GROUNDWATER FAUNAS AS INDICATORS OF GROUNDWATER QUALITY: THE SOUTH PLATTE RIVER SYSTEM

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ABSTRACT

This study, the first of its kind conducted in North America, examined the distribution, structure, and composition of groundwater animals to assess their potential value as indicators of groundwater quality. Phreatic and hyporheic habitats, and surficial bed sediments were sampled at nine locations along the course of the South Platte River, Colorado. Samples were taken with a device procured from Europe that was specifically designed to collect groundwater animals from alluvial aquifers.

Aquatic animals have been widely used as indicators of surface water quality. Because faunal communities integrate past and present environmental conditions, aquatic animals may provide valuable information on water quality that might not be detected by chemical analyses alone. However, to be useful as biomonitors, groundwater animals must be an integral component of riverine aquifers. Results from this study document that a relatively diverse and abundant fauna inhabits the aquifer system of the South Platte River, and data from another western river suggest that groundwater animals will prove to be an integral component of alluvial rivers throughout North America. The responses of aquatic animals to degradation of surface water quality have been extensively investigated at organismic (indicator organism schemes) and community (diversity indices) levels of organization, but such data are not available for groundwater animals. Implementation of biomonitoring as an integrative management tool to protect groundwater resources requires knowledge on the environmental requirements of specific groundwater animals and the responses of community parameters to changes in groundwater quality.

I. INTRODUCTION

Groundwater animals associated with river systems inhabit the interstitial spaces in alluvial sediment deposits. The fauna of alluvial aquifers consists of two major elements, 1) the portion of the stream benthos that temporarily move some distance into the substrate and 2) specialized groundwater forms that rarely if ever occur in the surficial stream bed.

The hyporheic zone may be regarded as an ecotone between the surficial stream bed ($\approx$top 15 cm) and the true groundwaters that constitute the phreatic zone. Most members of the surface benthos inhabit the hyporheic zone during a portion of their life cycle. The hyporheic zone serves as a refuge for the surface benthos, offering shelter from floods, drought, and extreme temperatures and it provides suitable and predictable conditions for immobile stages such as eggs, pupae and diapausing larvae. The hyporheic zone offers some protection from large predators and contains a faunal reserve capable of recolonizing the surface benthos should the latter be depleted by adverse conditions. Being a transition zone, the spatial extent of the hyporheic zone is not precisely delineated. The most extensive hyporheic zones are associated with alluvial deposits dominated by coarse sand and gravel derived from crystalline rock (Stanford and Ward 1988). In such cases substrate porosity tends to be high and silt-free interstices contain adequate dissolved oxygen levels. Streams flowing over bedrock or compacted clay (hardpan) lack a hyporheic zone, but the surface benthos typically extends 30 cm or more into the coarse substrate of streams (Angelier 1962, Schwoerbel 1967, Coleman and Hynes 1970, Bishop 1973, Poole and Stewart 1976, Danielopol 1976, Bou 1979, Bretschko 1981, Pennak and Ward 1986). With increasing depth below the stream bed or distance laterally away from the channel, members of the stream benthos decline concomitant with the appearance of true groundwater animals of the phreatic zone.

The purpose of this study was to determine the distribution, structure, and composition of interstitial faunal communities associated with phreatic, hyporheic, and surficial bed sediments of the South Platte River, Colorado. Results from the study should provide data necessary to ascertain the potential value of groundwater animals as indicators of groundwater quality. The use of organisms as indicators of water quality is based upon the premise that they reflect past and present environmental conditions (Hellawell 1986). Because it is not feasible to continuously monitor every potential contaminant of groundwater (Loftis et al. 1986), the interstitial fauna of alluvial aquifers may prove to be valuable as integrators of groundwater quality.

II. THE STUDY AREA

The South Platte River drains a 62,238 km^2 catchment, most of which (49,262 km^2) lies within the state of Colorado (Caulfield et al. 1987). The river's headwaters are high elevation tributaries on the eastern slope of the Rocky Mountains. Mountain snowpack is the primary water source, with about 70 percent of the discharge occurring during spring runoff in a typical year. Annual discharge at Julesburg, near the Colorado/Nebraska state line, averaged 15.3 $m^3 sec^{-1}$ over an 83-year period of record.

Mountain segments of the South Platte River system are best characterized as cool to cold trout habitat. Studies of surface benthos and physico-chemical variables have been conducted at several locations (Ward 1974, 1975, 1976, 1986; Ward and Short 1978; Short and Ward 1980; Short et al. 1980; Canton et al. 1984; Rader and Ward 1987).

A variety of pollutants degrade the quality of surface and groundwaters in the plains segment of the South Platte River basin (U.S. EPA 1972, Caulfield et al. 1987). Domestic and industrial effluents contribute toxicants, nutrients, organics, and dissolved solids. Hazardous wastes and random spills from various sources contaminate water supplies. Urban stormwater runoff and oil field brine water disposal add to the problem.

The alluvial aquifer extending from Denver to Nebraska contains about 10.3 km^3 of water (Hurr et al. 1975). The width of this section of the aquifer ranges from 1.6-16 km and is up to 90 m thick (Warner et al. 1986). The aquifer consists of Pleistocene and Recent alluvium of high hydraulic conductivity that is hydrologically connected with the South Platte River.

Sampling locations traversed nearly 2000 vertical meters of elevation from the high altitude site on Hoosier Pass to the plains site near Sterling (Fig. 1). Sampling sites were located on riffles and adjacent point or lateral bars not

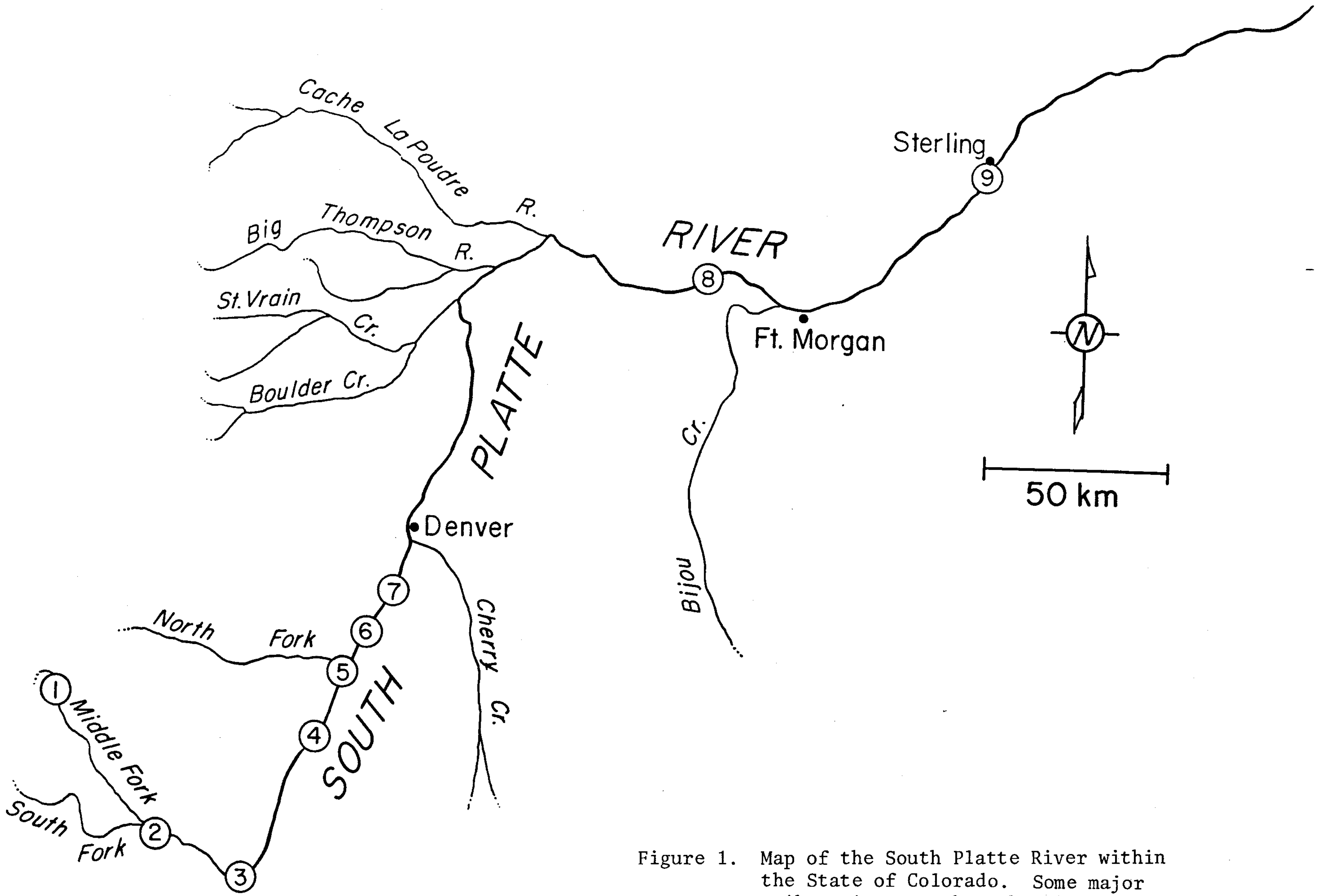

Figure 1. Map of the South Platte River within the State of Colorado. Some major tributaries are shown but impoundments are omitted. Locations of the nine sites are indicated.

directly influenced by known sources of pollution. The intent of this study was to investigate the groundwater fauna at locations deemed most suitable for their development. Because virtually no previous research on groundwater animals of alluvial rivers had been conducted in North America, background data at relatively undisturbed locations are essential for assessing their potential as indicators of groundwater quality. A brief description of the sampling sites follows.

