: 20 June 1995		Riser Height: 0.39
Drilling Method: Power auger and driven		Elev. Casing Top: 276.79
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 276.40
Depth	**Sample Description**	**Well Design**
See log for HF-6.5-WT and HF-13-12		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 3.30 Elevation: 276.40 - 273.10 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 3.30 - 3.40 Elevation: 273.10 - 273.00 Well Type: Naturally developed Annular Seal: Bentonite chips Depth: 2.21 - 2.36 Elevation: 274.19 - 274.04 Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 3.88
Well Number: HF-9-1.5		Screened Interval: 3.78 - 3.88
Date Drilled: 20 June 1995		Riser Height: 0.41
Drilling Method: Power auger and driven		Elev. Casing Top: 276.83
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 276.43
Depth	**Sample Description**	**Well Design**
	See log for HF-6.5-WT and HF-13-12	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 3.78 Elevation: 276.43 - 272.65 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 3.78 - 3.88 Elevation: 272.65 - 272.55 Well Type: Naturally developed Annular Seal: Bentonite chips Depth: 2.00 - 2.67 Elevation: 274.43 - 273.76 Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 3.51
Well Number: HF-13-12		Screened Interval: 3.41 - 3.51
Date Drilled: 18 May 1995		Riser Height: 0.58
Drilling Method: Hand auger		Elev. Casing Top: 278.15
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 277.57
Depth	**Sample Description**	**Well Design**
0-0.15	No surface vegetation. Gritty with few wood fragments. 72% sand, 18% silt, 10% clay. Color: 7.5YR 3/2, 2.5Y 4/2; light brown with some darker clay.	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 3.41 Elevation: 277.57 - 274.16
0.15-0.31	Loamy sand with plant roots. Color: 2.5Y 4/2.	
0.31-0.41	Sandy loam. 0.1% gravel, 0.2% VC sand, 36% sand, 45% silt, 19% clay. Color: darker, 5Y 3/1.	Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 3.41 - 3.51 Elevation: 274.16 - 274.06
0.41-0.66	Loamy sand. Similar to 0.15m. Color: 2.5Y 4/2.	
0.66-0.76	Slightly sandier loamy sand. Small oxide stains present near clay.	Well Type: Naturally developed
0.76-1.07	Silty sand. Low moisture content. Some oxide stains and woody particles present. 0.7% VC sand, 75% sand, 23% silt, 6.6% clay.	Annular Seal: Bentonite chips Depth: 2.84 - 2.92 Elevation: 274.73 - 274.65
1.07-1.37	Loamy sand. slight effervescence in HCl. Top of sample: 0.2% gravel 0.6% VC sand, 56% sand, 36% silt, 7.8% clay. Bottom of sample: 60% sand, 29% silt, 11% clay. Color: 2.5Y 4/2 or 5/2.	Annular Fill: Collapsed formation and cuttings
1.37-1.52	Loamy sand mottled with dark clay. Oxides present < 2 mm in size. High moisture content. Color: sand 2.5Y 3/2; clay 10YR 3/1	
	continued on next page	

Depth	Sample Description	Well Design
1.52 - 1.83	Sandy loam interbedded with moist, dark clay and coarse, sandy layers. Small pebbles are present in the sand layers. 1.6% gravel, 1.1% v. coarse sand, 70% sand, 20% silt, 7.7% clay. Color: sand 2.5Y 3/2 clay 10YR 3/1	
1.83 - 1.98	Very moist sand. Forms stable ball, but is friable. Slight effervescence near thin bands of oxidation.	
1.98 - 2.13	Loamy sand near saturation. Thin layers of coarse sand.	
2.13 - 2.97	Saturated interbedded sands and silty, sandy clays. Clays cohesive and soil hands. Some reduced organics and slight sulfur smell. 67% sand, 20% silt, 12% clay.	
2.97 - 3.35	Coarse, silty, saturated sand. Dark with reduced organics (wood fragments) and preserved shell fragments. 82% sand, 14% silt, 4.4% clay. Hole collapsed.	
	End of Boring.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Hinkle Farm, Cavalier, ND		Total Depth: 3.67
Well Number: HF-60-WT		Screened Interval: 2.68 - 3.67
Date Drilled: 20 June 1995		Riser Height: 1.56
Drilling Method: Power auger		Elev. Casing Top: 277.94
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 276.38
Depth	**Sample Description**	**Well Design**
See log for HF-13-12		Casing: 5.08-cm ID, sch 40 pvc Depth: 0.0 - 2.68 Elevation: 276.38 - 273.70 Screen: Hacksaw-slotted sch 40, 5.08-cm ID, PVC Depth: 2.68 - 3.67 Elevation: 273.70 - 272.71 Well Type: Naturally developed Annular Seal: Bentonite chips Depth: 1.09 - 1.52 Elevation: 275.29 - 274.86 Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: variable
Well Number: ISP-0-mini nest		Screened Interval: variable
Date Drilled: 21 June 1995		Riser Height: 1.55
Drilling Method:		Elev. Casing Top: variable
Logged By:		Elev. Ground Surface: 285.18
Depth	**Sample Description**	**Well Design**
See log for Borehole ISP-0.5		Casing: 1.27-cm polyethylene tubes Depths: 0-0.10 0-0.35 0-0.60 0-0.85 0-1.00 0-1.50 Screen: Perforated polyethylene tube, 0.10 m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth:
Well Number: Borehole ISP-0.5		Screened Interval:
Date Drilled: 12 October 1996		Riser Height:
Drilling Method: Modified Livingston corer		Elev. Casing Top:
Logged By: D. Rush		Elev. Ground Surface:
Depth	**Sample Description**	**Well Design**
0 - 0.15	0.38% gravel, 7.7% coarse sand, 26% medium sand, 60% fine sand, 8.6% silt, 4.6% clay.	
0.15 - 0.30	0.40% gravel, 5.9% coarse sand, 18% medium sand, 59% fine sand, 7.8% silt, 8.7% clay.	
0.30 - 0.46	11% gravel, 15% coarse sand, 23% medium sand, 44% fine sand, 3.4% silt, 5.3% clay.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 0.80
Well Number: ISP-0.5-70		Screened Interval: 0.70 - 0.80
Date Drilled: 29 May 1996		Riser Height: 0.73
Drilling Method: Driven		Elev. Casing Top: 286.19
Logged By:		Elev. Ground Surface: 285.46
Depth	**Sample Description**	**Well Design**
	See log for Borehole ISP-0.5	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 0.70 Elevation: 285.46 - 284.76 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 0.70 - 0.80 Elevation: 284.76 - 284.86 Well Type: Naturally developed Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.10
Well Number: ISP-0.5-2.0		Screened Interval: 2.00 - 2.10
Date Drilled: 29 May 1996		Riser Height: 1.05
Drilling Method:		Elev. Casing Top: 286.49
Logged By:		Elev. Ground Surface: 285.44
Depth	**Sample Description**	**Well Design**
See log for Borehole ISP-0.5		Casing: 1.27-cm polyethylene tube Depths: 0-2.00 Screen: Perforated poylethylene tube, 0.10 m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: variable
Well Number: ISP-1-mini nest		Screened Interval: variable
Date Drilled: 21 June 1995		Riser Height: 1.66
Drilling Method:		Elev. Casing Top: variable
Logged By:		Elev. Ground Surface: 285.26
Depth	**Sample Description**	**Well Design**
See log for Borehole ISP-0.5 and ISP-1.5		Casing: 1.27-cm polyethylene tubes Depths: 0-0.10 0-0.35 0-0.60 0-0.85 0-1.00 0-1.50 Screen: Perforated poylethylene tube, 0.10m length Well Type: Mini-piezometers Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth:
Well Number: Borehole ISP-1.5		Screened Interval:
Date Drilled: 12 October 1996		Riser Height:
Drilling Method: Modified Livingston corer		Elev. Casing Top:
Logged By: D. Rush		Elev. Ground Surface:
Depth	**Sample Description**	**Well Design**
0 - 0.15	0.28% gravel, 4.0% coarse sand, 30% medium sand, 66% fine sand, 0.55% silt and clay	
0.15 - 0.30	3.1% pebble gravel, 3.8% gravel, 15% coarse sand, 25% medium sand, 50% fine sand, 3.2% silt and clay.	
0.30 - 0.46	37% pebble gravel, 24% gravel, 25% coarse sand, 6.7% medium sand, 6.8% fine sand, 0.70% silt and clay.	
0.46 - 0.61	60% pebble gravel, 20% gravel, 16% coarse sand, 1.8% medium sand, 1.9% fine sand, 0.50% silt and clay.	
0.61 - 0.76	49% pebble gravel, 26% gravel, 20% coarse sand, 2.6% medium sand, 1.7% fine sand, 0.80% silt and clay.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 1.94
Well Number: ISP-2-85		Screened Interval: 1.84 - 1.94
Date Drilled: 21 June 1995		Riser Height: 0.75
Drilling Method: Power auger and driven		Elev. Casing Top: 287.23
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.49
Depth	**Sample Description**	**Well Design**
	See log for Borehole ISP-1.5 and ISP-4-50	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.84 Elevation: 286.49 - 284.65 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.84 - 1.94 Elevation: 284.65 - 284.55 Well Type: Naturally developed Annular Fill: Collapsed formation and bentonite chips

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.08
Well Number: ISP-2-110		Screened Interval: 1.98 - 2.08
Date Drilled: 21 June 1995		Riser Height: 0.96
Drilling Method: Power auger and driven		Elev. Casing Top: 287.45
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.49
Depth	**Sample Description**	**Well Design**
	See log for Borehole ISP-1.5 and ISP-4-50	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.98 Elevation: 286.49 - 284.51 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.98 - 2.08 Elevation: 284.51 - 284.40 Well Type: Naturally developed Annular Fill: Collapsed formation and bentonite chips

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.57
Well Number: ISP-2-1.5		Screened Interval: 2.47 - 2.57
Date Drilled: 21 June 1995		Riser Height: 0.43
Drilling Method: Power auger and driven		Elev. Casing Top: 286.97
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.54
Depth	**Sample Description**	**Well Design**
	See log for Borehole ISP-1.5 and ISP-4-50	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.47 Elevation: 286.54 - 284.07 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.47 - 2.57 Elevation: 284.07 - 283.97 Well Type: Naturally developed Annular Fill: Collapsed formation and bentonite chips

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.04
Well Number: ISP-4-50		Screened Interval: 1.94 - 2.04
Date Drilled: 21 June 1995		Riser Height: 0.94
Drilling Method: Hand auger		Elev. Casing Top: 287.85
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.91
Depth	**Sample Description**	**Well Design**
0-1.22	Loamy sand to sandy loam with variable amounts of silt and clay. Sand grades from fine to medium with few coarse fragments. Color: light brown to darker brown with increased moisture content.	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.94 Elevation: 286.91 - 284.97
1.22-1.52	Very moist, silty, clayey grey sand becomming coarser with depth. Mottled brown oxides and organic (wood) fragments present.	Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 1.94 - 2.04 Elevation: 284.97 - 284.87
1.52-1.83	Saturated, silty, coarse sand to fine gravel. Some sediment > 2cm. Grey with reduced sulfur smell and few shell fragments. Hole collapsed End of boring	Well Type: Naturally developed with drive point Annular Seal: none Annular Fill: Collapsed formation and cuttings

