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Biological Indicators of Ground Water - Surface Water Interaction: Update

Biological Indicators of Ground Water-Surface Water Interaction: An Update

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TABLE OF CONTENTS

Biological Indicators of Ground Water-Surface Water Interaction: An Update

I. Introduction

Ground water contributes approximately 40 percent of the surface water discharge in river systems of the United States (U.S. Geological Survey 1988). A growing volume of evidence indicates that contaminants contained within this ground water discharge can have a significant impact on surface water quality. As a result, the U.S. Environmental Protection Agency (EPA) has documented a series of methods for quantifying the local extent and quality of contaminated ground water discharge (EPA 1991). Until recently these assessment methods consisted primarily of hydrologic and physicochemical techniques to determine ground water flux and pollutant load to surface water. This chapter documents a new body of research that is focusing on the use of organisms that spend all or part of their life cycle living in contact with ground water, to characterize zones of ground water and surface water interaction (the hyporheic zone). This new research is also exploring methods to provide qualitative estimates of the ground water pollutant load impact on these organisms, as an indicator of impacts on surface water quality. In the approach presented in this document, the hyporheic zone is defined by the presence of a particular suite of indicator organisms that can be withdrawn by wells; these organisms spend part of their life cycle in surface water and part in ground water. This document describes techniques for determining the presence of these micro-organisms.

There are other approaches for defining the hyporheic zone, based on physical parameters; the boundary may be defined by the extent of the penetration of surface water into ground water as indicated by physical-parameter values in the ground water that are similar to the values in the surface water. The boundary of the zone can vary with the parameter used to define it. The size of the hyporheic zone can vary seasonally and in response to drought. Research has not determined how rapidly hyporheic-zone organisms spread following the episodes of extensive surface-water intrusion into ground water that result from periods of flooding, or how rapidly the extent of the zone varies seasonally or in response to drought..

Organisms are found at great depths beneath the land surface. In karst regions, microbes and invertebrates can be found in caves and other openings at 100 meters or more beneath the earth’s surface. Bacteria exist in ground water thousands of feet below the land surface (Frederickson, et al 1991). However, invertebrates are typically found within 1 to 10 meters of the earth’s surface in consolidated materials (Strayer 1994). Within this shallow ground water zone, many macroscopic invertebrates have been identified. Furthermore, the species richness and community structure of these organisms has been shown to change with alterations in ground water quality. Therefore, the relative presence or absence of different communities or populations of organisms may reflect the impact of changes in regional ground water quality. As a result, the organisms living within the shallow ground water zone can serve as indicators of the quality of the ground water resource (Job and Simons 1994).

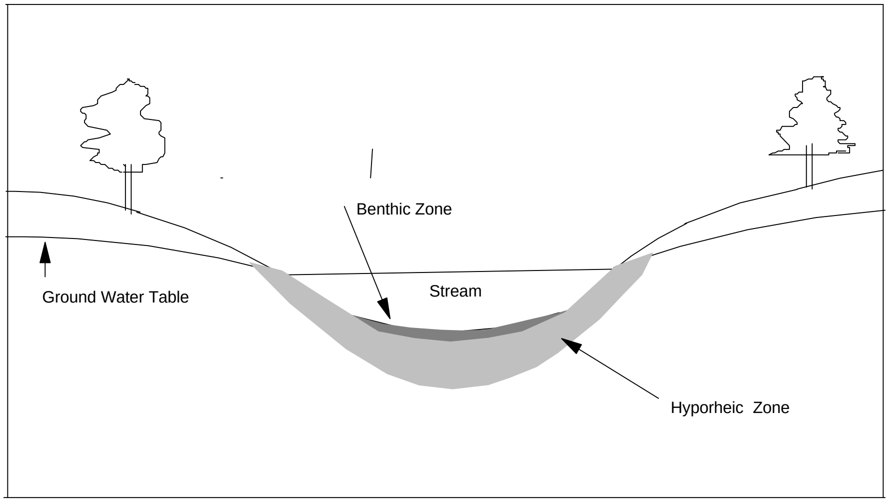

Figure 1 Hyporheic Zone

The hyporheic zone exists below, and is laterally linked to, lakes and streams and defines the area of ground water-surface water interaction (Figure 1). Within the hyporheic zone, biological community structure varies with depth or distance from the surface water body. Invertebrate, protozoa, and bacteria population densities appear to decline with depth (Strayer 1994), although high bacteria populations may be observed at great depths. Invertebrate and protozoa species richness and community structure also change with depth. Invertebrate communities within the hyporheic zone include a mixture of species that spend part of their life cycle in surface waters and a few specialized ground water species (Bretschko 1992). The ground water dwelling organisms decrease in relative abundance with depth. These generalized species distributions may alter along preferential ground-water flowpaths, such as those found in karst terrain (Strayer 1994).