Site 1 (3194 m a.s.l.) was located about 3 km upstream from the village of Alma on Hoosier Pass. This segment of the Middle Fork is a headwater brook meandering through a subalpine meadow. A well-defined floodplain (a few hundred m in width) is present with the woody riparian vegetation dominated by low-growing willows (*Salix* spp.). The substratum of riffles and bars was predominantly rubble, pebble, and gravel. The water was extremely clear during all seasons.

Site 2 (2670 m a.s.l.) was located about 1 km below the confluence of the Middle and South Forks. The stream meanders through South Park, a broad treeless mountain valley. The substratum consisted largely of small rubble, pebble, and gravel.

Site 3 (2451 m a.s.l.) was located in Eleven Mile Canyon about 11 km downstream from Eleven Mile Canyon Reservoir. The predominant woody riparian vegetation was willows. Rubble, pebble, and gravel predominated. Mean discharge at this location, based on 56 years of record, was 2.2 m^3 sec^{-1}.

Site 4 (1951 m a.s.l.) was located near the mouth of Cheesman Canyon 8.5 km below Cheesman Reservoir. Willows dominated the riparian vegetation and the substratum consisted largely of rubble, pebble, and gravel. Discharge (61 years of record) averaged 4.7 m^3 sec^{-1}.

Site 5 (1863 m a.s.l.) was located in the foothills at the confluence of the North Fork with the South Platte River proper. This is where subterranean amphipods were accidently discovered when sampling riverine benthos (Ward 1976, 1977) and it is the only location in Colorado where intensive studies of the groundwater fauna had been previously conducted (Pennak and Ward 1986). Riparian vegetation was predominantly willows. Rubble, pebble, and gravel constituted the majority of the substratum. The bars were mainly pebble and gravel with much less rubble than on the river bed.

Site 6 (1670 m a.s.l.), another foothills station, was located in Waterton Canyon about 8 km downstream from Strontia Springs Reservoir. Riparian vegetation consisted largely of willows. Large rubble, pebble, and gravel predominated.

Site 7 (1637 m a.s.l.), near the mouth of Waterton Canyon, was located about 5 km upstream from Littleton, Colorado. Riparian vegetation consisted of willow shrubs and scattered cottonwood trees (*Populus sargentii*). Rubble, pebble, and gravel predominated on the river bed, with bars consisting of less rubble and more sand. Discharge (33 years of record) at this location averaged 6.6 m^3 sec^{-1}

Sites 8 and 9 (1332 m and 1199 m a.s.l.) were located on the plains segment of the South Platte River. Anastomosed channel patterns occurred at both sites with bottomland gallery forests of cottonwoods, willows, and boxelder (*Acer negundo*). Site 8 was about 2 km south of the small village of Goodrich. Site 9 was about 2 km southeast of the town of Sterling. Alluvium consisted mainly of gravel and sand with some pebble. Discharge (22 years of record) at a gauging station between these two sites averaged 16.2 m^3 sec^{-1}.

III. METHODS

Groundwater animals were collected with a Bou-Rouch sampler (Bou 1974). This device consists of a standpipe, a percussion cap, and a hand pump. With the percussion cap affixed to the top of the standpipe, a sledge hammer was used to drive the tip of the standpipe, which has 6 mm inlet holes, to the desired depth. The percussion cap was then removed and replaced with the hand pump. The pump was primed with a known volume of filtered stream water, and was always cleared at the beginning of each sampling procedure. Samples were taken 30 cm below the stream bed (hyporheic habitat) and 30 cm below the water table of alluvial deposits adjacent to the river (phreatic habitat). A hole was dug down to the water table prior to insertion of the standpipe in the phreatic habitat, to reduce the chances of contamination from overlying deposits. Phreatic samples were taken at about 2 to 20 m from the water's edge, depending on the site and seasonal changes in water levels. For comparative purposes a third habitat, "surface gravel," was also sampled.

The three habitat types at each site were sampled during the spring, summer, and autumn of 1987. Site 5 was sampled monthly for one year in a previous study that did not include collections of surface gravel (Pennak and Ward 1986); data from spring, summer, and autumn hyporheic and phreatic samples (30 cm depths) are included herein.

Phreatic and hyporheic samples were collected by pumping the primer water plus 5 liters of groundwater through a plankton bucket (48 um mesh). Retained material was washed into a sample jar using a wash bottle containing 80% alcohol. Three replicate samples were collected from the phreatic habitat and three from the hyporheic habitat at each site on each date. Replicate samples were taken within 2 or 3 meters of each other. Because of the inordinate amount of time required to process samples in the laboratory, all three replicates were analyzed only from selected locations (Sites 1, 7 and 9).

A composite sample of the "surface gravel" habitat was collected with a core (7 cm diameter) driven about 10 cm below the surface of the substratum. The substratum contained within the core was placed into a plastic pail and the process was repeated until a sufficient volume of sediment (mainly gravel and sand) was obtained (1.5-3.0 liters, determined by displacement). The material within the pail was vigorously agitated and decanted through the same plankton bucket (thoroughly cleaned) used for the Bou-Rouch samples. This procedure was repeated until agitation produced only clear water. The material retained in the plankton bucket was washed into a sample jar using 80% alcohol.

In the laboratory, samples were elutriated to separate organisms and fine detritus from the heavier mineral particles. The mineral fraction (primarily fine sand) was examined for organisms with a dissecting microscope before being discarded. Each sample was then concentrated in a vial of 80% alcohol. Each sample was examined in its entirety at 10X to remove larger organisms. For some of the surface gravel samples it was necessary to remove the very large individuals before proceeding with the 10X scan. The remaining material was processed with procedures similar to those used for zooplankton samples. Aliquots were withdrawn with a Hensen-Stempel pipette and examined at 30X, removing all organisms. In some cases, aliquots were successively withdrawn until the entire sample has been examined at 30X (as well as at 10X). In most instances, the smaller organisms were sufficiently abundant to necessitate subsampling (usually one-fifth or one-tenth of the remaining sample).

A limited array of physico-chemical variables were also sampled. Spot water temperature measurements of the three habitat types were taken at each site on each date. This was accomplished by lowering a thermistor probe to the bottom of the standpipe for hyporheic and phreatic habitats. Surface, hyporheic, and phreatic waters were analyzed for pH, dissolved oxygen, total hardness, and free carbon dioxide during the autumn sampling period. A peristaltic pump, which does not introduce air during operation, was used to withdraw water samples from the bottom of the standpipe. All chemical analyses were conducted in the field.

The substratum of hyporheic and phreatic habitats was collected during autumn base flow conditions. Hyporheic substratum was collected by isolating a portion of the bed with a large open-ended cylinder, removing the large particles (rubble) and other surficial materials down to about 15 cm, and taking multiple cores of pebble and finer particles from within the larger cylinder. Phreatic substratum was collected by digging to the water table and taking multiple cores from that level. Coarse mineral fractions were separated in the laboratory by sieving. Sand and finer particles were separated into size classes using the hydrometer method. The Walkley-Black method was used to determine organic content.

IV. RESULTS AND DISCUSSION

Physico-Chemical Conditions

The limited physico-chemical data collected during the study are summarized in Tables 1 and 2. Rubble was the single most abundant mineral size category on riffles at all locations, except Sites 8 and 9 on the plains where coarse substratum was largely absent. Rubble was also the predominant size category on point bars at most sampling sites in the mountains.

The hyporheic substratum was similar at Sites 1-7, with pebble and gravel constituting the majority of material less than 64 mm in diameter (Table 1). At Sites 8 and 9 on the plains, the pebble size class diminished and sand markedly increased in hyporheic habitats. At mountain locations, sand was generally more abundant in phreatic than hyporheic habitats. Silts and clays constituted <2% of the hyporheic and phreatic substratum at all sites. Organic matter contributed <1%.

The physico-chemical data in Table 2 indicate only general conditions and even broad patterns are not always consistent. For example, spot temperatures reflect 1) time of day, which varied between sites, 2) weather conditions on the day a given site was sampled, and 3) the influence of upstream reservoirs (Sites 3, 4, 6, and 7). Surface waters exhibited oxygen levels near saturation, but hyporheic or phreatic habitats at four sites had concentrations <4.0 mg/l. Total hardness values were considerably higher at the plains sites than in mountain locations. The pH varied from circumneutral to basic. The lowest pH value (6.8 at Site 4 phreatic) occurred in a habitat with low oxygen and very high free CO_2 levels. Excessively high free CO_2 may indicate microsites of high microbial activity (Pennak and Ward 1986).