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.54
Well Number: ISP-4-100		Screened Interval: 2.44 - 2.54
Date Drilled: 21 June 1995		Riser Height: 0.56
Drilling Method: Power auger and driven		Elev. Casing Top: 287.48
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.92
Depth	**Sample Description**	**Well Design**
	See log for ISP-4-50	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.44 Elevation: 286.92 - 284.48 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.44 - 2.54 Elevation: 284.48 - 284.37 Well Type: Naturally developed Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 3.04
Well Number: ISP-4-1.5		Screened Interval: 2.94 - 3.04
Date Drilled: 21 June 1995		Riser Height: 0.75
Drilling Method: Power auger and driven		Elev. Casing Top: 287.67
Logged By: D. Rush and D. Goebel		Elev. Ground Surface: 286.92
Depth	**Sample Description**	**Well Design**
See log for ISP-4-50		Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.94 Elevation: 286.92 - 283.98 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.94 - 3.04 Elevation: 283.98 - 283.88 Well Type: Naturally developed Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log	Completion Report
Location: Icelandic State Park, Cavalier, ND	Total Depth: 2.26
Well Number: ISP-6.5-WT	Screened Interval: 1.09 - 2.26
Date Drilled: 14 May 1996	Riser Height: 0.37
Drilling Method: Hand auger	Elev. Casing Top: 287.60
Logged By: D. Rush	Elev. Ground Surface: 287.26

Depth	Sample Description	Well Design
0-0.49	Surface vegetated. Fine to medium brown sand with some silt and clay. Organic and root fragments.	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 1.09 Elevation: 287.26 - 286.17
0.49-0.82	Fine to medium, brown sand with some silt and clay. Organic fragments.	
0.82-1.31	Medium to coarse sand. Grey to black and iron oxide streaking. Saturated.	Screen: Hacksaw-slotted, 2.54-cm ID pvc Depth: 1.09 - 2.26 Elevation: 286.17 - 285.00
1.31-1.55	Clean, coarse sand with near pea sized gravel (>1.0 Φ). Grains are well rounded with some silt.	Well Type: Naturally developed
1.55-1.89	Coarse sand to pea gravel with some silt and clay. Oxide staining.	
1.89-2.29	Coarse grey sand to pea gravel with some silt and clay. Reduced organics and shale fragments.	Annular Fill: Collapsed formation and cuttings
2.29-2.68	Coarse sand to pea gravel with some pebbles larger than 3 cm. More that half shale fragments. Hole collapsed.	
	End of boring.	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 2.81
Well Number: ISP-9-50		Screened Interval: 2.71 - 2.81
Date Drilled: 21 June 1995		Riser Height: 0.25
Drilling Method: Hand auger		Elev. Casing Top: 287.97
Logged By: D. Rush		Elev. Ground Surface: 287.72
Depth	**Sample Description**	**Well Design**
	See log for ISP-9-100	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.71 Elevation: 287.72 - 285.01 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.71 - 2.81 Elevation: 285.01 - 284.92 Well Type: Naturally developed Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 3.35
Well Number: ISP-9-100		Screened Interval: 3.25 - 3.35
Date Drilled: 22 June 1995		Riser Height: 0.56
Drilling Method: Hand auger		Elev. Casing Top: 288.31
Logged By: D. Rush		Elev. Ground Surface: 287.75
Depth	**Sample Description**	**Well Design**
0-1.52	Loamy sand to sandy loam with variable amounts of clay and silt. Some clay layers are dense. Lenses of medium sand present. Color: Similar to B-4-50.	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 3.25 Elevation: 287.75 - 284.50
1.52-1.68	Coarse sand to pea-size gravel. Moist with iron oxide stains. Grains consist of shale, limestone, quartz and other minerals.	Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 3.25 - 3.35 Elevation: 284.50 - 284.40
1.68-1.98	Medium to coarse sand with few fines. Mostly quartz with dark brown bands of oxidation. Very moist.	Well Type: Naturally developed
1.98-2.13	Coarse to medium sand. Clean with little silt or clay. Nearly saturated. Oxide deposits present.	Annular Fill: Collapsed formation and cuttings
2.13-2.29	Saturated coarse sand with small gravel. Brown oxidation changes to grey-black reduced material. Hole collapsed.	
	End of boring	

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 3.83
Well Number: ISP-9-1.5		Screened Interval: 3.73 - 3.83
Date Drilled: 21 June 1995		Riser Height: 0.71
Drilling Method: Hand auger		Elev. Casing Top: 288.48
Logged By: D. Rush		Elev. Ground Surface: 287.77
Depth	**Sample Description**	**Well Design**
	See log for ISP-9-100	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 3.73 Elevation: 287.77 - 284.04 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 3.73 - 3.83 Elevation: 284.04 - 283.95 Well Type: Naturally developed Annular Fill: Collapsed formation

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 3.61
Well Number: ISP-14-WT		Screened Interval: 2.70 - 3.61
Date Drilled: 22 June 1995		Riser Height: 1.02
Drilling Method: Hand auger		Elev. Casing Top: 289.66
Logged By: D. Rush		Elev. Ground Surface: 288.64
Depth	**Sample Description**	**Well Design**
	See log for ISP-14-11	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0 - 2.70 Elevation: 288.64 - 285.94 Screen: 10-slot, sch 80, 2.54-cm ID pvc Depth: 2.70 - 3.61 Elevation: 285.94 - 285.04 Well Type: Naturally developed Annular Fill: Collapsed formation and bentonite

SOIL BOREHOLE LOG AND WELL COMPLETION REPORT

Depths are in meters and elevations are in meters above mean sea level

Lithologic Log		Completion Report
Location: Icelandic State Park, Cavalier, ND		Total Depth: 3.19
Well Number: ISP-14-11		Screened Interval: 3.09 - 3.19
Date Drilled: 19 May 1995		Riser Height: 0.28
Drilling Method: Hand auger		Elev. Casing Top: 288.89
Logged By: D. Rush and A.M. Coyle		Elev. Ground Surface: 288.61
Depth	**Sample Description**	**Well Design**
0-0.48	Surface vegetation includes various grasses, Equisetophyta, and Rosaceae. Top 10cm contains organics and vegetation. Animal burrows are present. Loamy sand, very low moisture content. 0.2% VC sand, 81% sand, 13% silt, 6.6% clay. Color: 2.5Y 4/2	Casing: 2.54-cm ID, sch 20 pvc Depth: 0.0-3.09 Elevation: 288.61 - 285.52 Screen: 10-slot, sch 80, 2.54-cm ID pvc
0.48-0.76	Moist loamy sand similar to above. Some mixed organics and clay.	Depth: 3.09 - 3.19 Elevation: 285.52 - 285.42
0.76-0.91	Very moist loamy sand with some coarser grains (3.5-3.0 ϕ). 73% sand, 16% silt, 11% clay. Clay is darker than above.	Well Type: Filter-packed Filter Pack: Medium silica sand
0.91-1.22	Fine, moist sand with interbedded layers of silt and clay. 73% sand 17% silt, 10% clay. Clay is dark brown and approx. 3cm thick. Sandy layers effervesce slightly. Color: sand 2.5Y 4/1; clay 2.5Y 3/1 or 10YR 3/1; dark clay 5Y 2.5/1.	Depth: 2.89 - 3.19 Elevation: 285.72 - 285.42 Annular Seal: Bentonite chips Depth: 2.79 - 2.89 Elevation: 285.82 - 285.72
1.22-1.83	Sandy loam with variable amounts of silt and clay. At 1.37m: 0.1% gravel, 0.1% VC sand, 63% sand, 25% silt, 12% clay. At 1.52m: 73% sand, 16% silt, 11% clay. Clays are dark and moist. Color: 2.5Y 4/2 continued on next page...	Annular Fill: Backfill with cuttings and bentonite.

Depth	Sample Description	Well Design
1.83 - 2.13	Interbedded sandy loam, with fine sand and clay. Sediment is very moist with some particulate organics and oxides. Fine sands effervesce. 0.1% gravel, 75% sand, 15% silt, 10% clay. Color: 2.5Y 5/2	
2.13 - 2.59	Saturated silty sand. Oxides are present in thin bands or mottled throughout. Slight reduced smell. 75% sand, 15% silt, 10.0% clay.	
2.59 - 3.05	Grey saturated sand. Reduced with black organic fragments. 0.1% gravel, 85% sand, 7.2% silt, 7.8% clay. Hole collapsed. End of boring.	

APPENDIX B

VEGEGATION SURVEY RESULTS

Table 8. Vegetation Survey at the Hinkle Farm Site

Three 10-meter transects, 101 sample points per transect

Common Name	Genus species	No. of Hits	% Cover	% Composition
Variety Grass	*Poa sp.*	71	23	45
Sedge	*Carex sp.*	23	7.6	14
Common Milkweed	*Asclepias syriaca*	23	7.6	14
Dandelion	*Taraxacum officinale*	16	5.3	10
Indian Grass	*Sorghastrum nutans*	6	2	4
Violet	*Viola sp.*	5	2	3
Catnip	*Nepeta cataria*	2	0.7	1
Wild Four O'Clock	*Allionia nyotaginea*	2	0.7	1
Wormwood	*Artemisia absinthium*	1	0.3	0.6
Hedge Bindweed	*Convolvulus sepium*	1	0.3	0.6
Unknown		1	0.3	0.6
Woody Vegetation		8	2.6	5.0
American Elm	*Ulmus americana*			
Willow	*Salix sp.*			
Linden	*Tilia americana*			
Box Elder	*Acer negundo*			
Total Vegetation		159	52	
Bare Ground		144	48	
Total		303		
Brillouin Index	0.71			

Table 9. Vegetation Survey at the Icelandic State Park Site

Three 10 meter transects, 101 sample points per transect

Common Name	Genus species	No. of Hits	% Cover	% Composition
Indian Grass	*Sorghastrum nutans*	46	15	16
Scouring Rush	*Equisetum kansanum*	29	9.6	10
Sedge	*Carex sp.*	28	9.3	9.9
Field Horsetail	*Equisetum arvense*	21	7.0	7.4
Variety Grass	*Poa sp.*	18	6.0	6.4
Late Goldenrod	*Solidago gigantea*	16	5.3	5.7
Wild Grape	*Vitis sp.*	13	4.3	4.6
Tansy	*Tanacetum vulgare*	12	4.0	4.3
Red Raspberry	*Rubus idaeus*	9	3	3
Virginia Creeper	*Parthenocissus quinquefolia*	8	3	3
Jerusalem Artichoke	*Helianthus tuberosus*	8	3	3
Common Milkweed	*Asclepias syriaca*	6	2	2
Wild Geranium	*Anemone canadensis*	6	2	2
Canada Thistle	*Cirsium arvense*	3	1.0	1
Northern Snow Bedstraw	*Galium boreale*	2	0.7	0.7
Hairy Vetch	*Vicia americana*	1	0.3	0.4
Wild Bergamot	*Monarda fistulosa*	1	0.3	0.4
Smooth Solomon's Seal	*Polygonatum biflorum*	1	0.3	0.4
<u>Woody Vegetation</u>		54	18	19
Choke Cherry	*Prunus virginiana*			
American Elm	*Ulmus americana*			
Willow	*Salix sp.*			
Russian Olive	*Elaeagnus angustifolia*			
Wolfberry	*Symphoricarpos occidentalis*			
White Ash	*Fraxinus americana*			
Linden	*Tilia americana*			
Box Elder	*Acer negundo*			
Bur Oak	*Quercus macrocarpa*			
Juneberry	*Amelanchier arborea*			
Prairie Wild Rose	*Rosa arkansana*			
<u>Total Vegetation</u>		282	94	
Bare Ground		19	6	
<u>Total</u>		301		
Brillouin Index	1.0344			

APPENDIX C

PROCEDURES FOR GROUNDWATER FAUNA SAMPLE

PREPARATION AND ENUMERATION

PROCEDURES FOR GROUNDWATER FAUNA SAMPLE PREPARATION AND ENUMERATION

Groundwater fauna, or meiofauna, are benthic invertebrates between the sizes of 43 and 1000 μm that live in the saturated sediments beneath and adjacent to surface waters. Common groups of taxa include nematoda, copepoda, oligochaeta, ostrocoda, and acarina (Thorp and Covich, 1991; Botosaneanu, 1986). The groups or families of meiofauna can be surface water dwellers, occasional sediment dwellers, or permanent sediment dwellers. Habitat preference can also vary with the life cycle. Meiofauna play an important role in the stream ecosystem by recycling detrital material and nutrients, and providing food for larger organisms.