Macroinvertebrates living in the hyporheic zone, such as oligochaetes, isopods, and ostracods, have evolved special adaptations to survive in a food-, oxygen-, space-, and light-limited environment. Studies of these environments have been designed to determine the structure and interactions of organisms within the hyporheic community. In fact, many hyporheic organisms have yet to be identified. However, general ecological assumptions regarding species diversity and abundance may be applied and assist in the evaluation of the hyporheic zone.

This chapter investigates the use of biological indicators as a tool to evaluate the interaction of ground water and surface water. Section II of this chapter provides background information on biological indicators related to ground water and surface water interaction. Section III provides a discussion of several hyporheic zone organism sample collection and study methods. Section IV discusses various study settings and contaminants. Finally, Section V provides a general evaluation of the use of biological indicators as a tool in the evaluation of ground water and surface water interaction.

II. Background

For many years, researchers have used planktonic, macroinvertebrate, and fish communities as indicators of pollution in both freshwater and marine environments. For example, an increase in abundance of benthic oligochaetes may indicate sewage pollution of a surface water body. Such biological indicators can highlight the water quality impact resulting from pollutant load from a variety of sources, including tributary discharge, upgradient point sources, atmospheric deposition, or ground water discharge.

Biological monitoring is typically conducted as part of an integrated assessment strategy, comparing biological measures of species, population, or community structure with measures of water quality. Rapid bioassessment protocols have been employed in surface water programs since the mid-1980s to assess the impact of multiple contaminants within aquatic ecosystems (EPA 1996). These protocols are designed to assess how multiple contaminants affect living systems over time, even when the concentration of any one contaminant in the system may be below detection limits. By comparing the biological and water quality characteristics of reference areas against the characteristics of impacted areas, the predictive power of the empirical relationship is enhanced. Once the relationship between water quality and biological characteristics is understood, water quality impacts can be objectively discriminated from habitat effects, and control and rehabilitation efforts can be focused on the most important source of impairment. This same rationale can be applied to the analysis of hyporheic organisms as indicators of water quality. It is important, however, to consider if a biological change is the result of hydrologic factors, rather than the result of contamination.

Hyporheic organisms provide an indicator of the impact of contaminated ground water discharge. If polluted ground water is flowing into surface water, it is reasonable to predict that organisms within the hyporheic zone will show the effects of pollution before organisms dwelling within the water column. As a result, changes in hyporheic organisms and communities can serve as early indicators of pollutants entering surface water through ground water discharge.

The hyporheic zone is the primary focus for the use of biological indicators to assess contaminant load from ground water discharge. Generally, the hyporheic zone may extend several meters below the stream bottom and a few meters horizontally on the stream banks (Bretschko 1992). In some cases, the hyporheic zone may extend over much larger areas. Stanford and others (1994) have concluded that based on diverse and abundant macroinvertebrate fauna, in some cases the hyporheic zone may extend over large areas of alluvial floodplains.

While some overlap of species between the top 10 to 15 cm of substrate (benthic zone) and hyporheic zone exists, researchers have discovered organisms that live only in the hyporheic zone. In fact, investigators use these organisms to delineate the extent of the hyporheic zone and examine ground water and surface water interaction. For example, Lafont and others (1992) found that the oligchaete worm *Phallodrilus sp.* appeared to be a good indicator of the magnitude of exchange between a river and an adjacent aquifer. Furthermore, investigators can assess the impact of pollutant load to the hyporheic zone by studying changes in relative community structure and species populations. For example, the hyporheic zone is typically food and oxygen limited. Sewage pollution increases available nutrients and may lead to the appearance and dominance of epigean species (species that live near the ground surface) within the hyporheic zone.