Table 1. Percentage composition of the mineral size classes (based on particles < 64 mm diameter) and the organic content of the substratum at phreatic (P) and hyporheic (H) habitats at each site.

	SAMPLING SITE																	
CATEGORY	1		2		3		4		5		6		7		8		9	
	P	H	P	H	P	H	P	H	P	H	P	H	P	H	P	H	P	H
Pebble	47.2	54.2	44.0	56.5	31.9	45.5	36.2	60.6	20.4	28.3	48.1	49.7	19.9	52.2	20.8	2.1	3.6	3.6
Gravel	25.4	35.5	22.1	30.9	37.3	29.5	38.5	31.5	52.4	44.1	33.9	38.0	38.8	43.0	40.9	43.7	48.2	47.4
Sand	24.9	9.8	32.5	11.9	29.3	23.9	22.0	7.5	26.1	26.2	16.6	11.9	38.5	4.6	37.2	52.6	46.9	47.4
Silt	0.8	0.1	0.3	0.1	0.3	0.2	1.5	<0.1	1.1	1.4	0.5	0.1	1.2	<0.1	0.4	1.1	1.0	0.5
Clay	1.6	0.4	1.0	0.5	1.2	0.7	1.8	0.3	<1.0	<1.0	0.7	0.2	1.7	0.2	0.8	0.5	0.5	1.0
Organic*	0.8	0.2	0.2	0.3	0.3	0.5	0.9	0.3	0.1	0.1	0.4	0.2	0.2	0.2	<0.1	<0.1	<0.1	<0.1

*As a percent of the sand and finer fraction.

Table 2. Spot measurements of temperature and chemical variables for surface (S), hyporheic (H), and phreatic (P) waters.

Variable			SAMPLING SITE 1	2	3	4	5	6	7	8	9
Temperature, °C	Autumn	S	8.0	14.0	12.5	14.0	---	7.5	10.0	9.0	11.5
		H	7.5	13.0	12.0	12.5	9.0	8.5	11.0	10.5	9.0
		P	5.0	12.0	12.0	11.5	12.5	8.5	11.5	8.0	12.0
	Spring	S	4.0	6.0	7.0	5.0	---	6.0	9.0	18.0	17.0
		H	5.0	7.0	6.5	4.5	7.0	8.0	10.0	17.0	14.0
		P	7.0	6.5	7.0	4.0	3.0	11.0	10.0	12.0	11.5
	Summer	S	10.5	15.0	18.5	18.0	---	16.0	24.0	25.5	26.0
		H	10.5	15.5	17.5	18.0	17.0	15.5	18.5	20.5	23.0
		P	9.0	17.5	18.0	15.0	20.0	20.0	19.5	22.0	22.0
Dissolved Oxygen, mg/l		S	9.4	9.4	8.6	9.1	---	10.5	10.0	9.4	10.2
		H	7.1	6.1	<1.0	5.6	10.7	9.8	2.9	4.6	7.7
		P	9.4	4.0	<1.0	6.1	3.1	7.2	3.5	4.3	0.6
Total Hardness, mg/l $CaCO_3$		S	112	260	222	166	---	160	200	544	746
		H	120	276	252	174	---	140	242	602	756
		P	120	264	240	136	---	156	282	652	580
pH units		S	7.7	8.2	8.4	8.3	---	8.2	8.2	8.1	8.2
		H	7.5	8.3	7.0	7.8	7.0	7.8	7.0	7.3	8.2
		P	7.3	7.6	6.8	7.2	7.3	7.6	7.1	7.3	7.6
Free CO_2, mg/l		S	2.5	3.0	0.0	0.0	---	1.0	2.0	3.0	2.0
		H	3.0	7.5	---	4.0	2.5	11.0	15.0	16.0	4.5
		P	4.5	11.0	35.0	6.0	3.5	6.0	---	15.0	15.0

General Faunal Patterns

Nearly 200 taxa of aquatic animals were identified from samples collected during the study (Table 3). Some groups were ubiquitous (chironomids, copepods, and oligochaetes), but most were restricted in their distribution to particular sites or habitat types (Table 4). Archiannelids and bathynellaceans, for example, are subterranean forms that occurred in phreatic and hyporheic samples, but not in surface gravels. Plecopterans, a cold stenothermal order of insects, were restricted to mountain sites. Eggs and fish larvae were enumerated, but these two categories are excluded from abundance and richness data, and from calculations of percentage composition.

Mean faunal densities, all dates combined, ranged from 163 to 1871 animals per 5-liter sample for hyporheic habitats at different sites, and from 83 to 441 animals per 5-liter sample for phreatic habitats. Abundance levels were appreciably higher in the hyporheic than the phreatic habitat, except at the plains sites where values were similar (Fig. 2). Mean densities in surface gravels ranged from 306 to 4886 animals per liter gravel. The fauna of all three habitats exhibited similar patterns of abundance along the course of the river (Fig. 2). The groundwater fauna was best developed at the high elevation location (Site 1) and at locations in the foothills/plains ecotone (Sites 5, 6, and 7).

Insects and crustaceans collectively contributed the majority of organisms at most sites in most habitats. The relative abundance of crustaceans characteristically declined, concomitant with an increase in the relative abundance of insects, in the series phreatic-hyporheic-surface gravel (Fig. 3). Nematodes and oligochaetes were also common in most habitats

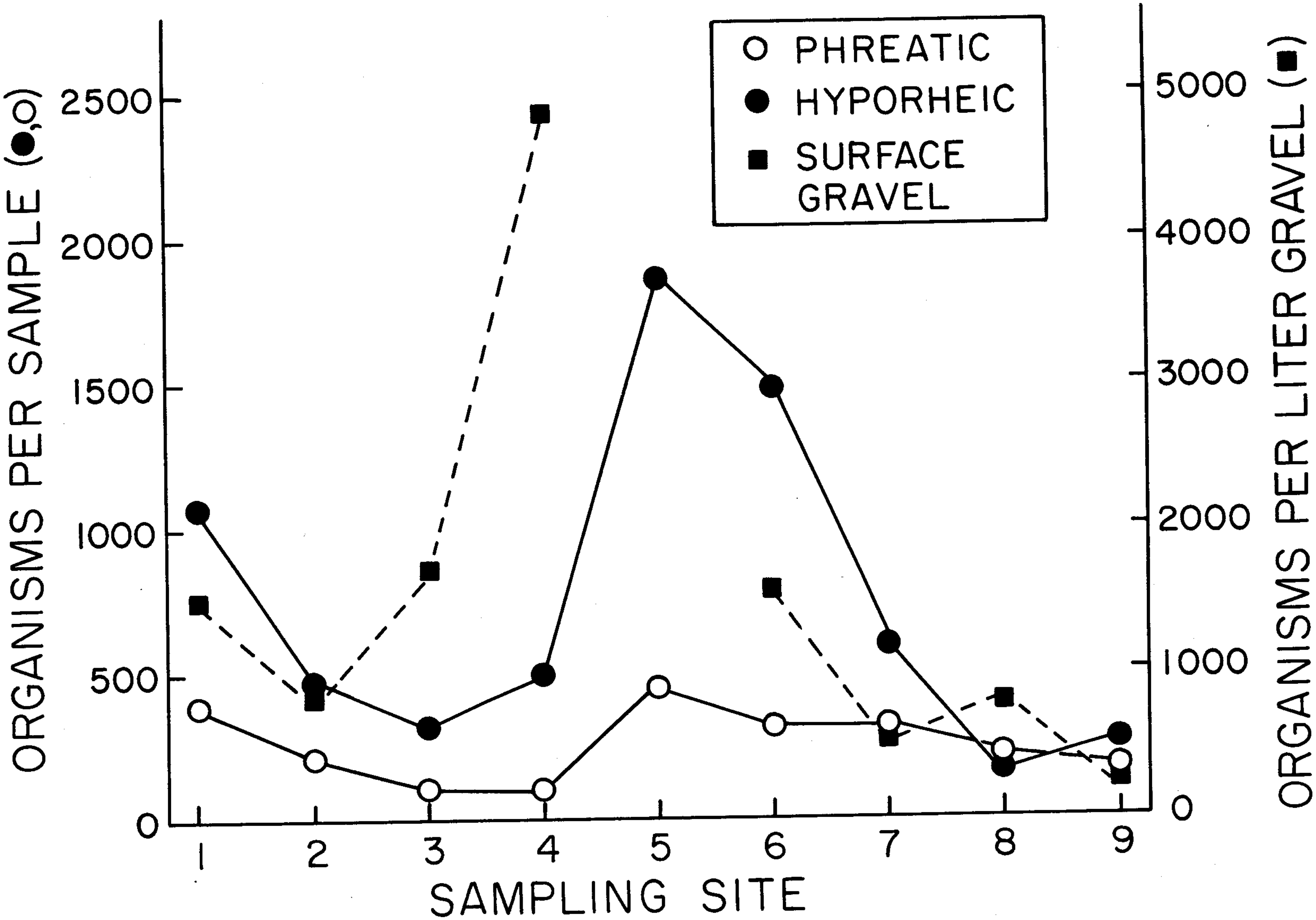

Figure 2. Mean abundance levels of the total fauna for the three habitat types at each site. Eggs and fish larvae are excluded, as is the extreme concentration of nematodes collected in one of the replicate hyporheic samples at Site 7 in summer (see text).