Sampling

Meiofauna samples can be collected from the stream bed and adjacent sediments in numerous ways, a few of which will be noted here. Corers and grab samplers are useful for shallow sediment samples. Deeper samples are more easily collected with dedicated wells or driven standpipes (Williams and Hynes,1974). With any sampling device, knowing the sample volume is essential for quantitative analysis. Once the sample has been collected, it should be field preserved in the following way as described below.

Field Preparation and Storage Procedures

1. Filter sample through a 63-μm (or smaller) sieve and rinse transport jar, grab sampler, or corer into the sieve as well.

2. Using distilled water and a lab rinse bottle, rinse all of the sediment to one side of the sieve. Rinsing from the back works well, but be sure not to tilt the sieve too far and spill the sample. Be sure not to leave any sediment on the

sides of the sieve. (Note: Tapping the sieve on the side will help the liquid drain faster)

3. Using a funnel, rinse the sediment from the sieve into a storage bottle. Continue to rinse the sieve into the bottle until no more sediment remains on the screen or sides. Rinse the funnel into the the bottle as well.

4. Place a very small amount of powdered Rose Bengal stain into the storage bottle and fill to the top with a 10% buffered formalin solution.

5. Place the cap tightly on the bottle and gently mix the contents.

6. Thoroughly rinse the sieve with distilled or tap water before the next use. This prevents contamination of the next sample.

Sorting

Sorting the samples for meiofauna can be a tedious process; careful attention must be paid to assure good qualitative and quantitative analysis. Samples with large amounts of sediment or numbers of organisms may be subsampled. There are many methods of subsampling such as sample splitting, use of a Hensen-Stemple pipette, or by using sectors on a sorting slide or tray. Samples can also be sorted by separating the organisms from the sediment by swirl decantation or density separation in a sugar solution (Britton and Greeson, 1987). Before the sample can be sorted, it must be prepared for laboratory analysis.

Presorting Preparation Procedures

1. Pour the formalin solution from the sample bottle into a 63-µm sieve. Collect formalin in a pitcher or beaker, and transfer to a sealed storage container.

2. Refill the sample bottle with distilled water, close the cap tightly, and mix gently.

3. Allow the sediment to settle 10–15 seconds.

4. Pour water from sample bottle into 63-μm sieve.

5. Repeat steps 2–4 two more times.

6. Wash sediment in sieve to one side of the screen with a lab rinse bottle and distilled water, making sure <u>not to tilt the sieve and spill the sample</u>. Either return sediment to the sample bottle or place it in a watch glass and sort (see Meiofauna Separation and Storage).

7. Fill sample bottle to near the top with 30–50% ethyl alcohol for storage and sorting.

8. Cap and label the bottle (include name and concentration of preservative).

Note: Higher concentrations of ethyl alcohol with remove the stain from the organisms

The purpose of swirl decantation is to remove as many of the organisms as possible from the sediment. Because most of the sediment is more dense than the organisms, it settles faster than the meiofauna. This process works best when the sediment is mostly sand. Swirl decantation can be followed by sorting of the remaining sediment in the sample to ensure no meiofauna had been missed. Swirl decantation follows a procedure similar to the presorting preparation.

<u>Swirl Decantation Procedure</u>

1. Gently mix the sample until all sediment is suspended.

2. Allow the the sand-size particles to settle to the bottom of the bottle (usually 5 seconds, depending on the bottle size).

3. Open the bottle, making sure that no sediment remains on the inside of the lid.

4. Pour the liquid through a 63-µm sieve. Rinse lid into sieve.

5. Refill the sample bottle with distilled water if continuing the decantation process, or fill with ethyl alcohol solution when finished (even if just for the day).

6. Rinse sediment to one side of the sieve (as described in presorting procedures), being sure not to leave any behind.

7. Wash sediment into watch glass, making sure not to leave any sediment or organisms behind. Try to leave only 0.5 to 1.0 cm of water in glass.

8. After separating meiofauna, repeat process from Step 1 ten or more times If not using, or in addition to, swirl decantation, use the procedure described below for sorting.

Whole Sample Sorting (Not Subsampling or Decanting)

1. Prepare sample for lab as described in Presorting Preparation Procedures above.

2. Using a chemical spatula or small spoon, place a nickle-size blob of sediment into the watch glass. Be careful not to spill the sediment when transferring from the sample bottle to the watch glass.

3. Rinse spatula well.

4. Add 0.5 cm of distilled water to the watch glass.

5. Separate meiofauna as described in Meiofauna Separation and Storage below.

Once the sample is in the watch glass, the procedures described below should be used for separating meiofauna.

Meiofauna Separation and Storage

1. Spread the sediment evenly around the watch glass. Less sediment is better for quicker sorting.

2. Place the watch glass usnder a 10–40x dissecting scope. Adequate lighting is essential (I recommend fiber optic or other bright lighting).

3. Move the watch glass across the scope field in a zigzag pattern, sifting through the sediment with a dissecting probe or other sharp utensil.

4. When an organism is located, it can be removed with fine forceps, a coarse syringe, or a drop of mounting medium on the tip of the dissecting probe.

5. The organism should be removed very gently, so as not to crush it.

6. Place the organism in a small vial. Add 30%—-50% ethyl alcohol. Cap the vial tightly.

7. Be absolutely certain the organism is in the vial and not on the transfer utensil or in the watch glass.

8. Label the vial with the sample name or number and date, the type of organism if known, and the preservative.

9. Note in lab notebook the date, time, sample number, and type of organism found.

10. Continue looking where organism was found. It may be necessary to start over if the sample has been disturbed during retrieval.

11. When finished, discard or save the contents of watch glass. Rinse watch glass with tap water and repeat from Step 1.

Mounting and Classification

Each group of groundwater invertebrates requires different methods for mounting and classification. Thorp and Covich (1991) outlines the methods for preservation and mounting of most types of freshwater invertebrates and presents general taxonomic keys. Other keys include Edmondson (1959), Botosaneau (1986), Pennak (1989), and many sources from current literature.

APPENDIX D

WATER LEVEL ELEVATIONS

Table 10. Water Level Elevations in Piezometers at HF Site, (elevations are in meters above msl).

Date Collected	HF-Staff	HF-0-10	HF-0-35	HF-0-60	HF-0-85	HF-0-110	HF-0-1.5	HF-0.5-2.0	HF-1-10	HF-1-35	HF-1-60
8/3/95	na[1]	na[2]	274.08	274.08	274.07	274.08	274.13	na[3]	274.11	274.17	274.08
8/27/95	na[1]	na[2]	274.13	274.10	274.10	274.10	274.11	na[3]	274.11	274.12	274.11
9/23/95	na[1]	na[2]	273.95	274.12	274.12	274.12	274.13	na[3]	274.13	274.15	274.13
10/14/95	274.29	na[2]	274.28	274.26	274.28	274.28	274.29	na[3]	274.29	274.27	274.26
6/6/96	274.28	274.28	274.28	274.28	274.29	273.12	274.29	274.30	274.27	274.27	274.27
7/7/96	274.16	274.17	274.17	274.17	274.18	na[4]	274.17	274.17	274.15	274.15	274.15
7/23/96	274.33	274.34	274.34	274.34	274.34	na[4]	274.34	274.34	274.32	274.32	274.32
7/31/96	274.12	274.13	274.13	274.14	274.14	na[4]	274.13	274.13	274.11	274.11	274.11
8/13/96	na[1]	274.04	274.04	274.04	274.04	na[4]	274.03	274.03	274.02	274.02	274.02

Date Collected	HF-1-85	HF-1-110	HF-1-1.5	HF-2-10	HF-2-35	HF-2-60	HF-2-85	HF-2-110	HF-2-1.5	HF-4-50	HF-4-100
8/3/95	274.08	274.07	274.05	274.07	274.07	274.07	274.09	273.75	274.08	274.09	274.15
8/27/95	274.12	274.11	274.00	274.10	274.09	274.10	274.12	274.13	274.11	274.13	274.11
9/23/95	274.13	274.12	274.09	274.17	274.12	274.12	274.13	274.15	274.14	274.16	274.17
10/14/95	274.28	274.22	274.25	274.43	274.27	274.27	274.30	274.30	274.30	274.30	274.31
6/6/96	274.27	274.27	274.27	274.28	274.28	274.28	274.32	274.32	274.33	274.32	274.37
7/7/96	274.15	274.15	274.15	274.17	274.17	274.17	274.19	274.18	274.21	274.18	274.23
7/23/96	274.32	274.32	274.32	274.34	274.34	274.34	274.36	274.36	274.38	274.36	274.38
7/31/96	274.11	274.11	274.11	274.25	274.14	274.14	274.17	274.17	274.17	274.17	274.19
8/13/96	274.01	274.02	274.01	274.04	274.04	274.04	274.06	274.07	274.07	274.06	274.08

Table 10 (continued)

Date Collected	HF-4-1.5	HF-6.5-WT	HF-9-50	HF-9-100	HF-9-1.5	HF-13-WT	HF-13-12	HF-60-WT
8/3/95	272.88	na[3]	274.14	274.15	272.74	274.14	274.17	274.33
8/27/95	273.20	na[3]	274.15	274.16	272.96	274.40	273.93	274.30
9/23/95	274.71	na[3]	274.18	274.19	274.64	274.18	274.19	274.30
10/14/95	273.07	na[3]	274.33	274.33	272.98	274.32	274.34	274.44
6/6/96	273.90	274.33	274.52	274.53	275.16	274.58	274.62	274.92
7/7/96	274.23	274.19	274.35	274.36	274.88	274.38	274.40	274.63
7/23/96	274.20	274.36	274.49	274.49	272.64	274.48	274.51	274.66
7/31/96	274.19	274.20	274.32	274.33	273.01	274.34	dry	274.57
8/13/96	274.09	274.06	274.19	274.20	273.67	274.20	dry	274.38

na[1] Water level in stream below staff gage.
na[2] Water level below piezometer screen.
na[3] Piezometer installed after 10/14/95.
na[4] Piezometer damaged.

Table 11. Water Level Elevations in Piezometers at ISP site, (elevations are in meters above msl).