Organisms living in karst channels or subterranean caves, or those that spend only a portion of their life cycle in the subsurface, can also indicate the presence of contaminated ground water. Physiological changes within hyporheic organisms and changes in population distribution may suggest the presence of a certain type of pollutant, such as nutrients, pesticides, or metals. For example, ecotoxicological study methods examine the effects of acute or chronic pollutant exposure on hyporheic organisms. Study methods are also being developed that examine changes in population characteristics to determine ground water and surface water exchange and the impacts of pollutants. For example, Malard and others (1996) divided cave-dwelling organisms into three ecological categories: stygobites, stygophiles, and stygoxenes. Stygobites live their whole lives in ground water, stygophiles live primarily in ground water but may also live in surface water, and stygoxenes are epigean organisms that do not develop properly when found in ground water. Ward and Stanford (1989) divided ground water organisms of alluvial aquifers into two groups, those that temporarily move from the stream floor to the subsurface, such as insect larvae, and those that live permanently below the surface and are rarely found on the stream floor, such as choronimids and amphipods. Observed changes in hyporheic community structure may serve as an indicator of pollutant load. However, little is known about the variety of organisms residing in this ecosystem and most studies are still attempting to determine the structure and distribution of the hyporheic community. Changes in community structure may also reflect a change in other factors, such as short- or long-term precipitation patterns or amounts, which can alter the near-stream hydraulic gradient (the slope and direction of the water table).

III. Sampling Methods

In the last ten years, a relatively small number of researchers has been responsible for much of the published literature addressing the use of biological indicators in the hyporheic zone. New biological-indicator methods are under constant development. Each of the methods described below is designed to collect organisms living within a portion of the hyporheic zone. Most studies completed to date use the Bou-Rouch sampler (Bou and Rouch, 1967), but there are variations on this method, including the colonization corer and freeze corer. In addition, investigators have recently developed a new method for sampling ground water organisms in karst aquifers. The following discussions present a description of several sampling methods and associated assumptions and limitations.

Bou-Rouch

The Bou-Rouch sampler consists of a calibrated pipe, called a standpipe, about 1.5 meter (m) long and 2.5 centimeters (cm) in diameter. A steel cone seals the bottom of the standpipe; its shape assists insertion into sediment. Ten centimeters from the steel cone there is a 15 cm perforated screen section with 5 millimeter (mm) diameter holes. This screen section allows entry of animals and sediment into the standpipe. Investigators drive the standpipe into the sediment with a 2 kilogram (kg) weight. When collecting samples from streambank alluvium, a hole can be dug to the water table before insertion of the pipe to reduce the chance of collecting non-hyporheic organisms (Ward et al 1989). After standpipe insertion, the investigator removes the weight and fits a pump to the top of the pipe. The pump pulls water, organisms, and sediment into the standpipe through the screen section. The water, organisms, and sediment travel up the standpipe and eventually through a 1-mm mesh sieve and silk plankton net. Dole-Olivier and Marmonier (1992), who were studying the effects of storms on the vertical distribution of organisms, left permanent standpipes in place over a 15 month period and sampled from them at given intervals after storms.

Assumptions and limitations

The Bou-Rouch standpipe has only a small portion of its length (10-15 cm) open to the interstitial (between-grain) environment. It can collect organisms only at the depth to which the investigator places the open segment. This makes it useful for comparing organisms found at a specific depth across a transect, but not for determining the vertical distribution of organisms at one site. In order to obtain vertical distributions of species, the investigator must insert the standpipe into the sediment several times at one site, to a different depth each time.

The Bou-Rouch method may result in inaccuracies in the number of animals depending on the size of the corer used. Small standpipes (25 cubic cm) may collect a smaller proportion of large sediment particles with which large animals are associated. Likewise, large standpipes (100 cubic cm) may collect a larger proportion of large particles and the large organisms associated with them.

Freezing Core

The freezing core method (Stocker and Williams 1972) uses a standpipe similar to that of the Bou-Rouch method, except the screen section covers the last 60 cm of the standpipe rather than the last 15 cm. The investigator inserts the standpipe into the sediment by pounding with a sleeve that fits over the pipe. After insertion, the investigator removes the sleeve and releases liquid nitrogen into the standpipe tubing. The investigator removes the standpipe tubing after the liquid nitrogen flows for 15 minutes. At the bottom of the standpipe, the nitrogen passes through the holes in the pipe and freezes everything within a 10 cm radius of a 30 cm length of the pipe. The investigator uses a winch to remove the standpipe from the sediment. Application of ice will preserve the core for several weeks. For processing, the investigator cuts the standpipe into

10 cm sections and removes the core from the standpipe with a knife. Subsequent processing of the sections involves melting, drying, and sieving. Researchers are experimenting with a variation of this method that introduces electricity to paralyze the organisms before the liquid nitrogen application.