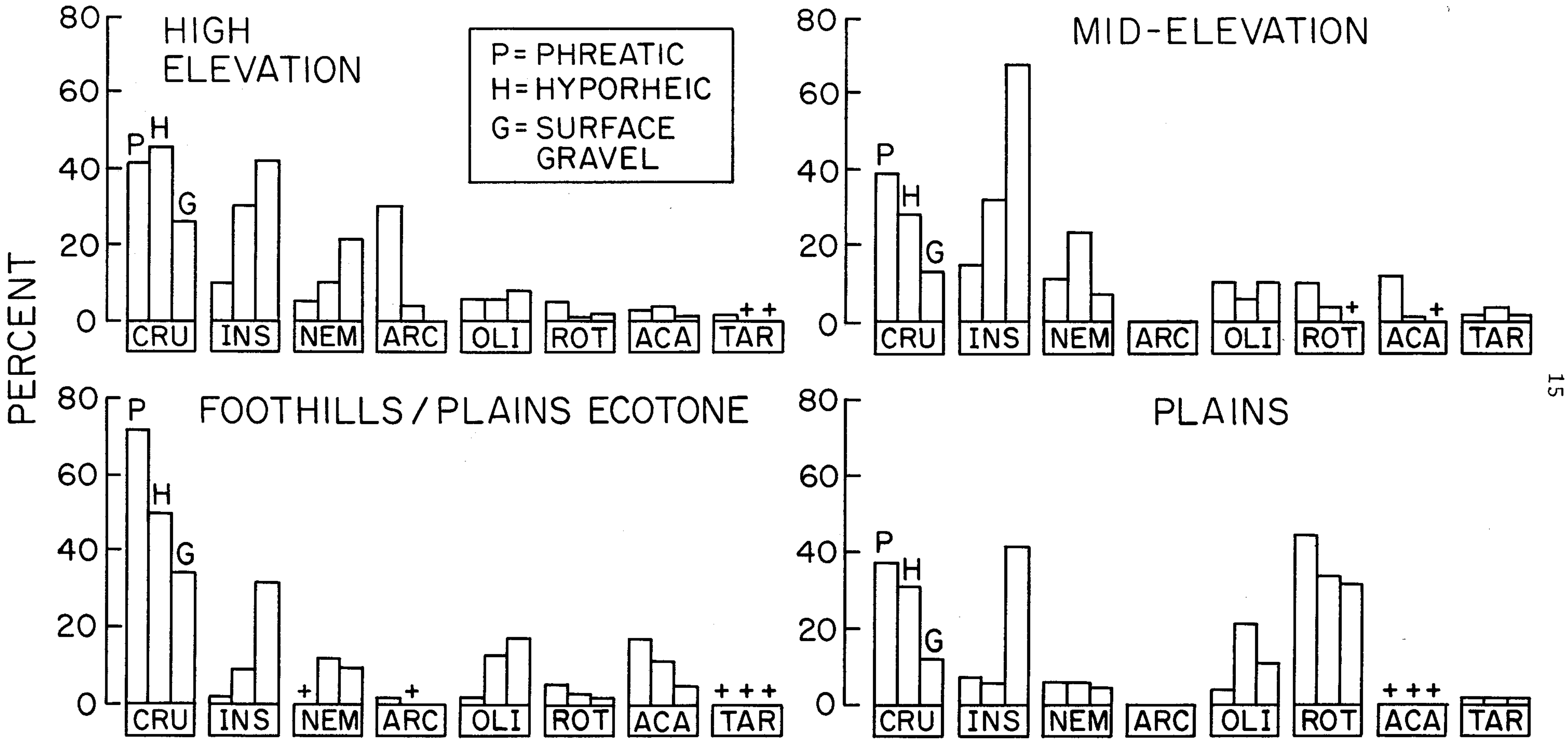

Figure 3. Relative abundances of the eight major faunal groups in the three habitat types grouped according to elevation zones. CRU=crustaceans; INS=insects; NEM=nematodes; ARC=archiannelids; OLI=oligochaetes; ROT=rotifers; ACA=acarines; TAR=tardigrades. +=present at <1.0 %.

Table 3. Total number of taxa identified from major faunal groups in each habitat, all sites and dates combined.

Taxon [a]	Phreatic Habitat	Hyporheic Habitat	Surface Gravel
Archiannnelida (1)	1	1	0
Oligochaeta (19)	9	15	18
Tardigrada (1)	1	1	1
Nematoda (1) [b]	1	1	1
Rotatoria (7)	7	6	5
Amphipoda (2) [b]	1	1	1
Bathynellacea (1)	1	1	0
Copepoda (4) [b]	3	4	4
Ostracoda (15)	6	13	12
Cladocera (5)	2	3	4
Acarina (16)	9	11	8
Collembola (12)	9	5	6
Ephemeroptera (10)	2	5	10
Odonata (1)	0	0	1
Plecoptera (10)	2	5	10
Trichoptera (9)	1	4	9
Coleoptera (2)	0	2	1
Chironomidae (47)	13	37	46
Other Diptera (23)	7	11	19
Miscellaneous Taxa (8)	3	3	6
TOTAL TAXA (194)	78	129	162

[a] Numbers in parentheses indicate total taxa identified from that faunal group.
[b] Taxa undergoing further examination by specialists.

Table 4. Number of taxa identified from major faunal groups by site and habitat (P=Phreatic, H= Hyporheic, G=Surface Gravel).

TAXON	SITE AND HABITAT 1			2			3			4			5		6			7			8			9		
	P	H	G	P	H	G	P	H	G	P	H	G	P	H	P	H	G	P	H	G	P	H	G	P	H	G
Archiannelida	1	1	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	1	1	-	-	-	-	-	-	-
Oligochaeta	1	2	1	1	2	6	3	1	3	2	8	13	2	2	1	2	6	2	6	9	1	1	3	4	2	4
Tardigrada	1	1	1	1	1	1	1	1	1	-	1	1	-	-	1	1	-	1	1	1	1	1	1	1	1	1
Nematoda [b]	1	1	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	-	1	1	1	1	1	1	1	1
Rotatoria	3	2	2	3	3	2	1	2	2	2	1	1	-	-	1	-	2	2	4	3	3	3	3	3	2	2
Crustacea																										
Amphipoda [b]	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	-	1	1	1	1	-	-	-	-	-	-
Bathynellacea	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	1	-	-	-	-	-	-	-
Copepoda [b]	3	3	2	1	2	3	1	2	2	1	2	1	3	2	3	3	2	3	4	3	2	2	1	2	2	1
Ostracoda	2	7	3	-	1	3	2	2	2	-	1	1	-	2	1	3	3	-	3	2	-	-	1	1	2	1
Cladocera	-	-	-	-	-	1	-	-	-	-	-	1	-	-	-	-	2	1	1	1	-	1	1	1	1	2
Acarina	5	5	4	4	4	1	1	1	1	1	-	2	1	1	1	5	4	1	2	2	-	-	-	1	1	-
Insecta																										
Collembola	1	1	1	3	-	-	2	-	-	2	-	-	-	-	-	1	-	2	3	4	2	-	2	1	1	1
Ephemeroptera	1	4	6	-	4	6	-	2	5	-	3	4	-	2	1	2	4	-	2	2	-	1	3	2	2	1
Odonata	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Plecoptera	2	4	9	1	1	6	-	2	2	-	1	3	-	1	-	2	4	-	-	-	-	-	-	-	-	-
Trichoptera	-	1	2	-	2	2	1	1	5	-	1	3	-	-	-	1	3	-	1	3	-	-	1	-	-	1
Coleoptera	-	-	-	-	-	1	-	-	1	-	1	1	-	2	-	-	1	-	-	-	-	-	-	-	-	-
Chironomidae	7	11	13	2	10	11	2	12	18	1	12	23	1	7	3	11	18	2	7	15	3	6	12	2	2	11
Other Diptera	1	2	5	-	1	2	2	1	4	-	1	1	-	2	2	1	3	-	2	2	2	1	6	1	4	5
Miscellaneous taxa [a]	-	-	3	-	-	-	-	1	-	-	1	4	-	-	-	-	1	1	1	2	-	-	-	2	1	1
TOTAL TAXA	30	45	53	17	32	47	17	29	47	10	34	60	10	24	16	33	55	18	41	51	15	17	35	22	22	32

[a] Hydra, Turbellaria, Hirudinea, Myriopoda, Gastropoda, Pelecypoda

[b] Taxa undergoing further examination by specialists.

at most sites. Archiannelids were abundant only in the phreatic habitat at Site 1. Rotifers were abundant in all three habitats at the plains sites. Acarines were best developed in foothills/plain ecotone sites. Tardigrades were present at most sites, but never in high numbers. The eight taxa in Figure 3 collectively accounted for 99.6% to 100% of the total organisms found in each habitat type.