Date Collected	ISP-Staff	ISP-0-10	ISP-0-35	ISP-0-60	ISP-0-85	ISP-0-110	ISP-0-1.5	ISP-0.5-70	ISP-0.5-2.0	ISP-1-10	ISP-1-35
8/3/95	285.38	285.35	285.36	285.35	285.36	285.36	285.39	na3	na3	285.38	285.39
8/27/95	285.48	285.45	285.45	285.45	285.47	285.45	285.45	na3	na3	285.45	285.45
9/23/95	na1	285.51	285.51	285.50	285.51	285.51	285.46	284.53	na3	285.51	285.52
10/14/95	285.70	285.68	285.68	285.68	285.68	285.68	285.69	285.70	na3	285.68	285.67
6/6/96	285.79	285.74	285.74	285.75	285.74	285.74	285.79	285.77	285.53	285.74	285.7s4
7/7/96	285.60	285.56	285.55	285.56	285.56	285.56	285.58	285.57	285.34	285.55	285.55
7/23/96	285.80	285.77	285.76	285.77	285.76	285.77	285.78	285.77	285.52	285.77	285.76
7/31/96	285.59	285.55	285.54	285.55	285.55	285.55	285.56	285.56	285.29	285.54	285.54
9/13/96	285.73	285.68	285.69	285.69	na4	na4	na4	285.69	285.42	285.69	285.68

Date Collected	ISP-1-60	ISP-1-85	ISP-1-110	ISP-1-1.5	ISP-2-10	ISP-2-35	ISP-2-60	ISP-2-70	ISP-2-85	ISP-2-110	ISP-2-1.5
8/3/95	285.39	285.39	285.39	285.39	285.37	285.37	285.37	na3	285.39	285.39	285.42
8/27/95	285.45	285.45	285.45	285.72	285.42	285.42	285.44	na3	285.48	285.49	285.50
9/23/95	285.51	285.52	285.51	285.35	285.49	285.50	285.51	na3	285.55	285.54	285.54
10/14/95	285.68	285.68	285.67	285.66	285.66	285.64	285.64	285.11	285.70	285.70	285.71
6/6/96	285.75	285.75	285.74	285.74	dry	dry	dry	dry	285.77	285.78	285.78
7/7/96	285.56	285.56	285.56	285.56	dry	dry	dry	dry	285.59	285.59	285.59
7/23/96	285.77	285.77	285.77	285.77	dry	dry	dry	dry	285.80	285.80	285.81
7/31/96	285.55	285.55	285.55	285.55	dry	dry	dry	dry	285.60	285.59	285.60
9/13/96	285.69	285.68	285.68	285.69	dry	dry	dry	dry	285.72	285.72	285.72

Table 11 (continued)

Date Collected	ISP-4-50	ISP-4-100	ISP-4-1.5	ISP-6.5-WT	ISP-9-50	ISP-9-100	ISP-9-1.5	ISP-14-WT	ISP-14-11
8/3/95	285.38	285.38	284.00	na[3]	285.38	285.38	285.40	285.50	285.46
8/27/95	285.48	285.48	284.15	na[3]	285.49	285.48	285.49	285.52	285.52
9/23/95	285.54	285.54	284.23	na[3]	285.54	285.53	285.54	285.58	285.57
10/14/95	285.70	285.69	284.18	na[3]	285.70	285.69	285.71	285.73	285.73
6/6/96	285.78	285.78	286.63	285.78	285.79	285.78	285.79	285.85	285.87
7/7/96	285.59	285.59	284.83	285.59	285.60	285.59	285.60	285.66	dry
7/23/96	285.81	285.79	284.07	285.80	285.80	285.80	285.80	285.84	dry
7/31/96	285.98	285.23	284.18	285.59	285.60	285.59	285.61	285.66	dry
9/13/96	285.73	285.73	284.44	285.72	285.73	285.71	285.73	285.74	dry

na[1] Water level in stream below staff gage.
na[2] Water level below piezometer screen.
na[3] Piezometer not installed.
na[4] Piezometer damaged.

APPENDIX E

RESULTS OF WATER CHEMISTRY ANALYSES

Table 12. Field and Laboratory Water Chemistry Data

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-surface	8/27/95	5.94	475	7.82		0.576	<0.09	19.4
ISP-0-10	8/27/95		460	6.56		0.502	<0.09	21.0
ISP-0-35	8/27/95		610	7.01		0.348	0.148	20.8
ISP-0-60	8/27/95	not sampled						
ISP-0-85	8/27/95	not sampled						
ISP-0-110	8/27/95	1.33	590	6.76		0.288	<0.09	17.5
ISP-0-1.5	8/27/95	1.49	460	6.80		0.317	<0.09	19.8
ISP-1-10	8/28/95	0.99	610	6.71		0.358	0.173	19.7
ISP-1-35	8/28/95	0.54	610	6.83		0.405	<0.09	18.3
ISP-1-60	8/28/95	not sampled						
ISP-1-85	8/28/95	not sampled						
ISP-1-110	8/28/95	0.56	565	6.93		0.310	<0.09	16.3
ISP-1-1.5	8/28/95	not sampled						
ISP-2-10	8/28/95	not sampled						
ISP-2-35	8/28/95	not sampled						
ISP-2-60	8/28/95	not sampled						
ISP-2-85	8/28/95		540	7.16		0.404	<0.09	16.0
ISP-2-110	8/28/95	0.44	545	7.01		0.368	<0.09	13.9
ISP-2-1.5	8/28/95	0.62	500	7.06		0.390	<0.09	13.6
ISP-4-50	8/28/95	0.47	475	6.77		0.381	<0.09	13.1
ISP-4-100	8/28/95	0.54	430	6.90		0.378	<0.09	11.7
ISP-4-1.5	8/28/95	dry						
ISP-9-50	8/28/95	0.58	360	6.89		0.318	<0.09	11.9
ISP-9-100	8/28/95	0.57	350	6.90				13.3
ISP-9-1.5	8/28/95	0.56	365	7.03		0.331	<0.09	11.2
ISP-14-WT	8/28/95	dry						
ISP-14-11	8/28/95	dry						
HF-surface	8/28/95	7.11	460	7.98		0.592	<0.09	20.8
HF-0-10	8/28/95	not sampled						
HF-0-35	8/28/95	0.47	1040	6.78		0.501	1.410	21.7

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-0-60	8/28/95	0.52	960	6.88		0.443	0.637	20.8
HF-0-85	8/28/95	0.35	770	6.90		0.368	0.434	19.2
HF-0-110	8/28/95	0.45	830	6.90		0.396	0.467	18.6
HF-0-1.5	8/28/95	0.63	615	6.97		0.371	0.265	17.3
HF-1-10	8/28/95	not sampled						
HF-1-35	8/28/95	0.44	1300	6.93				22.8
HF-1-60	8/28/95	not sampled						
HF-1-85	8/28/95	0.61	800	7.01		0.336	0.183	19.5
HF-1-110	8/28/95	0.44	750	6.92		0.372	0.427	20.0
HF-1-1.5	8/28/95	0.62	660	6.91		0.343	0.292	18.8
HF-2-10	8/28/95	not sampled						
HF-2-35	8/28/95	0.45	820	6.97		0.378	<0.09	17.8
HF-2-60	8/28/95	0.48	810	7.03		0.353	<0.09	17.3
HF-2-85	8/28/95	0.53	600	6.95		0.316	0.306	16.6
HF-2-110	8/28/95	0.50	525	7.07		0.275	0.334	15.2
HF-2-1.5	8/28/95	0.56	510	7.08		0.282	0.244	14.0
HF-4-50	8/28/95	0.47	500	7.01		0.282	0.141	14.3
HF-4-100	8/28/95	0.52	485	6.99		0.284	0.140	13.6
HF-4-1.5	8/28/95	not sampled						
HF-9-50	8/28/95		490	7.16		0.273	<0.09	12.3
HF-9-100	8/28/95	0.68	500	7.34				13.1
HF-9-1.5	8/28/95	na	500	7.13		0.287	0.128	11.6
HF-13-WT	8/28/95	na	430	7.18		0.287	<0.09	11.6
HF-13-12	8/28/95	not sampled						
HF-60-WT	8/28/95	0.59	460	7.03		0.270	0.135	11.9
ISP-surface	9/23/95	9.39	385	7.43		0.075	0.128	13.4
ISP-0-10	9/23/95	9.41	395	7.24		0.081	0.181	13.7
ISP-0-35	9/23/95	1.27	490	6.97		0.043	0.616	16.0
ISP-0-60	9/23/95	na						
ISP-0-85	9/23/95	na						
ISP-0-110	9/23/95	0.61	480	6.89		0.043	0.387	14.9
ISP-0-1.5	9/23/95	0.63	395	6.98		0.042	0.643	17.0

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-1-10	9/23/95	0.49	510	6.85		0.043	1.570	15.1
ISP-1-35	9/23/95	0.55	495	6.96		0.042	0.189	13.9
ISP-1-60	9/23/95	na						
ISP-1-85	9/23/95	na						
ISP-1-110	9/23/95	0.65	495	7.17		0.046	0.496	14.1
ISP-1-1.5	9/23/95	na						
ISP-2-10	9/23/95	na						
ISP-2-35	9/23/95	na						
ISP-2-60	9/23/95	na						
ISP-2-85	9/24/95	0.59	460	6.74		0.049	0.193	12.6
ISP-2-110	9/24/95	0.58	450	6.95		0.043	0.236	12.2
ISP-2-1.5	9/24/95	0.57	435	7.05		0.046	0.252	12.2
ISP-4-50	9/24/95	0.54	430	6.92		0.044	0.508	12.8
ISP-4-100	9/24/95	0.54	435	7.05		0.043	0.938	12.5
ISP-4-1.5	9/24/95	dry						
ISP-9-50	9/24/95	0.54	345	7.13		0.042	0.105	11.1
ISP-9-100	9/24/95	0.64	320	7.17		0.041	0.122	10.9
ISP-9-1.5	9/24/95	0.74	340	7.10		0.041	0.081	10.9
ISP-14-WT	9/24/95	0.46	295	6.96				13.2
ISP-14-11	9/24/95	na						
HF-surface	9/24/95	7.77	375	7.71		0.090	0.017	12.6
HF-0-10	9/24/95	not sampled						
HF-0-35	9/24/95	4.67	530	6.85		0.072	1.030	14.0
HF-0-60	9/24/95	0.57	730	6.95		0.052	2.680	14.3
HF-0-85	9/24/95	0.61	550	6.97		0.050	1.970	13.8
HF-0-110	9/24/95	0.58	655	6.94		0.059	1.760	13.5
HF-0-1.5	9/24/95	0.48	540	7.03		0.053	1.330	13.5
HF-1-10	9/24/95	dry						
HF-1-35	9/24/95	0.52	770	7.02		0.068	>10	12.6
HF-1-60	9/24/95	na						
HF-1-85	9/24/95	0.44	620	7.04		0.064	0.714	12.5
HF-1-110	9/24/95	0.47	550	7.00		0.059	1.760	13.3

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-1-1.5	9/24/95	0.57	555	7.00		0.056	1.590	14.2
HF-2-10	9/24/95	na						
HF-2-35	9/24/95	0.80	665	7.02		0.060	0.238	12.1
HF-2-60	9/24/95	0.52	530	6.98		0.055	0.253	12.3
HF-2-85	9/24/95	0.57	490	7.13		0.054	1.120	12.5
HF-2-110	9/24/95	0.53	430	7.07		0.014	1.240	12.2
HF-2-1.5	9/24/95	na						
HF-4-50	9/24/95	0.54	415	6.98		0.014	0.528	12.2
HF-4-100	9/24/95	0.47	415	7.09		0.016	0.452	12.0
HF-4-1.5	9/24/95	dry						
HF-9-50	9/24/95	na	450	7.07		0.014	0.019	11.1
HF-9-100	9/24/95	0.35	420	7.15		0.015	0.419	10.4
HF-9-1.5	9/24/95	dry						
HF-13-WT	9/24/95	0.60	390	7.18		0.017	0.076	10.2
HF-13-12	9/24/95	dry						
HF-60-WT	9/24/95	0.55	440	7.08		0.013	0.579	10.7
ISP-surface	10/14/95	9.78	310	8.18		<0.01	<0.01	9.3
ISP-0-10	10/14/95	9.33	320	8.08		0.016	<0.01	9.3
ISP-0-35	10/14/95	1.63	400	7.17		<0.01	0.095	9.5
ISP-0-60	10/14/95	na						
ISP-0-85	10/14/95	na						
ISP-0-110	10/14/95	0.76	400	7.15		<0.01	0.056	10.1
ISP-0-1.5	10/14/95	0.94	300	7.18		<0.01	0.108	9.6
ISP-0.5-70	10/14/95	0.99	365	7.18		<0.01	0.053	10.4
ISP-1-10	10/14/95	1.10	395	7.07		<0.01	0.305	9.4
ISP-1-35	10/14/95	0.75	400	7.05		<0.01	0.023	10.2
ISP-1-60	10/14/95	na						
ISP-1-85	10/14/95	na						
ISP-1-110	10/14/95	0.71	360	7.11		<0.01	0.073	9.7
ISP-1-1.5	10/14/95	na						
ISP-2-10	10/14/95	na						
ISP-2-35	10/14/95	na						