Assumptions and limitations

The freezing core method is most useful for its preservation of animals and sediment in situ. It also preserves the vertical distribution for depths up to a 30 cm. However, fewer animals can be obtained with this method as compared to other methods. This reduction in sampling efficiency may result from the ability of mobile animals to escape from the cold before freezing occurs. The variation of the freezing core method that introduces electricity into the corer to paralyze or "electroposition" the organisms before the liquid nitrogen application may increase efficiency. This "electropositioning" may eliminate the escape of organisms and therefore, increase the number of organisms captured.

Air-lift

Malard and others (1994) developed the air-lift method for karst aquifers. Previously, investigators could only collect samples from springs or caves when floods washed the organisms into a collection device. However, organisms live throughout karst systems in fractures or other areas not accessible to humans. The air-lift system enables sample collection from these areas. Air-lift pumps are useful for sampling fauna because they contain no parts that can damage the organisms. In addition, air-lift pumps install easily into observation wells. However, they are not for use in production wells, since production wells alter the hydrology and thus, the ecology of the sampled area.

Air-lift pumps (Figure 2) force compressed air to the bottom of a well through a small diameter air injection pipe. At the bottom of the well, the air injection pipe feeds into a ground water discharge pipe. Inside the discharge pipe, the air mixes with the water producing a mixture with a relative density that is lower than that of the water in the well. This air-water mixture rises up the discharge pipe to the ground surface, carrying fauna with it. At ground surface, the air-water mixture containing the ground water fauna passes through a mesh collection filter.

For effective operation, investigators must balance the relationship between the densities of the well water and the air-water mixture. Theoretically, one could compensate for a low water level or a deep well by increasing the rate of air injection, thereby decreasing the density of the air and water mix. In practice, at high injection rates, the air and water do not mix at all, and the air rises by itself. In addition, the diameter of the discharge pipe and specific type of air injection equipment are critical factors of effective air-lift method operation.

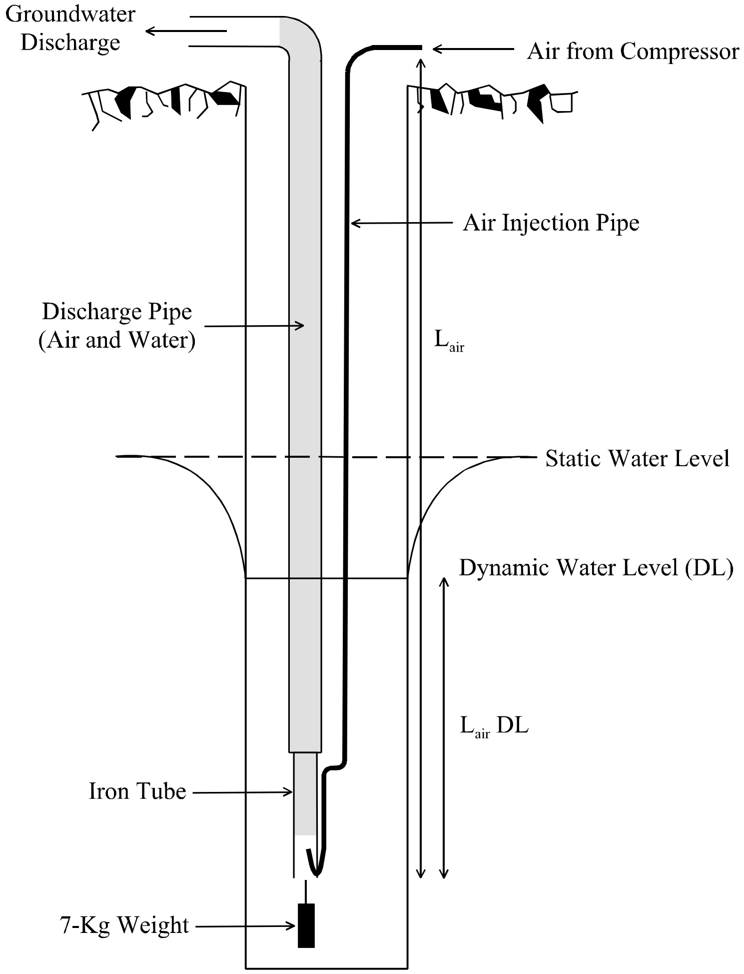

Figure 2 Design of the air-lift used for sampling groundwater invertebrates in deep wells (Malard and others 1994).

Ward and Stanford (1989) used a similar method in an alluvial aquifer. Their method differed from the air-lift method in that they pumped water directly, without the use of compressed air. They lowered a tube into the 10 m deep wells and used a gasoline engine pump to collect samples.