The pattern of taxonomic richness in the phreatic habitat declined from the headwaters to the middle reaches then increased with further distance downstream (Table 4, Total Taxa). The hyporheic habitat, in contrast, exhibited a general decline from the headwaters to the plains, except for a major peak in taxonomic richness at Site 7. The fauna inhabiting surface gravels exhibited yet another pattern, with maximum taxonomic richness in the middle reaches. Insects and crustaceans collectively contributed the majority of taxa at most sites in most habitats, just as they dominated population numbers. Insects were especially diverse in surface gravels.

Faunal Composition

In this section, the distribution, composition, and abundance of major faunal groups will be examined in greater detail. Faunal densities are arbitrarily categorized (Table 5) as follows, based on mean numbers of individuals of a given taxon at a site, all dates combined: Rare = less than 10 individuals (per 5 liter water sample for phreatic and hyporheic habitats; per liter gravel for the surface gravels); Common = 10-99 individuals; Abundant = 100-500 individuals; and Very Abundant = greater than 500 individuals. Table 6 lists the numerical co-dominant in each habitat at each site.

Archiannelids. This group is represented by what appears to be a single widespread species, *Troglochaetus beranecki*. *T. beranecki*, commonly

Table 5. Abundance of major faunal groups based on means of all sampling dates as follows: R (Rare)<10; C (Common) 10-99; A (Abundant) 100-500; and V (Very abundant) >500 animals per 5-liter sample (phreatic and hyporheic) or per liter gravel (surface gravel). Habitat designated by P (Phreatic), H (Hyporheic), and G (Surface Gravel).

TAXON	SITE AND HABITAT																									
	1			2			3			4			5		6			7			8			9		
	P	H	G	P	H	G	P	H	G	P	H	G	P	H	P	H	G	P	H	G	P	H	G	P	H	G
Archiannelida	A	C	-	-	-	-	-	-	-	-	-	-	R	C	-	-	-	C	R	-	-	-	-	-	-	-
Oligochaeta	C	C	A	R	C	C	C	R	C	C	C	V	C	A	R	C	A	R	C	A	C	C	A	R	C	C
Tardigrada	R	R	R	C	R	R	R	C	C	-	C	C	-	-	R	R	-	R	C	R	R	R	C	R	R	R
Nematoda	C	A	A	C	C	A	R	C	C	C	A	A	-	R	R	A	C	-	A	A	C	C	C	R	R	R
Rotatoria	C	C	C	C	C	C	R	C	C	C	R	R	-	-	R	-	C	C	C	C	C	C	C	A	A	A
Crustacea																										
Amphipoda	-	-	-	-	-	-	-	-	-	-	-	-	R	R	R	-	R	R	R	R	-	-	-	-	-	-
Bathynellacea	R	-	-	-	-	-	-	-	-	-	-	-	C	-	-	-	-	C	R	-	-	-	-	-	-	-
Copepoda	A	A	A	R	C	C	C	C	C	C	C	A	A	V	A	V	A	C	C	C	A	C	C	C	C	R
Ostracoda	C	C	A	C	R	C	R	C	C	-	R	C	-	C	C	C	C	-	R	R	-	-	R	R	R	R
Cladocera	-	-	-	-	-	R	-	-	-	-	-	C	-	-	-	-	C	R	R	C	-	R	R	R	R	R
Acarina	C	C	C	C	R	R	R	R	R	R	-	R	R	R	A	A	A	R	C	R	-	-	R	R	R	R
Insecta																										
Collembola	R	R	R	C	-	-	R	-	-	R	-	-	-	-	-	R	-	R	C	C	R	-	R	R	R	R
Ephemeroptera	C	A	C	-	C	C	-	R	C	-	R	C	-	C	R	R	C	R	R	C	-	R	R	R	R	R
Odonata	-	-	-	-	-	R	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Plecoptera	R	C	C	R	R	R	-	R	R	-	R	C	-	R	-	R	R	-	-	-	-	-	-	-	-	-
Trichoptera	-	R	R	-	R	R	R	R	R	-	R	C	-	-	-	R	R	-	R	R	-	-	R	-	-	R
Coleoptera	-	-	-	-	-	R	-	-	R	-	R	C	-	C	-	-	R	-	-	-	-	-	-	-	-	-
Chironomidae	C	A	A	R	A	A	R	C	V	R	A	V	R	C	C	A	V	R	C	A	C	C	A	R	R	C
Other Diptera	R	R	C	-	R	R	R	R	C	-	R	R	-	C	R	R	R	-	R	R	R	R	C	R	R	C
Miscellaneous taxa [a]	-	-	R	-	-	-	-	R	-	-	R	A	-	-	-	-	R	R	R	C	-	-	-	R	R	R

[a] Hydra, Turbellaria, Hirudinea, Myriopoda, Gastropoda, Pelecypoda

Table 6. Numerically co-dominant faunal groups in the three habitats at each site.

	Habitat Type		
SITE	Phreatic	Hyporheic	Surface Gravel
1	Archiannelids	Copepods	Chironomids
	Copepods	Chironomids	Nematodes
2	Acarines	Chironomids	Chironomids
	Collembolans	Copepods	Nematodes
3	Copepods	Chironomids	Chironomids
	Oligochaetes	Ostracods	Nematodes
4	Copepods	Nematodes	Chironomids
	Oligochaetes	Chironomids	Oligochaetes
5	Copepods	Copepods	-------------
	Bathynellids	Oligochaetes	-------------
6	Acarines	Copepods	Chironomids
	Copepods	Acarines	Copepods
7	Copepods	Nematodes	Oligochaetes
	Rotifers	Copepods	Chironomids
8	Copepods	Oligochaetes	Chironomids
	Rotifers	Rotifers	Oligochaetes
9	Rotifers	Rotifers	Rotifers
	Copepods	Copepods	Chironomids

reported from European groundwater habitats (Husmann 1962), is an ancient species of marine ancestry.

The highest densities occurred at the high elevation site where populations were Abundant in the phreatic habitat (constituting 30% of the total fauna) and Common in the hyporheic habitat. *Troglochaetus* was also collected from phreatic and hyporheic habitats at sites in the foothills/plains ecotone at densities ranging from Rare to Common. Larger numbers may have been taken had samples been collected from greater depths (Pennak and Ward 1986). *Troglochaetus* is a true groundwater animal that was not encountered in surface gravels.

Oligochaetes. The oligochaete fauna consisted of nineteen taxa. Oligochaetes were ubiquitous, occurring in all three habitats at all sites. Individual taxa, however, rarely attained high densities and their distribution along the course of the river did not exhibit discernible patterns. The number of taxa progressively increased from the phreatic habitat to surface gravel (Table 3) and the composite oligochaete fauna attained Abundant or Very Abundant density levels in surface gravel at some sites (Table 5). Three of the genera designated by Juget and Dumnicka (1986) as having stygobiontic species (i.e., species found only in subterranean environments) were present. However, the South Platte representatives of these genera occurred in all three habitat types.

Tardigrades. The "water bears", were represented by a single taxon, the genus *Macrobiotus*. Specimens were collected from all three habitats at most sampling sites, but were notably absent from Site 5. Tardigrades were Rare at most sites, were Common in a few habitat/site combinations, but were never Abundant.

Nematodes. This group occurred at all sites and in all habitats, except the phreatic habitat at two foothills/plains ecotone locations. Nematodes were Rare or Common in the phreatic habitats, and either Abundant or Common in hyporheic habitats and surface gravels at most locations. The third replicate sample taken from the hyporheic at Site 7 in July contained an estimated 31,420 nematodes. The abnormally high population of nematodes in this replicate, perhaps a result of sampling the microsite of a recently-hatched egg mass, was excluded from calculations of mean densities of nematodes and total fauna.

The nematode fauna is being examined by E. M. Noffsinger, Division of Nematology, University of California-Davis. The following species were identified from specimens collected during an earlier study (Pennak and Ward 1986) at Site 5:

	Hyporheic	Phreatic
Amphidelus sylphus gr.	+	--
Tobrilus sp.	+	--
Tripyla sp.	+	--
Ironus americanus	+	--
Ironus ignavus	+	--
Mononchus truncatus	+	--
Dorylaimus stagnalis	+	--
Eudorylaimus carteri gr.	+	--
Eudorylaimus humilis	--	+
Aquatides aquaticus	+	--
Mermithidae sp.	+	+
Plectus annulatus	+	--
Theristus sp.	+	--

Rotifers. Seven genera of rotifers were collected. Most occurred in all three habitat types, attaining highest densities in surface gravels. Only one of the genera, *Cephalodella*, is known to contain some species that are restricted to subterranean waters (Tzschaschel 1986), but that is not the case for the species collected from the South Platte River. Some of the rotifers are distinctly planktonic forms (*Kellicottia longispina, Polyarthra* sp.), that are accidentals in subterranean habitats.