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-2-60	10/14/95	na						
ISP-2-70	10/14/95	dry						
ISP-2-85	10/14/95	0.88	380	7.10		<0.01	0.479	9.8
ISP-2-110	10/14/95	0.72	380	7.13		<0.01	0.065	9.8
ISP-2-1.5	10/14/95	na	340	7.13		<0.01	0.072	9.5
ISP-4-50	10/15/95	1.09	350	7.25		<0.01	0.016	7.9
ISP-4-100	10/15/95	0.80	395	7.12		<0.01	0.029	10.6
ISP-4-1.5	10/15/95	dry						
ISP-9-50	10/15/95	0.51	315	7.17		<0.01	0.046	9.8
ISP-9-100	10/15/95	0.63	290	7.12		<0.01	0.036	9.8
ISP-9-1.5	10/15/95	0.52	315	7.12		<0.01	0.019	10.7
ISP-14-WT	10/15/95	dry						
ISP-14-11	10/15/95	na	330	7.44		<0.01	<0.01	10.3
HF-surface	10/15/95	9.04	300	7.84		<0.01	<0.01	9.0
HF-0-10	10/15/95	not sampled						
HF-0-35	10/15/95	0.46	580	6.71		<0.01	1.050	10.6
HF-0-60	10/15/95	0.57	575	6.57		<0.01	0.787	11.7
HF-0-85	10/15/95	0.44	460	6.69		<0.01	0.456	11.9
HF-0-110	10/15/95	0.50	545	6.64		<0.01	0.510	11.9
HF-0-1.5	10/15/95	0.45	480	6.72		<0.01	0.353	12.1
HF-1-10	10/15/95	3.46	450	6.88		0.012	0.832	10.9
HF-1-35	10/15/95	0.64	610	6.78		0.012	3.850	11.4
HF-1-60	10/15/95	na				<0.01		
HF-1-85	10/15/95	0.51	560	7.15		<0.01	0.181	11.5
HF-1-110	10/15/95	0.54	455	7.03		<0.01	0.475	11.5
HF-1-1.5	10/15/95	0.55	465	6.94		<0.01	0.428	11.6
HF-2-10	10/15/95	0.65	540	6.97		<0.01	2.220	11.1
HF-2-35	10/15/95	0.52	555	7.05		<0.01	0.045	10.2
HF-2-60	10/15/95	0.49	460	7.09		<0.01	0.052	10.2
HF-2-85	10/15/95	0.56	410	7.33		<0.01	0.269	10.1
HF-2-110	10/15/95	0.46	400	7.19		<0.01	0.305	10.2
HF-2-1.5	10/15/95	0.42	390	7.28		<0.01	0.273	10.2

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-4-50	10/15/95	0.35	380	7.10		<0.01	0.139	10.0
HF-4-100	10/15/95	0.66	370	7.17		<0.01	0.110	10.2
HF-4-1.5	10/15/95	dry						
HF-9-50	10/15/95	0.71	370	7.12		<0.01	<0.01	9.5
HF-9-100	10/15/95	0.73	370	7.18		<0.01	0.108	9.3
HF-9-1.5	10/15/95	dry						
HF-13-WT	10/15/95	1.02	340	7.04		<0.01	<0.01	8.8
HF-13-12	10/15/95	dry						
HF-60-WT	10/15/95	0.78	365	7.11		<0.01	0.127	9.6
ISP-surface	6/9/96	7.08	555	6.78	453	<0.01	<0.01	19.6
ISP-0-10	6/9/96	1.15	750	6.90	275	<0.01	0.045	22.5
ISP-0-35	6/9/96	0.75	655	6.86	89	<0.01	0.378	18.7
ISP-0-60	6/9/96	na	790	6.77	67	<0.01	0.394	29.9
ISP-0-85	6/9/96	0.64	610	6.82	33	<0.01	0.359	16.5
ISP-0-110	6/9/96	na	770	6.78	58	<0.01	0.342	28.8
ISP-0-1.5	6/9/96	na	650	6.80	72	0.013	0.569	28.3
ISP-0.5-70	6/9/96	0.65	630	7.01	30	<0.01	0.323	17.1
ISP-0.5-2.0	6/9/96	0.78	545	6.84	72	<0.01	0.632	20.3
ISP-1-10	6/9/96	0.77	660	6.95	221	<0.01	0.073	19.0
ISP-1-35	6/9/96	0.76	625	6.92	98	<0.01	0.294	18.2
ISP-1-60	6/9/96	0.77	625	7.02	43	<0.01	0.200	15.4
ISP-1-85	6/9/96	0.67	625	7.04	43	<0.01	0.608	19.0
ISP-1-110	6/9/96	dry						
ISP-1-1.5	6/9/96	dry						
ISP-2-10	6/9/96	dry						
ISP-2-35	6/9/96	dry						
ISP-2-60	6/9/96	dry						
ISP-2-70	6/9/96	na	565	6.91	146	<0.01	<0.01	16.8
ISP-2-85	6/9/96	0.88	550	6.96	118	0.220	0.148	13.6
ISP-2-110	6/9/96	0.50	550	7.13	77	0.010	0.187	10.2
ISP-2-1.5	6/9/96	dry						
ISP-4-50	6/9/96	0.82	555	6.97	127	0.081	0.084	11.9

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-4-100	6/9/96	na	530	7.12	65	0.011	0.105	9.2
ISP-4-1.5	6/9/96	0.68	480	7.07	68	0.184	0.124	9.9
ISP-9-50		not sampled						
ISP-9-100		not sampled						
ISP-9-1.5		not sampled						
ISP-14-WT		not sampled						
ISP-14-11		not sampled						
HF-surface	6/8/96	6.47	580	6.29	476	0.010	0.014	22.0
HF-0-10	6/8/96	0.92	820	6.72	438	<0.01	0.235	16.8
HF-0-35	6/8/96	0.72	730	6.89	362	<0.01	0.578	15.2
HF-0-60	6/8/96	0.66	720	6.98	124	<0.01	0.973	15.8
HF-0-85	6/8/96	0.66	720	6.96	63	<0.01	1.113	15.1
HF-0-110	6/8/96	dry						
HF-0-1.5	6/8/96	0.59	730	6.87	70	<0.01	0.934	14.1
HF-0.5-2.0	6/8/96	0.51	750	7.05	66	0.013	0.621	13.5
HF-1-10	6/8/96	0.70	750	6.77	486	0.013	0.065	16.9
HF-1-35	6/8/96	0.55	710	7.00	401	<0.01	0.181	14.1
HF-1-60	6/8/96	0.61	730	6.98	149	<0.01	0.573	15.2
HF-1-85	6/8/96	na	840	6.88	82	<0.01	1.290	23.9
HF-1-110	6/8/96	0.64	710	6.89	86	<0.01	na	16.6
HF-1-1.5	6/8/96	0.68	740	7.01	66	0.011	1.020	15.0
HF-2-10	6/8/96	0.70	1050	6.76	56	<0.01	1.030	19.8
HF-2-35	6/8/96	0.67	830	6.86	109	<0.01	0.479	14.9
HF-2-60	6/8/96	0.67	705	6.99	74	<0.01	0.271	13.0
HF-2-85	6/8/96	0.65	650	7.05	50	0.010	0.783	12.6
HF-2-110	6/8/96	na	640	7.08		<0.01	0.926	9.7
HF-2-1.5	6/8/96	na	680	7.19		0.023	0.821	12.2
HF-4-50	6/8/96	0.97	630	7.05	91	0.013	0.506	11.2
HF-4-100	6/8/96	na	610	7.09		0.010	0.458	11.3
HF-4-1.5	6/8/96	0.98	600	7.10	96	0.020	0.545	10.5
HF-9-50		not sampled						
HF-9-100		not sampled						

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-9-1.5		not sampled						
HF-13-WT		not sampled						
HF-13-12		not sampled						
HF-60-WT		not sampled						
ISP-surface	7/9/96	6.00	530	8.55	272	0.063	<0.01	20.5
ISP-0-10	7/9/96	1.05	640	6.81	142	0.016	<0.01	20.3
ISP-0-35	7/9/96	0.73	615	6.86	70	0.019	0.069	19.3
ISP-0-60	7/9/96	not sampled						
ISP-0-85	7/9/96	0.68	590	6.95	55	0.020	<0.01	17.1
ISP-0-110	7/9/96	na	610	6.91	76	0.027	<0.01	na
ISP-0-1.5	7/9/96	not sampled						
ISP-0.5-70	7/9/96	0.65	570	6.83	44	<0.01	<0.01	15.2
ISP-0.5-2.0	7/9/96	0.56	485	6.99	88	0.011	0.409	18.8
ISP-1-10	7/9/96	1.13	590	6.70	141	<0.01	<0.01	20.0
ISP-1-10 Old	7/9/96	0.87	630	6.60	202	0.010	<0.01	20.7
ISP-1-35	7/9/96	0.63	595	6.78	109	<0.01	<0.01	18.8
ISP-1-60	7/9/96	0.63	595	6.80	56	<0.01	<0.01	17.4
ISP-1-85	7/9/96	0.64	530	6.84	69	<0.01	0.442	16.8
ISP-1-110	7/9/96	na	580	6.95	70	0.014	0.632	18.9
ISP-1-110 Old	7/9/96	0.68	590	6.90	74	0.017	0.065	17.8
ISP-1-1.5	7/9/96	not sampled						
ISP-2-10	7/9/96	not sampled						
ISP-2-35	7/9/96	not sampled						
ISP-2-60	7/9/96	not sampled						
ISP-2-70	7/9/96	not sampled						
ISP-2-85	7/9/96	0.59	570	6.62	114	0.020	<0.01	15.4
ISP-2-110	7/9/96	0.69	550	6.79	100	0.017	<0.01	13.2
ISP-2-1.5	7/9/96	0.74	520	6.75	91	0.027	<0.01	12.6
ISP-4-50	7/9/96	0.98	500	6.71	149	0.022	<0.01	12.7
ISP-4-100	7/9/96	0.78	510	6.66	119	0.017	<0.01	12.2
ISP-4-1.5	7/9/96	na				>2.9	<0.01	
ISP-9-50	7/9/96	0.73	425	6.67	94	0.019	<0.01	12.1