Assumptions and limitations

The air-lift method is still in the early stages of development, however it appears quite useful. It is difficult to examine sampling consistency with this method, because the sampling environment, fractured rock, is highly irregular. Fractures may vary greatly in size and distribution.

Colonization Corer

Fraser and others (1996) developed a colonization corer that is a combination of a fauna sampler and a hydrologic sampler. It allows hyporheic organisms to colonize artificial substrate. Similarly, investigators have widely employed the use of an artificial substrate for sample collection of benthic organisms. The colonization corer consists of an internal acrylic tube 160 cm long and 3.2 cm in diameter that contains an artificial substrate. Typically, the artificial substrate is sediment with a vertical particle distribution matching that of the stream bed. The tube consists of five sections with a distance between each section of 20 cm. Each section contains 100 5-mm diameter holes. This tube fits inside an outer 4.2 cm diameter steel pipe. The outer steel pipe has the same perforation configuration as the inserted acrylic tube. Therefore, organisms can enter the corer through the holes and colonize the artificial substrate in the acrylic tube. Protective steel caps seal the bottom and top of the colonization corer.

Attached to the outer pipe are five, 1.3 cm diameter steel pipes that provide access for water collection and water level readings. Each of these small diameter pipes has two rows of 0.2 cm diameter holes 55, 75, 95, 115, or 135 cm from the top of the pipe. To determine depth of water collection and obtain water level readings, the investigator seals the small diameter pipes below the desired row of holes or depth. The colonization corer is left in place for at least nine weeks to allow fauna and organic matter to infiltrate to levels found in the natural environment. The investigator pulls the tubes from the sediment with a winch and wraps the tube in plastic to keep organisms from falling out. The investigator then cuts the inner acrylic tube into the 20 cm sections and places the contents in plastic jars with preservative and stain.

Essafi and others (1992) also used an artificial substrate to retrieve *Niphargus rhenorhodanensis*. They used a perforated pipe 10 cm in diameter and 50 cm long. The artificial substrate was five stacked 6 mm mesh baskets containing clean, dry, local sediments. The artificial substrate was left in place for one month.

Assumptions and limitations

The colonization corer obtained accurate results compared to the freezing core and standpipe methods. It assumes, though, that the distribution of animals colonizing the corer is the same as that in the sediment of the hyporheic zone, and that the artificial substrate correctly approximates the real substrate. This method is more time consuming, because colonization requires several weeks.

IV. Study Methods

The literature review (summarized in Table 2) completed for this chapter, identified two general types of hyporheic-organism studies. The first is the community approach, in which researchers determine abundance, location, and richness of species. The second is the ecotoxicological approach, in which researchers expose organisms to specific pollutants, usually in the laboratory, to determine lethal and sub-lethal doses which can then be extrapolated to the field. The following discussion focuses on the community and the ecotoxicological approaches.

Community Approach

As previously stated, the community approach determines species abundance, location, and richness. Species distribution in the hyporheic zone may indicate the direction and magnitude of exchange between ground water and surface water. Pollutant presence in the hyporheic zone can alter abundance, distribution, and diversity of hyporheic organisms. Investigations in polluted aquifers or streams determine changes in hyporheic ecology with distance from the pollution source, or note differences between generally polluted sites and unpolluted sites.

While some studies simply display raw data such as the number of species and number of organisms in each sample, many studies use statistics to determine patterns in organism distribution, accuracy of sampling methods, correlation with physical and chemical parameters, etc. Methods used include Analysis of Variance (ANOVA), Non Centered Principal Component Analysis, and Range Correlation. In addition, researchers use the following statistical software; ADECO, TWINSPAN (community classification), STATISTIX, and DECORANA (ordination).

The community approach is heavily dependent on prior knowledge of unimpacted hyporheic zone community structure. Because little is known about the organisms of this ecosystem, most studies are still attempting to determine the structure and distribution of the hyporheic community in order to provide a background for future studies on organisms as pollution indicators. Background or “ambient” community structure characteristics are difficult to define. When the general assumption is made that relatively low species diversity and perhaps presence of epigean species may indicate a pollution problem at a site, other possible causes should be considered. In addition, research indicates that the direction and magnitude of exchange between ground water and surface water may be described by the vertical distribution of hypogean species (organisms that live in the subsurface). These general assumptions rely on studies of benthic, surface, and ground water environments.