No rotifers were collected from Site 5, despite monthly year-round sampling, although all other sites yielded two or more genera. Rotifers attained highest absolute and relative abundances at the plains sites; over 70 percent of the organisms collected from the phreatic habitat of Site 9 were rotifers. The predominance of sand likely accounts for the well developed rotifer populations at plains locations (Tzschaschel 1986). Most rotifer genera extended over a broad range of elevation without discernible attitudinal zonation patterns.

Amphipods. Epigean amphipods of the *Crangonyx gracilis* complex were collected in small numbers from surface gravels at sites in the foothills/plains ecotone. *Stygobromus*, a blind subterranean amphipod of ancient freshwater ancestry (Ward 1977) was also found only at sites in the foothills/plains ecotone, but was spatially segregated from *Crangonyx* by being restricted to the two groundwater habitats.

Bathynellaceans. This small order of primitive crustaceans consists entirely of subterranean forms (Pennak and Ward 1985a). In the South Platte River system, *Bathynella* exhibited the same distribution pattern as archiannelids, being restricted to groundwater habitats at Site 1 and at sites in the foothills/plains ecotone. However, *Bathynella* only rarely occurred in the hyporheic, being largely restricted to the phreatic habitat as reported by Pennak and Ward (1986). Population levels ranged from Rare to Common.

Copepods. All three groups of free-living copepods were represented. Harpacticoid copepods commonly inhabit bottom sediments. Their small size, vermiform morphology, short antennae, and the absence of long plumose setae, are adaptations for residing in interstitial spaces. These morphological adaptations are best exemplified by the harpacticoid *Parastenocaris*, a genus reported from subterranean habitats worldwide. The distribution pattern of *Parastenocaris* was similar to that of the archiannelid *Troglochaetus* (i.e. occurring in phreatic and hyporheic habitats at Site 1 and at sites in the foothills/plains ecotone), with one major difference. Whereas *Troglochaetus* was not collected from the plains sites, *Parastenocaris* occurred in hyporheic and phreatic habitats at Sites 8 and 9. *Parastenocaris* was not taken in surface gravels with the exception of a few specimens at Site 1 in October. *Parastenocaris* was notably absent from mid-elevation sites, as were *Troglochaetus* and *Bathynella*. In subterranean habitats, population levels ranged from Rare to Abundant.

Other harpacticoids occurred at all sites except those on the plains and were most abundant in surface gravels. Population levels ranged from Rare to Very Abundant, the latter values occurring at sites in the Foothills/plains ecotone. Harpacticoid copepods are undergoing further taxonomic examination by Dr. R. L. Whitman.

Although most cyclopoid copepods are planktonic rather than benthic, some species are true inhabitants of interstitial habitats (Pennak and Ward 1985b). Interstitial species may not exhibit any obvious morphological adaptations, retaining the usual bulbous cephalothorax; however, at least some species show reductions in body size and antennal length. In the South Platte River system, cyclopoid copepods occurred at all sites and were collected from all habitats except surface gravel at Sites 1 and 4. Population levels ranged from Rare to Common at most sites; Abundant and Very Abundant levels were attained in hyporheic habitats at sites in the foothills/plains ecotone. Cyclopoid copepods are undergoing further taxonomic examination by Dr. J. W. Reid of the Smithsonian Institution.

A very few calanoid copepods were found in surface gravels and hyporheic samples. Although true subterranean forms have been reported from this largely planktonic group (Bowman 1986), the specimens from the present study all appear to be "accidentals" of surface water origin. Calanoid copepods are undergoing further taxonomic examination by Dr. T. E. Bowman of the Smithsonian Institution.

Ostracods. Fifteen taxa of ostracods were identified. Ostracods occurred in surface gravels at all sites and in phreatic and hyporheic habitats at most locations. Population levels ranged from Rare to Abundant. *Cavernocypris wardi*, the most abundant species, occurred at high elevation sites and at locations in the plains/foothills ecotone. Additional research is being conducted on the ostracods collected during this study. Some species are typically found in surficial sediments, but others exhibit morphological features of specialized groundwater forms (Danielopol and Hartmann 1986).

Cladocera. Five genera of cladocerans were identified during the study. Cladocerans were found in surface gravels at most sites and were common at Sites 4, 6 and 7. A very few specimens were collected from the phreatic habitat at Sites 7 and 9, and from the hyporheic habitat at Sites 7, 8 and 9.

It is contentious whether any cladocerans are exclusively subterranean, but there is no doubt that some species regularly inhabit the interstitial spaces of alluvial gravels (Dumont 1986). The daphnids (*Daphnia*, *Ceriodaphnia*) collected in the present study are most certainly contaminants from surface waters, whereas the chydorids (*Chydorus*, *Alona*) and the macrothricid (*Acantholeberis*) are more likely to be regular inhabitants of near-surface groundwaters.

Acarina. The South Platte River samples yielded a relatively diverse mite fauna consisting of at least 16 taxa. Many taxa, however, were represented by a few individuals found only at one or two sites. True water mites (Hydracarina) were best developed at Site 1 and in the phreatic habitat were found only at that location. Most of the true water mites collected in this study are known to occur in interstitial habitats; this is the primary habitat of *Neoacarus* (Cook 1974). The Mesostigmata, Oribatida, and some of the Prostigmata are largely terrestrial groups, a few members of which have invaded aquatic habitats (Cook 1974). The Limnohalicaridae apparently diverged from the marine Halacaridae and invaded freshwaters (Schwoerbel 1986). The limnohalacarids identified in the present study, *Soldanellonyx* and *Lobohalacarus*, have a long evolutionary history in freshwater (Petrova 1973). Both genera lack eyes, an apparent modification for subterranean life. *Stygothrombium*, of the family Stygothrombiidae, is vermiform and, as the name implies, subterranean. This mite was found only at Site 1 in phreatic and hyporheic habitats.

Insects. The aquatic insect fauna consisted of 114 taxa, 34 of which occurred in the phreatic habitat, 69 in the hyporheic habitat, and 102 in surface gravels. Chironomids were most diverse, contributing 13, 37, and 46 taxa, respectively, in phreatic, hyporheic, and surface gravel habitats (Table 3).

Collembolans (springtails) are small, wingless insects commonly inhabiting soil and other moist terrestrial habitats. Waltz and McCafferty (1979) categorized those associated with freshwaters into Primary, Secondary, and Tertiary aquatic associates. However, the Primary aquatic associates are largely neustonic forms that reside on the surface film. Collembolans occur in the interstices of marine beaches (Delamare Deboutteville 1953), but virtually nothing is known regarding the occurrence of collembolans in freshwater interstitial habitats (Thibaud and Massoud 1986). Collembolans were best developed at Site 7 in the foothills/plains ecotone (Tables 4 and 5).

Ephemeroptera (mayflies) rarely occurred in phreatic habitats, except at Site 1 where a single taxon (*Ameletus* sp.) constituted 6% of the total animals from that habitat and 10% of the hyporheic fauna. Mayflies occurred in hyporheic and surface gravel samples from all sites. Groundwater forms are unknown among mayflies; all species encountered in hyporheic and phreatic samples were epigean species.

Plecoptera (stoneflies) were confined to mountain stream sites. All taxa encountered occurred in surface gravels. Many of these penetrated hyporheic habitats, but stoneflies occurred in phreatic samples only in low numbers at the two uppermost sites. Stoneflies confined to groundwaters during their entire nymphal lives have been reported from alluvial Rocky Mountain rivers (Stanford and Ward 1988), but those species were not collected from the South Platte River system.

Trichoptera (caddisfiles), while abundant on rocky substrata within the basin (e.g., Ward 1976, 1986, 1987), were poorly represented in the three habitats sampled in the present study. Caddisflies occurred in low numbers in surface gravels. Some of these also occurred in hyporheic habitats, but only a single *Rhyacophila* larva penetrated the phreatic zone (Site 3).

Elmid beetles are typically the only coleopterans recorded from hyporheic habitats (e.g. Bou 1979, Williams 1984) and such was the case in the present study. Two species of elmids were collected from surface gravels. Neither was found in phreatic habitats, but *Optioservus* occurred in hyporheic samples at Sites 4 and 5. Some elmid beetles are specialized for a subterranean existence, although none are known to occur in North America (Spangler 1986).

One family of dipterans, the Chironomidae (midges), contained nearly half of all the species of insects identified during the study. This was the only family (insects or non-insects) to occur in all habitats at all sites. The numerical abundance of chironomids was greater than all other groups of insects combined in surface gravel at all sites, in the hyporheic habitat at most sites, and in the phreatic habitat at some sites. Most of the chironomids collected are members of the surface benthos, some individuals of which may move into groundwater habitats, especially as early instar larvae. *Krenosmittia, Lopescladius*, and *Parakiefferiella*, appear to be hypogean forms that complete all larval instars in subsurface waters (Ferrington 1984 and personal communication).