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-9-100	7/9/96	0.94	395	6.75	130			10.6
ISP-9-1.5	7/9/96	0.95	450	7.19	107	0.019	<0.01	13.4
ISP-14-WT	7/9/96	not sampled						
ISP-14-11	7/9/96	not sampled						
HF-surface	7/8/96	6.68	410	8.35	250	0.062	<0.01	18.8
HF-0-10	7/8/96	0.96	550	7.07	109	0.014	0.061	16.6
HF-0-35	7/8/96	0.87	490	7.07	149	0.016	0.170	15.4
HF-0-60	7/8/96	0.60	460	7.10	74	0.016	0.798	14.3
HF-0-85	7/8/96	0.64	620	7.13	69	0.014	0.850	13.4
HF-0-110	7/8/96	not sampled						
HF-0-1.5	7/8/96	0.70	625	7.15	67	0.017	0.677	12.5
HF-0.5-2.0	7/8/96	0.63	620	7.13	83	0.016	0.271	11.5
HF-1-10	7/8/96	0.86	790	6.89	164	0.017	<0.01	15.8
HF-1-35	7/8/96	0.84	640	6.93	181	0.011	<0.01	15.2
HF-1-60	7/8/96	0.70	590	6.97	117	<0.01	0.338	15.2
HF-1-85	7/8/96	na	610	7.06	80	0.010	0.664	15.4
HF-1-110	7/8/96	0.69	590	7.01	85	0.011	0.904	14.4
HF-1-1.5	7/8/96	0.67	620	7.08	78	0.011	0.302	13.9
HF-2-10	7/8/96	0.68	880	6.84	57	<0.01	1.570	17.5
HF-2-35	7/8/96	0.63	900	6.90	84	0.014	0.160	16.8
HF-2-60	7/8/96	0.55	730	6.91	73	<0.01	<0.01	15.9
HF-2-85	7/8/96	0.58	580	7.02	69	<0.01	0.557	13.9
HF-2-110	7/8/96	0.62	555	7.04	84	0.011	0.636	11.1
HF-2-1.5	7/8/96	0.75	590	7.14	94	0.013	0.727	11.6
HF-4-50	7/8/96	0.94	610	7.13	97	0.011	0.127	12.7
HF-4-100	7/8/96	0.59	530	7.10	97	0.013	<0.01	10.9
HF-4-1.5	7/8/96	not sampled						
HF-9-50	7/8/96	not sampled						
HF-9-100	7/8/96	1.44-dry	610	6.90	233	0.086	<0.01	9.8
HF-9-1.5	7/8/96	not sampled	415	7.11	122	0.081	<0.01	9.3
HF-13-WT	7/8/96	1.54 dry	520	7.17	133	0.019	<0.01	8.9
HF-13-12	7/8/96	1.15	465	7.03	182			8.5

Table 12 (continued)

Well number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-60-WT	7/8/96	1.77	390	6.90	233	0.098	<0.01	8.2
ISP-surface	8/1/96	5.30	490	7.08	234	0.020	<0.01	21.7
ISP-0-10	8/1/96	0.52	625	6.77	182	<0.01	<0.01	21.5
ISP-0-35	8/1/96	0.56	625	6.75	119	<0.01	<0.01	20.9
ISP-0-60	8/1/96	not sampled						
ISP-0-85	8/1/96	0.50	590	6.75	94	<0.01	<0.01	18.6
ISP-0-110	8/1/96	not sampled						
ISP-0-1.5	8/1/96	0.66	540	6.84	94	<0.01	0.081	na
ISP-0.5-70	8/1/96	0.55	575	6.78	102	<0.01	<0.01	17.0
ISP-0.5-2.0	8/1/96	0.54	490	6.93	101	0.019	0.108	22.9
ISP-1-10	8/1/96	0.73	620	6.65	153	0.010	<0.01	20.8
ISP-1-10 Old	8/1/96	0.91	600	6.54	181	<0.01	<0.01	21.1
ISP-1-35	8/1/96	0.53	560	6.71	129	<0.01	<0.01	20.6
ISP-1-60	8/1/96	0.57	600	6.83	111	<0.01	<0.01	18.3
ISP-1-85	8/1/96	0.53	560	6.92	93	<0.01	0.170	19.6
ISP-1-110	8/1/96	0.54	540	6.94	86	0.011	0.278	18.9
ISP-1-110 Old	8/1/96	0.55	570	6.89	91	0.011	<0.01	19.1
ISP-1-1.5	8/1/96	not sampled						
ISP-2-10	8/1/96	not sampled						
ISP-2-35	8/1/96	not sampled						
ISP-2-60	8/1/96	not sampled						
ISP-2-70	8/1/96	not sampled						
ISP-2-85	8/1/96	0.74	560	6.86	113	0.011	<0.01	17.0
ISP-2-110	8/1/96	0.61	560	6.94	100	<0.01	<0.01	14.6
ISP-2-1.5	8/1/96	0.73	520	6.94	100	0.013	<0.01	13.8
ISP-4-50	8/1/96	0.71	520	6.91	97	<0.01	<0.01	12.8
ISP-4-100	8/1/96	0.71	500	6.83	116	<0.01	<0.01	13.9
ISP-4-1.5	8/1/96	not sampled						
ISP-9-50	8/1/96	not sampled						
ISP-9-100	8/1/96	not sampled						
ISP-9-1.5	8/1/96	not sampled						
ISP-14-WT	8/1/96	not sampled						

Table 12 (continued)

Well Number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-14-11	8/1/96	not sampled						
HF-surface	8/2/96	7.75	470	7.84	257	0.038	<0.01	21.8
HF-0-10	8/2/96	0.55	660	6.94	189	0.016	0.108	18.8
HF-0-35	8/2/96	0.63	600	6.97	159	0.013	0.017	17.3
HF-0-60	8/2/96	0.57	580	6.97	99	0.013	0.632	16.6
HF-0-85	8/2/96	0.49	570	6.95	90	0.010	0.664	15.9
HF-0-110	8/2/96	not sampled						0.0
HF-0-1.5	8/2/96	0.64	585	7.00	83	<0.01	0.613	15.6
HF-0.5-2.0	8/2/96	0.59	590	7.07	94	<0.01	0.236	14.7
HF-1-10	8/2/96	0.64	755	6.91	133	0.011	0.108	18.5
HF-1-35	8/2/96	0.54	675	6.88	153	0.010	<0.01	17.1
HF-1-60	8/2/96	0.66	570	6.93	135	<0.01	0.170	16.5
HF-1-85	8/2/96	0.54	570	7.01	96	<0.01	0.651	17.5
HF-1-110	8/2/96	0.54	565	6.96	96	<0.01	0.861	16.6
HF-1-1.5	8/2/96	0.56	570	6.97	94	<0.01	0.301	16.2
HF-2-10	8/2/96	0.56	855	6.77	71	<0.01	2.930	20.4
HF-2-35	8/2/96	0.64	830	6.85	87	0.048	<0.01	18.2
HF-2-60	8/2/96	0.56	760	6.84	86	0.019	<0.01	17.0
HF-2-85	8/2/96	0.65	580	6.93	93	0.026	0.297	15.6
HF-2-110	8/2/96	0.60	540	7.03	97	0.025	0.387	13.4
HF-2-1.5	8/2/96	na	575	7.06		0.065	0.108	13.4
HF-4-50	8/2/96	na	565	6.80		0.017	0.039	14.5
HF-4-100	8/2/96	na	530	6.99		0.029	<0.01	13.9
HF-4-1.5	8/2/96	na	550	6.98		0.034	0.141	12.5
HF-9-50	8/2/96	not sampled						
HF-9-100	8/2/96	not sampled						
HF-9-1.5	8/2/96	not sampled						
HF-13-WT	8/2/96	not sampled						
HF-13-12	8/2/96	not sampled						
HF-60-WT	8/2/96	not sampled						
ISP-surface	9/14/96	7.32	510	6.56	251	0.031	0.022	19.6
ISP-0-10	9/14/96	0.61	710	6.55	170	<0.01	0.361	19.5

Table 12 (continued)

Well Number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
ISP-0-35	9/14/96	0.72	760	6.68	163	<0.01	0.151	17.4
ISP-0-60	9/14/96	na	750	6.77	123	<0.01	0.262	na
ISP-0-85	9/14/96	0.57	615	6.87	117	<0.01	0.256	17.8
ISP-0-110	9/14/96	0.65	660	6.93	93	<0.01	0.306	19.4
ISP-0-1.5	9/14/96	0.82	525	6.93	164	<0.01	0.422	na
ISP-0.5-70	9/14/96	0.75	630	6.96	149	<0.01	0.178	17.0
ISP-0.5-2.0	9/14/96	0.41	510	7.03	136	<0.01	0.410	na
ISP-1-10	9/14/96	0.81	700	6.73	149	<0.01	0.105	17.1
ISP-1-10 Old	9/14/96	not sampled						
ISP-1-35	9/14/96	0.70	640	6.79	146	<0.01	0.291	17.3
ISP-1-60	9/14/96	0.40	660	6.87	152	<0.01	0.102	17.0
ISP-1-85	9/14/96	0.72	555	6.96	127	<0.01	0.493	17.1
ISP-1-110	9/14/96	0.85	535	7.14	118	<0.01	0.573	16.1
ISP-1-110 Old	9/14/96	not sampled						
ISP-1-1.5	9/14/96	not sampled						
ISP-2-10	9/14/96	not sampled						
ISP-2-35	9/14/96	not sampled						
ISP-2-60	9/14/96	not sampled						
ISP-2-70	9/14/96	not sampled						
ISP-2-85	9/14/96	0.78	620	6.96	162	<0.01	0.138	14.3
ISP-2-110	9/14/96	0.69	600	7.06	138	<0.01	0.135	13.5
ISP-2-1.5	9/14/96	0.70	590	7.10	132	<0.01	0.173	13.7
ISP-4-50	9/14/96	0.53	560	6.94	200	<0.01	0.062	9.9
ISP-4-100	9/14/96	0.84	560	6.85	171	<0.01	0.044	11.8
ISP-4-1.5	9/14/96	not sampled						
ISP-9-50	9/14/96	0.64	435	6.98	152	<0.01	0.058	10.0
ISP-9-100	9/14/96	0.78	390	7.05	141	<0.01	0.066	10.1
ISP-9-1.5	9/14/96	0.70	425	6.99	156	<0.01	0.054	8.7
ISP-14-WT	9/14/96	not sampled						
ISP-14-11	9/14/96	not sampled						
HF-surface	9/15/96	8.64	500	8.04	142	0.080	<0.0017	16.2
HF-0-10	9/15/96	0.63	830	6.90	168	0.025	0.448	16.5

Table 12 (continued)

Well Number	Date sampled	Dissolved oxygen (mg/L)	Electrical conductivity (µmS/cm)	pH	Eh[1] (mV)	NO_3^- (mg/L N)	NH_4^+ (mg/L NH_3)	Temperature (°C)
HF-0-35	9/15/96	0.54	690	6.91	143	0.017	0.316	16.9
HF-0-60	9/15/96	0.57	680	6.92	141	0.014	0.930	16.5
HF-0-85	9/15/96	0.52	670	6.91	140	0.016	1.020	16.5
HF-0-110	9/15/96	not sampled						
HF-0-1.5	9/15/96	0.54	660	6.94	121	0.017	1.030	15.5
HF-0.5-2.0	9/15/96	0.56	655	6.96	127	0.022	0.532	14.1
HF-1-10	9/15/96	0.69	800	6.86	207	0.023	0.382	15.4
HF-1-35	9/15/96	0.56	740	6.90	191	0.019	0.241	16.1
HF-1-60	9/15/96	0.57	680	6.91	175	0.017	0.516	16.2
HF-1-85	9/15/96	0.76	675	6.98	146	0.013	1.150	16.8
HF-1-110	9/15/96	0.67	620	7.00	135	0.011	1.380	15.7
HF-1-1.5	9/15/96	0.58	620	7.04	162	0.011	0.645	13.3
HF-2-10	9/15/96	2.33	1020	6.86	155	0.019	16.000	14.5
HF-2-35	9/15/96	0.95	780	7.10	119	0.018	0.231	14.0
HF-2-60	9/15/96	0.88	800	6.98	147	0.013	0.216	14.0
HF-2-85	9/15/96	0.81	620	7.06	124	0.014	0.536	13.6
HF-2-110	9/15/96	0.91	570	7.20	116	0.011	0.813	12.1
HF-2-1.5	9/15/96	0.80	620	7.18	120	0.023	0.590	12.0
HF-4-50	9/15/96	0.88	585	7.14	125	0.010	0.316	12.6
HF-4-100	9/15/96	0.90	570	7.16	129	0.014	0.157	12.2
HF-4-1.5	9/15/96	0.93	600	7.19	131	<0.01	0.366	11.6
HF-9-50	9/15/96	na	625	6.62		0.023	0.160	10.2
HF-9-100	9/15/96	0.94	515	6.94	257	<0.01	0.263	9.7
HF-9-1.5	9/15/96	not sampled						
HF-13-WT	9/15/96	0.72	475	7.00	217	<0.01	<0.01	9.3
HF-13-12	9/15/96	not sampled						
HF-60-WT	9/15/96	0.92	480	6.93	208	<0.01	0.225	10.4