Researchers are also studying variations in structure with time and the effect of weather, streamflow, hydraulic gradient, temperature, dissolved oxygen, and other parameters. Studies show high variability within hyporheic zone communities, even at unpolluted sites. At sites along the South Platte River in Colorado, the dominant species at each site were often different, although the same species may have been present at every site. Researchers attributed this finding to the slow migration rates of organisms within ground water communities, thereby causing a patchy distribution of species. Thus, investigations of ground water community structure are site-specific and cannot be extrapolated. This also means that it is difficult to select an “indicator” organism that signifies pollution presence or delineates the hyporheic zone. Biological indicators by definition must be widespread, and occupy the same niche in the community at various sites.

Expertise required

The communtiy approach involves collection, preservation, and identification of hyporheic zone organisms. Specifically, the community approach requires expertise in hyporheic organism identification and knowledge of hyporheic zone community structure. Because this area of research is fairly new, the level of expertise required for community approach studies may not be widely available. However, as the background information on hyporheic zone ecology grows, so will the pool of available expertise in hyporheic organism identification and community structure. In addition, this method may require statistical analysis. Some studies may require simple ANOVA's, but others may require more difficult packages that necessitate in-depth knowledge of statistics. A comprehensive understanding of hydrochemistry and hydrology is needed in order to make valid assumptions about the relationship of the community and organisms to the hydrologic, hydrochemical and hydrogeologic setting.

Assumptions and limitations

The primary limitation of community approach studies is the lack of site-specific ambient or background hyporheic zone community structure information. Given the apparent temporal and spatial hetereogeniety of the hyporheic community, subtle pollution impacts may be diffult for investigators to assess. However, the general assumption that low species abundance and diversity may indicate the presence of pollution appears to be valid. Expanded communication between ecologists and hydrologists will help to identify factors, in addition to water quality, that can impact the extent and nature of communities.

Ecotoxicological Approach

There are two types of ecotoxicological studies; those that study acute and those that study chronic toxicity. Acute toxicity studies determine pollutant concentration and exposure necessary to kill one or more organisms. Typically, the result of an acute toxicity study is determination of the lethal concentration that kills 50 percent of the study organisms or LC_{50}. Within a given time, chronic toxicity studies determine the effect of long-term pollutant exposure to an organism in terms of physiological disruptions such as reproductive or digestive problems. Unlike the community approach study methods, the ecotoxicological approach requires collection of live hyporheic organisms. Therefore, sample collection method is a critical component of the ecotoxicological approach.

Ideally, the ecotoxicological study approach would identify pollutant impacts by lack of abundance of an expected hyporheic organism (acute toxicity) or changes within hyporheic organisms (chronic toxicity). However, extrapolating LC_{50} bioassay[1] results to assess hypogean population dynamics is not advised because of the complex life cycle characteristics of hypogean organisms (Gibert and others 1994). As with the community approach, prior knowledge of the expected hyporheic organisms and community structure, and the hydrologic and hydrochemical setting, are important components in assessing pollutant impact.

Expertise Required

The ecotoxicological approach requires personnel familiar with, and facilities that can follow, toxicity testing protocols. In addition, this approach requires expertise in hyporheic organism identification and biology. Facilities and personnel that perform general toxicity testing are available, however hyporheic organisms require environmental conditions for survival that are not well understood.

Assumptions and limitations

Because very little is known about hyporheic organisms under their normal conditions, investigators find it difficult to determine chronic toxicity. Such studies are also more time-consuming and it is difficult to detect changes in small organisms. Therefore, acute toxicity studies dominate.

Ecotoxicological studies, by nature, cannot be entirely representative of an organism's response to pollution because the studies are performed ex situ. In addition, the pollutant levels used in acute toxicity studies may not be representative of the levels occurring in the ground water habitat. Low diversity of taxa in the ground water environment may be due to chronic effects of pollution, not a specific acute event. Low diversity may also be due to the nature of the ground water environment, low light, oxygen and nutrients.

Studies using ground water organisms are difficult, because the organisms are not thought to survive well outside of the ground water environment. In addition, their adaption to the ground water environment makes them poor candidates for toxicological studies. The ground water environment is low in dissolved oxygen (hypoxic) and very confined. Hyporheic organisms adapt by reducing mobility, respiratory rates, and metabolic functions. For pollutants such as metals, ground water organisms actually are much more resistant to impacts than surface or benthic organisms (Notenbloom et al 1994).