Tipulidae (crane flies) are represented by nine genera. Tipulid larvae were collected from most sites, but were always rare. All taxa occurred in surface gravel and some were restricted to that habitat type. Others also occurred in hyporheic samples and two genera, *Molophilus* and *Ormosia*, penetrated the phreatic. None appear to be specialized groundwater forms.

Six taxa of Ceratopogonidae (biting midges) were identified, each of which occurred at from one to three sites at Rare to Common levels of abundance. All are thought to belong to the surface benthos although some also occurred in hyporheic or phreatic habitats.

Larvae of *Protanyderus margarita*, a primitive crane fly (Tanyderidae), are rarely collected in general stream surveys because they burrow in the sand and gravel substrata. Specimens were collected from the hyporheic habitat of Site 4 and the phreatic habitat of Site 6.

The poor representation and restricted distribution patterns of other dipteran families (e.g., black flies) is attributed to their primary association with habitat types not sampled during this study. Additional groups, known to occur in the South Platte River, were not collected because of their confinement to rock faces in rapid water (Blephariceridae, Deuterophlebiidae).

Other Fauna. Members of other faunal groups were also collected, usually in small numbers. Hydra, usually Rare and confined to surface gravel, were Abundant at Site 4 below an impoundment and occurred in all three habitat types at Site 9. The paucity of triclad turbellarians is attributable to the type of substratum sampled. The rarity of microturbellarians most likely relates to inappropriate sampling techniques (Kolasa et al. 1987). The Bou-Rouch technique is also not efficient in collecting leeches, snails or fingernail clams.

Habitat Distribution Patterns

The taxa collected during this study may be placed in one of three general groups, based on their habitat distribution patterns.

True Groundwater Forms. The following taxa were rarely, if ever, collected from surface gravel and are adapted for a subterranean existence: bathynellids, *Stygobromus* (a blind amphipod), archiannelids, *Parastenocaris* (a vermiform harpacticoid copepod), and *Stygothrombium* (a vermiform acarine).

Surface Forms. Some of the taxa are clearly members of the surface gravel habitat. While they may occasionally penetrate the hyporheic habitat, they rarely, if ever, occur in phreatic waters. Surface forms include most of the aquatic insects, *Crangonyx* (an epigean amphipod), and molluscs.

Euryzonal Forms. The following groups were well represented in all three habitat zones: nematodes, oligochaetes, tardigrades, rotifers, ostracods, some harpacticoid and cyclopoid copepods, some acarines, collembolans, chironomids, and ceratopogonids. These taxa move freely within the substrate interstices without restriction to a particular habitat type.

V. GROUNDWATER ANIMALS AS BIOMONITORS

Despite the heavy reliance on groundwater as a source of drinking water and to irrigate crops, it is not feasible to continuously monitor every potential contaminant of groundwater (Loftis et al. 1986). Aquatic animals have been widely used as indicators of surface water quality (e.g., Wilhm and Dorris 1968, Goodnight 1973, Sládeček 1973, Winner et al. 1980, Hellawell 1986) because the biotic community integrates past as well as present environmental conditions. There is no reason to presume that groundwater animals could not be used in a similar fashion, thereby serving as a valuable management tool to help protect groundwater resources (Ward and Stanford 1989).

However, to be useful as indicators of groundwater quality, groundwater animals must be an integral component of alluvial river-aquifer systems. It has been known for some time that this is true for European alluvial rivers (e.g., Schwoerbel 1967, Husmann 1971, Danielopol 1976, Gibert et al. 1977). But no comparable data were available for North American rivers until very recently. In 1983 one of the world's leading authorities on running water ecology stated that phreatic forms occur in the groundwaters of Europe but not in North America (Hynes 1983).

This study has clearly shown that an abundant and diverse aquatic fauna inhabits the alluvium of the South Platte River system and preliminary data from a grid of unscreened wells on the floodplain of the Flathead River in Montana also reveal a remarkable hyporheic and phreatic fauna (Stanford and Ward 1988). We predict that groundwater animals will prove to be integral components of alluvial river-aquifer systems throughout North America.

What we do not know is how various groundwater animals respond to differences in environmental quality. Even in Europe, where the groundwater fauna is relatively well known, remarkably few investigators have even attempted to relate faunal composition to pollution levels (Danielopol 1981, Meštrov and Lattinger-Penko 1981). In contrast, there are extensive compilations of the environmental requirements and pollution tolerance of aquatic animals of surface waters (e.g., Sládeček 1973, Beck 1977, Harris and Lawrence 1978, Hubbard and Peters 1978, Surdick and Gaufin 1978).

There are two basic ways to assess water quality using aquatic organisms (Washington 1984). Indicator organism schemes rely on placing each kind of organism within a pollution category (e.g., tolerant, intolerant, facultative relative to a particular pollutant) or assigning them a numerical score. Such data do not exist for groundwater animals. The community structure approach measures the collective response of the assemblage of species to alterations in water quality, often using a diversity index. Diversity indices derive a numerical score that combines the number of species (the richness component) with the relative abundances of the species present (the equilability component). High species diversity is characteristic of natural, unimpacted biotic communities. Severe pollution typically depresses diversity, either through a reduction in the number of species or by allowing a few species to dominate the community thereby reducing the equitability component. However, to be meaningful there must be standards against which a diversity index score can be evaluated. Such standards exist for the biotic communities of surface waters (Wilhm 1970), but have not been determined for groundwater faunas.

VI. FUTURE RESEARCH NEEDS

The "growing concern over contamination of the nation's groundwater resources" (Ross 1981) has not abated. Groundwater animals offer an unexploited source of information for managing groundwaters that we cannot afford to overlook. We contend that it should be possible to utilize specific groundwater animals and community level parameters as an integrative management tool to monitor and assess groundwater quality degradation. When used properly and cautiously, biological approaches may provide valuable information on groundwater quality that might not be detected by chemical analyses alone. Full implementation of such a biomonitoring management plan will require research efforts in the following areas:

1. Investigations designed to further understanding of groundwater animals associated with other alluvial rivers in North America, including their environmental requirements, population dynamics, and trophic relationships under natural conditions.

2. Field assessment of faunal changes occurring at locations of known or suspected groundwater contamination, or at sites subject to future impacts (e.g., a proposed waste dump). Standpipes or unscreened monitoring wells can be installed at such locations and periodically sampled for groundwater animals.

3. Laboratory and in situ bioassays with representative groundwater animals. Despite the need for single-species tests to determine the environmental tolerances of groundwater animals, this should be regarded only as a first step to predicting responses at higher levels of organization (Kimball and Levin 1985, Cairns 1986).

VII. LITERATURE CITED

Angelier, E. 1962. Remarques sur la repartition de la fauna dans le milieu interstitiel hyporheique. Zool. Anz. 168, Parts 7-10, 351-356.

Beck, W. M. 1977. Environmental requirements and pollution tolerance of common freshwater Chironomidae. U.S. Environmental Protection Agency, Cincinnati. 261 pp.

Bishop, J. E. 1973. Observations on the vertical distributions of the benthos in a Malaysian stream. Freshwater Biology 3:147-156.

Bou, C. 1974. Les méthodes de récolte dans les eaux souterraines interstitielles. Ann. Spéléol. 29:611-619.

Bou, C. 1979. Étude de la faune interstitielle des alluvions du Tarn mise en place d'une station d'étude et résultats preliminaires. Bull. Féd. Tarn Spéléo.-Archéol. 16:117-129.

Bowman, T. E. 1986. Copepoda: Calanoida, p. 295-298. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Bretschko, G. 1981. Vertical distribution of zoobenthos in an alpine brook of the Ritrodat-Lunz study area. Verh. Int. Verein. Limnol. 21:873-876.

Cairns, J., Jr. (ed.). 1986. Community Toxicity Testing. Am. Soc. Testing Mat., Philadelphia. 348 pp.

Canton, S. P., L. D. Cline, R. A. Short and J. V. Ward. 1984. The macroinvertebrates and fishes of a Colorado stream during a period of fluctuating discharge. Freshwater Biology 14:311-316.

Caulfield, H. P., Jr., N. A. Evans, J. E. Flack, N. S. Grigg, D. W. Hendricks, J. W. Labadie, D. McWhorter, H. J. Morel-Seytoux, W. L. Raley, R. A. Young and J. G. Milliken. 1987. Voluntary Basinwide Water Management: South Platte River Basin, Colorado. Colorado Water Resources Research Institute Report No. 133. 151 pp.

Coleman, M. J. and H. B. N. Hynes. 1970. The vertical distribution of the invertebrate fauna in the bed of a stream. Limnol. Oceanogr. 15:31-40.

Cook, D. R. 1974. Water Mite Genera and Subgenera. Memoirs Am. Ent. Soc. 21:1-860.