Table 13. Ion Concentrations in mg/L from the Stream Channel and Select Wells at Both Study Sites (data from North Dakota from North Dakota Department of Health)

Sample Location	Date Collected	Fe^{2+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-1}	N^2	SO_4^{2-}	Cl^-	F^-	SiO_2	Ion Balance (%)
HF-Surface	8/28/95	0.067	0.198	75.2	22.0	32.0	7.0	282	0.08					
HF-0-35	8/28/95	12.8	11.7	201	56.7	30.4	8.4	978	<0.02					
HF-0-105	8/28/95	11.5	10.9	180	49.8	14.2	4.4	935	<0.02					
HF-1-35	8/28/95	4.58	35.0	243	67.5	41.2	14.1	1000	0.02					
HF-1-105	8/28/95	16.5	5.60	162	41.4	13.5	3.2	839	0.03					
HF-2-35	8/28/95	5.76	6.02	215	52.0	37.2	5.6	887	<0.02					
HF-2-105	8/28/95	2.88	3.86	116	30.3	7.5	2.3	626	<0.02					
HF-9-100	8/28/95	3.90	1.93	121	33.4	7.8	1.9	526	<0.02					
ISP-Surface	8/28/95	0.052	0.773	75.5	23.1	34.2	6.8	265	0.05					
ISP-0-35	8/27/95	2.17	6.05	112	29.3	7.6	3.9	562	0.03					
ISP-0-105	8/27/95	5.73	4.36	106	28.2	6.5	3.3	542	<0.02					
ISP-1-35	8/27/95	12.9	6.49	125	31.8	7.6	2.9	568	<0.02					
ISP-1-105	8/27/95	8.91	5.81	128	33.0	7.2	2.9	562	<0.02					
ISP-2-105	8/27/95	15.9	4.95	128	33.4	7.1	2.5	599	0.02					
ISP-9-100	8/27/95	6.06	1.68	85.2	23.0	3.1	1.0	391	<0.02					
HF-Surface	7/8/96	0.011	0.136	74.4	20.7	26.3	6.2	273	0.18					
HF-0-35	7/8/96	1.07	18.5	137	35.4	6.4	6.7	599	0.06					
HF-0-1.5	7/8/96	5.79	5.41	138	36.1	7.0	2.4	572	0.08					
HF-1-35	7/8/96	0.158	11.4	123	31.7	6.2	2.9	699	0.03					
HF-1-105	7/8/96	5.03	7.29	127	33.1	6.9	3.1	599	0.08					
HF-2-35	7/8/96	7.74	14.4	191	48.1	25.5	5.6	783	0.10					
HF-2-105	7/8/96	6.62	3.62	140	36.5	4.3	2.3	560	0.14					
HF-9-100	7/8/96	3.17	0.959	76.7	19.9	6.2	3.2	339	0.86					

Table 13 (continued)

Sample Location	Date Collected	Fe^{2+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-1}	N[2]	SO_4^{2-}	Cl^{-}	F^{-}	SiO_2	Ion Balance (%)
ISP-0-35	7/9/96	12.8	6.55	112	28.5	2.8	3.0	511	0.03					
ISP-0-105	7/9/96	13.6	4.76	117	30.2	2.9	3.1	476	0.11					
ISP-1-35	7/9/96	11.5	7.58	115	28.9	6.1	3.9	532	0.10					
ISP-1-105	7/9/96	9.86	7.88	106	27.0	1.8	2.4	475	0.11					
ISP-2-105	7/9/96	17.6	5.08	121	30.8	2.8	2.5	518	0.11					
ISP-9-100	7/9/96	11.5	2.08	92.7	24.1	<0.1	1.1	400	0.12					
HF-Surface	9/14/96	0.007	0.258	89.3	25.0	30.2	7.5	305	0.08	88	11.6	0.35	28.8	5.6
HF-0-35	9/14/96	8.15	13.3	149	37.9	5.1	4.2	573	<.02	45	<3.0	0.35	38.4	6.0
HF-0-1.5	9/14/96	10.5	6.05	155	40.0	9.4	3.3	579	<0.02	40	3.7	0.71	46.1	7.3
HF-1-35	9/14/96	12.0	12.2	168	42.9	21.8	4.5	663	<0.02	44	4.5	0.45	36.2	7.5
HF-1-105	9/14/96	12.3	8.03	153	39.6	8.5	3.7	624	<0.02	10	4.3	0.35	50.2	6.7
HF-2-35	9/14/96	17.9	15.4	197	49.0	32.5	5.1	777	<0.02	58	5.4	0.37	35.9	8.1
HF-2-105	9/14/96	10.9	4.27	156	40.5	5.8	3.0	570	<0.02	32	3.1	0.33	47.9	8.5
HF-9-100	9/15/96	9.63	2.10	144	38.6	4.6	3.0	505	0.02	55	<3.0	0.31	37.3	7.9
ISP-Surface	9/15/96	<0.007	0.545	84.7	23.5	30.4	7.4	297	0.07	97	11.4	0.33	30.6	3.1
ISP-0-35	9/15/96	9.00	18.9	171	43.5	8.3	6.1	697	<0.02	25	3.3	0.25	35.1	6.2
ISP-0-110	9/15/96	18.3	5.60	139	35.2	6.6	4.2	529	<0.02	44	3.7	0.24	34.2	6.7
ISP-1-35	9/15/96	24.6	10.2	146	35.8	6.8	4.3	602	<0.02	13	4.5	0.25	39.0	7.3
ISP-1-110	9/15/96	14.9	9.34	131	32.7	3.8	3.4	526	<0.02	9	3.9	0.25	41.8	7.4
ISP-2-110	9/15/96	23.8	5.90	142	35.6	4.4	3.4	531	<0.02	52	4.1	0.25	31.2	6.8
ISP-4-50	9/16/96	30.2	3.90	140	34.9	3.0	2.6	537	<0.02	28	3.0	0.26	32.4	8.7
ISP-9-100	9/16/96	12.3	1.87	95.8	25.2	<0.1	1.2	391	<0.02	9	<3.0	0.24	36.7	5.6

[1]CO_3^{2-} and OH^{-} below detection limits of 1 mg/L

[2]$NO_3^{-} + NO_2$ as N

Table 14. Detection Limits and Standard Errors for Water Chemistry Analysis Performed by the North Dakota Department of Health

Analyte[1]	Detection Limit	Standard Error, %
Na+	0.1	7.5
Mg^{2+}	0.1	9.8
SiO^2	0.02	10.0
K^+	1.0	5.1
Ca^{2+}	0.03	7.2
Mn^{2+}	0.002	6.7
Fe^{2+}	0.007	7.4
F^-	0.01	3.3
Cl^-	3.0	3.9
NH_3-N	0.01	na[2]
pH	na	na
CO_3^{2-}	1.0	na
HCO_3^-	1.0	5.1
OH^-	1.0	na
SO_4^{2-}	3.0	15.0
NO_3+NO_2	0.02	8.1

[1]All analytes are reported in mg/L.
[2]na = not available.

REFERENCES

Arndt, M.B., 1975, Geology of Cavalier and Pembina Counties: North Dakota Geological Survey Bulletin 62, Part I, 68 p.

Bencala, K.E., 1993, A perspective on stream-catchment connections: Journal of the North American Benthological Society, v. 12, no. 1, p. 44–47.

Bencala, K.E., J.H. Duff, J.W. Harvey, A.P. Jackman, and F.J. Triska, 1993, Modelling within the stream-catchment continuum: in A.J. Jakeman, M.B. Beck, and M.J. McAleer (eds), Modelling change in environmental systems: John Wiley and Sons, Ltd., p. 163–187.

Bluemle, J.P., 1991, The face of North Dakota: North Dakota Geological Survey Educational Series 21, 177 p.

Botosaneau, L., (ed.), 1986, Stygofauna Mundi: E.J.Brill, Dr. W. Backhuys,Leiden.

Bouwer, H., and R.C. Rice, 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423–428.

Bouwer, H., 1989, The Bouwer and Rice slug test – An update: Ground Water, v. 27, no. 3, p. 304–309.

Breschta, R.L. and W.L. Jackson, 1979, The intrusion of fine sediments into a stable gravel bed: Journal of the Fisheries Research Board of Canada, v. 36, p. 204–209.

Britton, L.J., and P.E. Greeson, (eds.), 1987, Methods for collection and analysis of aquatic biological and microbiological samples: Techniques of Water Resources Investigations of the United States Geologial Survey, Book 5, Chapter A4.

Castro, N.M., and G.M. Hornberger, 1991, Surface–subsurface water interactions in an alluviated mountain stream channel: Water Resources Research, v. 27, no. 7, p. 1613–1621.

Chappuis, P.A., 1942, Eine neue methode zur untersuchung der grundwasserfuana: Acta Sc. Math. Nat. Univ. Franzisco-Josephina, v. 6, p. 1–7.

Danielopol, D.L., 1976, The distribution of the fauna in the interstitial habitats of riverine sediments of the Danube and the Pisting (Austria): International Journal of Speleology, v. 8, p. 23–51.

Danielopol, D.L., 1980, The role of limnologists in groundwater studies: Internationale Revue der Gesamten Hydrobiologie, v. 65, p. 777–791.

Dodson, S.I., and D.G. Frey, 1991, Cladocera and other Branchiopoda: in J.H. Thorp and A. P Covich (eds.), Ecology and Classification of North American freshwater invertebrates: Academic Press, San Diego, California, p. 723–786.

Dole-Olivier, M.J., P. Marmonier, M. Creuze des Chatelliers, and D. Martin, 1994, Interstitial fauna associated with the alluvial floodplains of the Rhone River (France): in J. Gibert, D.L. Danielopol, and J.A. Stanford (eds.), Groundwater Ecology: Academic Press, San Diego, California, p. 287–305.

Drever, J.I., 1988, The Geochemistry of Natural Waters: Prentice Hall, Englewood Cliffs, New Jersey, p. 309–314.

Duff, J.H., F. J. Triska, A.P. Jackman, and J.W. LaBaugh, 1997, The influence of streambed sediments on the solute chemistry of ground-water discharge in the upper Shingobee River: USGS Water Resources Investigation Report 96-4215, p. 143–147.

Edmondson, W.T., (ed.), 1959, Ward and Whipple's Fresh-water biology: Wiley, New York, 1248 p.