V. Study Settings and Contaminants

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[1] an assay of pollutants, using living organisms; performed to show the effects of pollution on living communities

Table 1 provides a summary of representative settings in which investigators have used biological indicator methods. These studies may focus upon specific environment types such as a transect across a river, a gravel bar, or a grid in a floodplain, or compare community structure across environmental gradients such as the interface between karst and alluvial aquifers, a longitudinal section of a riffle-pool sequence, or a survey along a river from its headwaters to its entrance into a lake or another river. In addition, some studies may only observe the spatial or vertical distribution of a single species.

Most studies summarized in the Table 1 investigate the effects of heavy metals from sewage or other organic pollution. For example, studies of karst ground water systems indicate that surface water organisms displace indigenous fauna during episodes of sewage pollution (Gibert et al 1994). Several studies address pesticide and nitrate pollution. These studies demonstrate that in alluvial aquifers insect larvae tend to disappear in polluted areas, although crustaceans remain present. In addition, abundance and species richness also declines in the polluted areas.

Overall, most of the current literature focuses on gathering background information on ground water communities. These studies address vertical and spatial distributions of indicator species and community richness relating to dissolved oxygen levels and temperature distribution. Ecotoxicological studies primarily focus on the effects of cave-dwelling asellid isopods, low oxygen levels on cave-dwelling amphipods, and chlorophenols and metals on interstitial copepods.

VI. General Evaluation

Because using ground-water organisms to evaluate the interaction of ground water and surface water is a relatively new field, many differences remain in methodologies and definitions. For example, investigators disagree on whether benthic organisms, such as insect larvae that live both in the hyporheic and benthic zones, should be used to define the hyporheic zone. Ecologists need to work closely with hydrologists, hydrogeologists and hydrochemists to determine what factors, other than pollution, may impact the nature and extent of communities. Other factors include, but are not limited to: climate, low light, oxygen and nutrients.

There has been difficulty in sampling the hyporheic zone for organisms because gravel and pebbles dominate the alluvial hyporheic environment. Corers typically used in soil or other more cohesive media are ineffective. Therefore, corer insertion distrupts the vertical distribution of sediment and organisms and valuable information is lost. Investigators have developed methods to circumvent this problem only to face problems with recovering an accurate number of organisms.

There are other general difficulties with using ground water organisms as indicators. The methods are not sufficiently refined to provide quantitative estimates of pollution load. Therefore the methods should be used in conjunction with chemical or other quantitative methods to estimate pollutant load and ground water and surface water exchange. The use of biological indicators is perhaps even more time consuming than chemical analyses. Investigators must preserve, hand separate, count, and identify organisms. A single sample may yield hundreds to thousands of organisms. In addition, because this is a new field and researchers are continously discovering new organisms, there are very few people who can identify organisms to the species level, although, in many cases identification to a higher taxic level may be sufficient.

Biological indicators can serve as effective tools for identifying areas generally impacted by pollution loading and ground water and surface water exchange. Without testing for the presence of multiple contaminants, changes in community structure or population can indicate current or past contamination events. However, researchers have characterized very few hyporheic organisms to date, and few researchers are familiar with hyporheic taxa. Sufficient research has not yet been performed and standards have not yet been set, to determine if biological indicator methods can be effectively applied in the assessment of ground water and surface water interaction and pollutant loading to the hyporheic zone.

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TABLE 1

SUMMARY OF STUDY SETTINGS

Geographic Location	Setting	Contaminant	Notes	Author
Speed River southern Ontario		[a]		B. G. Fraser, D. D. Williams, K. W. F. Howard
Multiple (review article)	Multiple	Multiple		J. Notenboom, S. Plenet, M.-J. Turquin
Upper Arkansas River, Colorado	Stream bed	Heavy metals	benthic[b]	W. H. Clements
Convict Creek, Sierra Nevadas, California	Stream bed	Copper	benthic[b]	H. V. Leland, S. V. Fend, T. L. Dudley, J. L. Carter
Templeton, New Zealand	Downgradient of sewage disposal area	Sewage		L. W. Sinton
Terrieu stream, near Montpellier, France	Fractured rock	Sewage		F. Malard, J. L. Reygrobellet, J. Mathieu, M. Lafont
Meuse River St. Agatha, Holland	Alluvium	Chlorophenols, heavy metals	crustacean; acute toxicity	J. Notenboom, K. Cruys, J. Hoekstra, P. van Beelen

TABLE 1
(CONTINUED)