Danielopol, D. 1976. The distribution of the fauna in the interstitial habitats of riverine sediments of the Danube and the Piesting (Austria). Int. J. Speleol. 8:23-51.

Danielopol, D. 1981. Distribution of ostracods in the groundwater of the northwestern coast of Euboea (Greece). Int. J. Speleol. 11:91-103.

Danielopol, D. L. and G. Hartmann. 1986. Ostracoda, p. 265-294. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Delamare Deboutteville, C. 1953. Collemboles marins de la zone Souterraine humide de sables littoraux. Vie et Milieu 4:290-319.

Dumont, H. J. 1986. Cladocera, p. 263-264. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Ferrington, L. C. 1984. Evidence for the hyporheic zone as a microhabitat of *Krenosmittia* spp. larvae (Diptera: Chironomidae), J. Freshwater Ecol. 2:353-358.

Gibert, J., R. Ginet, J. Mathieu, J.-L Reygrobellet and A. Seyed-Reihani. 1977. Structure et fonctionnement des écosystèmes du Haut-Rhône francais. IV. Le peuplement des eaux phréatiques; premier resultats. Ann. Limnol. 13:83-97.

Goodnight, C. J. 1973. The use of aquatic macroinvertebrates as indicators of stream pollution. Trans. Am. Microscop. Soc. 92:1-13.

Harris, T. L. and T. M. Lawrence. 1978. Environmental requirements and pollution tolerance of Trichoptera. U. S. Environmental Protection Agency, Cincinnati. 310 pp.

Hellawell, J. M. 1986. Biological Indicators of Freshwater Pollution and Environmental Management. Elsevier Applied Science Publishers, London. 546 p.

Hubbard, M. D. and W. L. Peters. 1978. Environmental Requirements and Pollution Tolerance of Ephemeroptera. U. S. Environmental Protection Agency, Cincinnati. 460 pp.

Hurr, R. T., P. A. Schneider, Jr. and D. R. Minges. 1975. Hydrology of the South Platte Valley, northeastern Colorado. Colorado Water Conservation Board, Colorado Water Resources Circular No. 28, Denver, Colorado.

Husmann, S. 1962. Ökologisches und verbreitungsgeschichtliche Studien über den Archianneliden *Troglochaetus beranecki* Delachaux; Mitteilung uber Neufunde aus den Grundwasserströmen von Donau, Ybbs, Ötz, Isar, Lahn, Ruhr, Niederrhein und Unterweser. Zool. Anz. 168:312-325.

Husmann, S. 1971. Ecological studies on freshwater meiobenthon in layers of sand and gravel. Smithsonian Contrib. Zool. 76:161-169.

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

Juget, J. and E. Dumnicka. 1986. Oligochaeta (incl. Aphanoneura) des eaux souterraines continentales, p. 234-244. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Kimball, K. D. and S. A. Levin. 1985. Limitations of laboratory bioassays: the need for ecosystem-level testing. BioScience 35:165-171.

Kolasa, J., D. Strayer and E. Bannon-O'Donnell. 1987. Microturbellarians from interstitial waters, streams, and springs in southeastern New York. J. N. Am. Benthol. Soc. 6:125-132.

Loftis, J. C., R. H. Montgomery, J. Harris, D. Nettles, P. S. Porter, R. C. Ward, and T. G. Sanders. 1986. Monitoring Strategies for Groundwater Quality Management. Colorado Water Resources Research Institute Report No. 140. 125 pp.

Meštrov, M. and R. Lattinger-Penko. 1981. Investigation of the mutual influence between a polluted river and its hyporheic. Int. J. Speleol. 11:159-171.

Pennak, R. W. and J. V. Ward. 1985a. Bathynellacea (Crustacea: Syncarida) in the United States, and a new species from the phreatic zone of a Colorado mountain stream. Trans. Am. Microscop. Soc. 104:209-215.

Pennak, R. W. and J. V. Ward. 1985b. New cyclopoid copepods from interstitial habitats of a Colorado mountain stream. Trans. Am. Microsc. Soc. 104:216-222.

Pennak, R. W. and J. V. Ward. 1986. Interstitial faunal communities of the hyporheic and adjacent groundwater biotopes of a Colorado mountain stream. Arch. Hydrobiol. Monographische Beiträge 74:356-396.

Petrova, A. 1973. On halacarid migration into freshwaters, p. 169-171. IN: M. Daniel and B. Rosicky (eds.), Proc. Third Int. Congress Acarology. Dr. W. Junk, The Hague.

Poole, W. C. and K. W. Stewart. 1976. The vertical distribution of macrobenthos within the substratum of the Brazos River, Texas. Hydrobiologia 50:151-160.

Rader, R. B. and J. V. Ward. 1987. Resource utilization, overlap and temporal dynamics in a guild of mountain stream insects. Freshwater Biology 18:521-528.

Ross, B. J. 1981. Protecting the nation's ground water. J. Wat. Poll. Contr. Fed. 53:287-290.

Schwoerbel, J. 1967. Die stromnahe phreatische Fauna der Donau (hyporheische Fauna), p. 284-294. IN: R. Liepolt (ed.), Limnologie der Donau, Stuttgart, Germany.

Schwoerbel, J. 1986. Acari: Limnohalacaridae and Hydrovolziidae, p. 643-647. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Short, R. A., S. P. Canton and J. V. Ward. 1980. Detrital processing and associated macroinvertebrates in a Colorado mountain stream. Ecology 61:727-732.

Short, R. A. and J. V. Ward. 1980. Macroinvertebrates of a Colorado high mountain stream. Southwestern Nat. 25:23-32.

Sládeček, V. 1973. System of water quality from the biological point of view. Arch. Hydrobiol. Beitr. Ergebn. Limnol. 7:1-218.

Spangler, P. J. 1986. Insecta: Coleoptera, p. 622-631. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Stanford, J. A. and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature 335:64-66.

Surdick, R. F. and A. R. Gaufin. 1978. Environmental requirements and pollution tolerance of Plecoptera. U. S. Environmental Protection Agency, Cincinnati. 417 pp.

Thibaud, J.-M. and Z. Massoud. 1986. Insecta: Collembola, p. 616-617. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

Tzschaschel, G. 1986. Rotatoria, p. 76-85. IN: L. Botosaneanu (ed.), Stygofauna Mundi. Brill, Leiden.

U. S. Environmental Protection Agency. 1972. Water quality investigations in the South Platte River Basin, Colorado, 1971-1972. Denver, Colorado. 74 pp.

Waltz, R. D. and W. P. McCafferty. 1979. Freshwater springtails (Hexapoda: Collembola) of North America. Res. Bull. Purdue Univ. Agric. Exp. Sta. 960:1-32.

Ward, J. V. 1974. A temperature-stressed stream ecosystem below a hypolimnial release mountain reservoir. Arch. Hydrobiol. 74:247-275.

Ward, J. V. 1975. Bottom fauna-substrate relationships in a northern Colorado trout stream: 1945 and 1974. Ecology 56:1429-1434.

Ward, J. V. 1976. Comparative limnology of differentially regulated sections of a Colorado mountain river. Arch. Hydrobiol. 78:319-342.

Ward, J. V. 1977. First records of subterranean amphipods from Colorado with descriptions of three new species of *Stygobromus* (Crangonyctidae). Trans. Am. Microsc. Soc. 96:452-466.

Ward, J. V. 1986. Altitudinal zonation in a Rocky Mountain stream. Arch. Hydrobiol. Suppl. 74:133-199.

Ward, J. V. 1987. Trichoptera of regulated Rocky Mountain streams. Series Entomologica 39:375-380.

Ward, J. V. and R. A. Short. 1978. Macroinvertebrate community structure of four special lotic habitats in Colorado, U.S.A. Verh. Int. Verein. Limnol. 20:1382-1387.

Ward, J. V. and J. A. Stanford. 1989. Groundwater animals of alluvial river systems: A potential management tool. Proc. Colorado Water Engineering and Management Conference, Fort Collins, CO. (in press).

Warner, J. W., D. K. Sunada and A. Hartwell. 1986. Recharge as augmentation in the South Platte River Basin. Colorado Water Resources Research Institute Report No. 144. 116 pp.

Washington, H. G. 1984. Diversity, biotic and similarity indices: A review with special relevance to aquatic ecosystems. Water Res. 18:653-694.

Wilhm, J. L. 1970. Range of diversity index in benthic macroinvertebrate populations. J. Wat. Poll. Control Fed. 42(5):R221-R224.

Wilhm, J. L. and F. C. Dorris. 1968. Biological parameters for water quality criteria. BioScience 18:477-483.

Williams, D. D. 1984. The hyporheic as a habitat for aquatic insects and associated arthropods, p. 430-455. IN: V. H. Resh and D. R. Rosenberg (eds.), The Ecology of Aquatic Insects. Praeger, New York.

Winner, R. W., M. W. Boesel and M. P. Farrell. 1980. Insect community structure as an index of heavy metal pollution in lotic ecosystems. Can. J. Fish. Aquatic. Sci. 37:647-655.