Gibert, J., J.A. Stanford, M.J. Dole-Olivier, and J.V. Ward, 1994, Basic attributes of groundwater ecosystems and prospects for research: in J. Gibert, D. L. Danielopol, and J.A. Stanford (eds.), Groundwater Ecology: Academic Press, p. 8–33.

Gibert, J., P. Marmonier, V. Vanek, and S. Plenet, 1995, Hydrological exchange and sediment characteristics in a river bank: relationships between heavy metals and invertebrate community structure: Canadian Journal of Fisheries and Aquatic Sciences, v. 52, no. 10, p. 2084–2097.

Godbout, L., and H.B.N. Hynes, 1982, The three dimensional distribution of the fauna in a single riffle in a stream on Ontario: Hydrobiologia, 97, p. 87–96.

Grimm, N.B. and S.G. Fisher, 1984, Exchange between surface and interstitial water: implications for stream metabolism and nutrient cycling: Hydrobiologia, v. 111, p. 219–228.

Harkness, R.E. , N.D. Haffield, W.R. Berkas, S.W. Norbeck, and M.L. Strobel, 1995, Water resources data North Dakota water year 1995: U.S. Geological Survey Water-Data Report ND-95-1, p. 154–155.

Harkness, R.E., W.R. Berkas, and S.W. Norbeck, 1996, Water resources data North Dakota water year 1996 volume 1 surface water: U.S. Geological Survey Water-Data Report ND-96-1, p. 132–133.

Harvey, J.W., and K.E. Bencala, 1993, The effect of streambed topography on surface–subsurface water exchange in mountain catchments: Water Resources Research, v. 29, p. 89–98.

Harvey, J.W., B.J. Wagner, and K.E. Bencala, 1996, Evaluating the reliability of the stream tracer approach to characterize stream–subsurface water exchange: Water Resources Research, v. 32, no. 8, p. 2441–2451.

Hendricks, S.P., and D.S. White, 1991, Physicochemical patterns within a hyporheic zone of a northern Michigan river, with comments on surface water patterns: Canadian Journal of Fisheries and Aquatic Science, v. 48, p. 1645–1654.

Hilsenhoff, W.L., 1991, Diversity and classification of insects and Colembola: in J.H. Thorp and A. P Covich (eds.), Ecology and Classification of North American Freshwater Invertebrates: Academic Press, San Diego, California, p. 593–653.

Husmann, S., 1971, Ecological studies on freshwater meiobenthon in layers of sand and gravel: Smithsonian Contributions to Zoology, v. 76, p. 161–169.

Hynes, H.B.N., 1983, Groundwater and stream ecology: Hydrobiologia, v. 100, p. 93-99.

Jackman, A.P., F.J. Triska, and J.H. Duff, 1997, Hydrologic examination of ground–water discharge into the upper Shingobee River: U.S. Geological Survey Water Resources Investigation Report 96-4215, p. 137–142.

Korom, S.F., 1992, Natural denitrification in the saturated zone: A review: Water Resources Research, v. 28, no. 6, p. 1657–1668.

Malard, F., S. Plenet, and J. Gilbert, 1996, The use of invertebrates in ground water monitoring: A rising research field: Ground Water Monitoring and Remediation, Spring, p. 103–113.

McPherson, L., 1995, Correlating conductivity to ppm of total dissolved solids: WATER/Engineering & Management, p. 31–33.

Metzler, G. M., and L.A. Smock, 1990, Storage and dynamics of subsurface detritus in a sand-bottomed stream: Canadian Journal of Fisheries and Aquatic Sciences, v. 47, p. 588–594.

Moring, J.R., 1982, Decrease in stream gravel permeability after clear-cut logging: an indication of intragravel conditions for developing salmonid eggs and alevins: Hydrobiologia, v. 88, p. 295–298.

Morrice, J.A., H.M. Valett, C.N. Dahm, and M.E. Campana, 1997, Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams: Hydrological Processes, v. 11, p. 253–267.

Newbold, J.D., J.W. Elwood, R.V. O'Neill, and W. Van Winkle, 1981, Measuring nutrient spiralling in streams: Canadian Journal of Fisheries and Aquatic Sciences, v. 38, p. 860–863.

Notenboom, J., S. Plenet, and M.-J. Turquin, 1994, Groundwater contamination and its impact on groundwater animals and ecosystems: in J. Simons and J.A. Stanford (eds.), First International Conference on Ground Water Ecology: American Water Resources Association, p. 477–504.

Palmer, M.A., and C.C. Hakenkamp, 1992, Problems associated with quantative sampling of shallow groundwater invertebrates: in J. Simons and J.A. Stanford (eds.), First International Conference on Ground Water Ecology: American Water Resources Association, p. 101–109.

Patch, J.C., and G. Padmanabhan, 1994, Investigation of vertical nitrate gradients in a shallow unconfined aquifer in North Dakota: North Dakota State Water Commission Water Resources Investigation 31, p. 25–28.

Peterjohn, W.T., and D.L. Correll., 1984, Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest: Ecology, v. 65, p. 1466–1475.

Pennak, R.W., 1989, Fresh-water invertebrates of the United States: Protozoa to Mollusca, 3rd edition: Wiley, New York, 769 p.

Pennak, R. W. and J. V. Ward, 1986, Interstitial faunal communities of the hyporheic and adjacent groundwater biotopes of a Colorado mountain stream: Archiv fur Hydrobiologie, Supplementband, v. 74, no. 3, p. 356–396.

Perkins, R.L., 1977, The late Cenozoic geology of west-central Minnesota from Moorhead to Park Rapids: Master's Thesis, University of North Dakota, Grand Forks, 99 p.

Pinay, G., and H. Decamps. 1988, The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface water: a conceptual model: Regulated Rivers, v. 2, p. 507–516.

Plenet, S., P. Marmonier, J. Gibert, J.A. Stanford, A.M. Bodergat, and C.M. Schmidt, 1992, Groundwater hazard evaluation: A perspective for the use of interstitial and benthic invertebrates as sentinals of aquifer mettallic pollution: in J. Simons and J.A. Stanford (eds.), First International Conference on Ground Water Ecology: American Water Resources Association, p. 319–329.

Reid, J.W., National Museum of Natural History: Smithsonian Institution. Personal communication, April 1997.

Rosgen, D.L., 1994, A classification of natural rivers: Catena, v. 22, p. 169–199.

Royse, C.F., Jr., 1970, An introduction to sediment analysis: Arizona State University, p. 7–19.

Sassuchin, D.N., N.M. Kabanov, and K. Neiswestnova-Shadina, 1927, Uber die mikroskopische Pflanzen-und Tierwelt der Sandflache des Okaufers bei Murom: Russische Hydrobiologische Zeitschrift Saratow, v. 6, p. 59–83.

Schwoerbel, J., 1961, Uber die Lebensbedingungen und die Besiedlung des hyporheischen Lebensraumes: Archiv fur Hydrobiologie Supplement, v. 25, p. 182–214.

Schlosser, I.J., and J.R., Karr. 1981, Water quality in agricultural watersheds: impact of riparian vegetation during base flow: Water Resources Bulletin, v. 17, p. 233–240.

Stanford, J.A., and A.R. Gaufin, 1974, Hyporheic communities of two Montana rivers: Science, v. 185, p. 700–702.

Strayer, D.L., 1994, Limits to biological distributions in groundwater: in J. Gibert, D.L. Danielopol, and J. A. Stanford (eds.), Groundwater ecology: Academic Press, San Diego, California, p. 287–305.

Stream Solute Workshop, 1990, Concepts and methods for assessment of solute dynamics in stream ecosystems: Journal of the North American Benthological Society, v. 9, no. 2, p. 95–119.

Thompson, K.W., and R. L. Hetzler, 1977, Soil Survey of Pembina County, North Dakota: United States Department of Agriculture, Soil Conservation Service, 117 p.

Thorp, J.H., and A.P. Covich, (eds.), 1991, Ecology and classification of North American freshwater invertebrates: Academic Press, New York, 911 p.

Tiedje, J.M., A.J. Sexstone, D.D. Myrold, and J.A. Robinson, 1982, Denitrification: ecological niches, competition and survival: Antonie van Leeuwenhoek, v. 48, no. 6, p. 569–583.

Triska, F.J., V.C. Kennedy, R.J. Avanzino, G.W. Zellweger, and K.E. Bencala, 1989a, Retention and transport of nutrients in a third-order stream: channel processes: Ecology, v. 70, p. 1877–1892.

Triska, F.J., V.C. Kennedy, R.J. Avanzino, G.W. Zellweger, and K.E. Bencala, 1989b, Retention and transport of nutrients in a third-order stream in northwestern California: hyporheic processes: Ecology, v. 70, p. 1893–1905.

Triska, F.J., J.H. Duff, and R.J. Avanzino, 1990, Influence of exchange flow between the channel and hyporheic zone on nitrate production in a small mountain stream: Canadian Journal of Fisheries and Aquatic Sciences, v. 47, p. 2099–2111.

Triska, F.J. , J.H. Duff, and R.J. Avanzino, 1993a, The role of water exchange between a stream channel and its hyporheic zone in nitrogen cycling at the terrestrial–aquatic interface: Hydrobiologia, v. 251, p. 167–184.

Triska, F.J., J.H. Duff, and R.J. Avanzino, 1993b, Patterns of hydrological exchange and nutrient transformation in the hyporheic zone of a gravel-bottom stream: examining terrestrial–aquatic linkages: Freshwater Biology, v. 29, p. 259–274.

Triska, F.J., and J.H. Duff, 1997, Sediment-associated nitrification and denitrification potentials at the interface between a bankside ground-water seep and the channel of Shingobee River: U.S. Geological Survey Water Resources Investigation Report 96-4215, p. 155–160.

Vallet, H.M., S.G. Fisher, E.H. Stanley, 1990, Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream: Journal of the North American Benthological Society, v. 9, p. 201–215.

Vallet, H.M., C.C. Hakenkamp, and A.J. Boulton, 1993, Perspectives on the hyporheic zone: integrating hydrology and biology. Introduction: Journal of the North American Benthological Society, v. 12, no. 1, p. 40–43.

Wallace, R.L. and T.W. Snell, 1991, Rotifera: in J.H. Thorp and A.P Covich (eds.), Ecology and classification of North American freshwater invertebrates: Academic Press, San Diego, California, p. 187–240.

Ward, J.V., N.J. Voelz, and P. Marmonier, 1992, Groundwater faunas at riverine sites receiving treated sewage effluent: in Proceedings of the First International Conference on Groundwater Ecology: American Water Resources Association, p. 351–364.

Ward, J.V., 1989, The four dimensional nature of lotic ecosystems: Journal of the North American Benthological Society, v. 8, p. 2–8.

White, D.S., C.H. Elzinga, and S.L. Fortner, 1987, Temperature patterns within the hyporheic zone of a northern Michigan river: Journal of the North American Benthological Society, v. 6, no. 2, p. 85–91.

White, D.S., 1990, Biological relationships to convective flow patterns within streambeds: Hydrobiologia, v. 196, p. 148–159.

White, D.S., 1993, Perspectives on defining and delineating hyporheic zones: Journal of the North American Benthological Society, v. 12, no. 1, p. 61–69.

Williams, D.D., 1989, Towards a biological and chemical definition of the hyporheic zone in two Canadian rivers: Freshwater Biology, v. 22, p. 189–208.

Williams, D.D., 1993, Nutrient and flow vector dynamics at the hyporheic/groundwater interface and their effects on the interstitial fauna: Hydrobiologia, v. 251, p. 185–198.

Williams, D.D. and H.B.N. Hynes, 1974, The occurrence of benthos deep in the substratum of a stream: Freshwater Biology, v. 4, p. 233–256.