SUMMARY OF STUDY SETTINGS

Geographic Location	**Setting**	**Contaminant**	**Notes**	**Author**
Chalamont Dombes Forest, France	Forest drainage canal sediment	Low oxygen levels	amphipod	F. Hervant, J. Mathieu, D. Garin, A. Freminet
Merrybranch Cave, White County, Tennessee	Karst aquifer	Cadmium, zinc, total residual chlorine	isopod; acute toxicity	A. D. Bosnak, E. L. Morgan
Eastern North America formerly glaciated sites, unglaciated sites, and Coastal Plain	Streamside hyporheic zones, two springs	[a]		D. L. Strayer, S. E. May, P. Nielsen, W. Wollheim, S. Hausam
Clinch River, Virginia and artificial experimental sites	Gravel/cobble stream bed	Heavy metals	benthic[b]	W. H. Clements, D. S. Cherry, J. C. Cairns, Jr.
Elam’s Run and Shayler Run, southwestern Ohio	None--stream	Heavy metals		R. W. Winner, M. W. Boesel, M. P. Farrell
Southern Ontario, Canada	Sand gravel, cobble underlain by clay	[a]		D. Dudley Williams

TABLE 1
(CONTINUED)

SUMMARY OF STUDY SETTINGS

Geographic Location	Setting	Contaminant	Notes	Author
South Platte River, Colorado	Pleistocene and Recent alluvium	[a]		J. V. Ward, N. J. Voelz, J. H. Harvey
South Platte River, Colorado	Gravel alluvium	[a]		R. W. Pennak, J. V. Ward
Maple River, northern Michigan	Sandy alluvium	[a]	microbial ecology	S. Hendricks
Flathead River, Montana	Pleistocene alluvium	[a]		J. A. Stanford, J. V. Ward
Rhine River, France	Gravel alluvium	[a]		M. Creuze des Chatelliers. P. Marmonier, M. J. Dole-Olivier, E. Castella
Rhone River, France	None given	Sewage, heavy metals		F. Malard, S. Plenet, J. Gibert
Rhone River, France	None given	[a]	effect of storms	M. J. Dole-Olivier, P. Marmonier

TABLE 1
(CONTINUED)

SUMMARY OF STUDY SETTINGS

Geographic Location	Setting	Contaminant	Notes	Author
Rhone River, near Lyon, France	Glaciofluvial sediment	Heavy metals	effect of pumping	J. Gibert, P. Marmonier, V. Vanek, S. Plenet
Rhone River, near Lyon, France	Glaciofluvial sediment	General pollution	low flow, efficacy of bank filtration	C. M. Schmidt, P. Marmonier, S. Plenet, M. Creuze des Chatelliers, J. Gibert
Rhone River tributaries, France	Alluvium and karst	[a]		M. Chafiq, J. Gibert, P. Marmonier, M. J. Dole-Olivier, J. Juget
Loire, Galaure, and Drac Rivers, France	Loire-pebble, gravel, and sand. Galaure-varies Drac-boulders, pebbles, gravel	[a]		L. Maridet, J. G. Wasson, M. Phillipe
Rhine Valley alluvium, Rhone River, France	Gravel (Rhine Valley), gravel and sand (Rhone)	[a]	oligochaetes	M. Lafont, A. Durbec, C. Ille

TABLE 1
(CONTINUED)

SUMMARY OF STUDY SETTINGS

Geographic Location	**Setting**	**Contaminant**	**Notes**	**Author**
Rhone River floodplain, France	Former meandering and braided channels	[a]		P. Marmonier, M. J. Dole-Olivier, M. Creuze des Chatelliers
Verna and Pissoir sites, French Jura	Karst/floodplain interface	[a]		K. Essafi, J. Mathieu, J. L. Beffy
Lone des Iles Nouvelles, old channel of Rhone River, France	Floodplain spring	[a]		S. Plenet, J. Gibert, P. Vervier
Oberer Seebach, northern Alps, Vienna	Unsorted gravel	[a]	harpacticoid copepods	A. Verena Kowarc
Rhone River, France and Sycamore Creek, Arizona	Gravel	[a]		E. H. Stanley, A. J. Boulton
Sonoran Desert, Arizona	Sand and gravel	[a]		A. J. Boulton, H. M. Valett, S. G. Fisher

Notes:

a = The purpose of the study was to determine spatial or temporal distribution and variation of interstitial communities or, in some cases, of individual taxa.

TABLE 1
(CONTINUED)

SUMMARY OF STUDY SETTINGS

b = Some studies were done on benthic, not hyporheic, zones.

TABLE 2

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