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Macroinvertebrates in the bed sediment of the Yellow River

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Abstract

Extensive agricultural, industrial and urban development in the Yellow River, China, have modified the sediment-water balance, flow and inundation regimes, longitudinal connectivity, integrity of riparian vegetation, and water quality. Macroinvertebrate assemblages in the bed sediment of main channel and major reservoirs of the Yellow River are described in detail for the first time. A total of 74 taxa comprising 17 taxa of oligochaetes, 48 taxa of aquatic insects, 5 taxa of molluscs, and 4 taxa of other animals were recorded. A range of feeding guilds were represented, including, collector-gatherers (32 taxa), predators (17 taxa), scrapers (16 taxa), shredders (6 taxa) and collector-filterers (2 taxa). Both the mean density and biomass of macroinvertebrates were significantly higher in sites located in the artificial reservoirs compared with the main river channel. Assemblages varied spatially; Oligochaetes dominated assemblages in upper reaches, insects dominated in middle reaches and other animals (e.g. Crustacea) dominated in lower reaches. Collector-gatherers were dominant throughout the entire river. Classification analysis identified five site-groups on the basis of macroinvertebrate presence/absence: downstream of reservoirs; vegetated sites; reservoir sites; polluted sites, and; lower-reach sites. Lower macroinvertebrate richness, density and biomass, compared with other similar large rivers, were attributed to modification of the sediment-water balance and associated disturbance of benthic habitats. Pollution, stability of sediment and sediment concentration combined to influence the distribution of macroinvertebrates. This knowledge will substantially benefit the recent focus on the health and environmental water requirements of the Yellow River.

Key Words: Macroinvertebrates, Species composition, Distribution pattern, Sediment, The Yellow River

1 Introduction

Large rivers have played an important role in the development of both ancient and modern civilizations by providing water resources and fertile floodplain-soils necessary to sustain populations and develop agriculture-based economies. The Yellow River has provided water and fertile land for agriculture, and fisheries resources that have supported one of the most rapidly intensifying human developments the globe has experienced (Sun et al., 2008). This long history of resource dependence has resulted in substantial degradation to the health of the Yellow River and the ecosystem, social and economic services it supplies.

The Yellow River is one of the world's largest and arguably most ecologically important rivers. Massive sediment loads naturally transported downstream from the aeolian sediments of the Loess Plateau

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determines morphology of the lower river and delta, including its wetland habitats which are internationally recognized for their ecological values (Zhang et al., 2007; Huang et al., 2007). Development of oil and gas resources on the Yellow River delta has resulted in rapid agricultural and urban expansion (Sun et al., 2008). Much of this development has occurred on the floodplain which now supports intensive agriculture and associated rural populations that are protected from flooding by an elaborate system of dykes and levees (Zhang and Sun, 2005). This has resulted in significant modification to the river channel as well as the disconnection of floodplain habitats (Yue et al., 2002; Ru et al., 2003), especially wetlands (Zhang and Sun, 2005).

To supply water and electricity, 11 major reservoirs have been constructed in the mid and upper reaches of the basin since the 1970's (Sun et al., 2008). This has resulted in a substantial reduction in sediment loads (and flow), now estimated to be approximately 1/10 of natural (Wang et al., 2008). This alteration to the natural sediment-water balance is considered the primary cause of ecosystem degradation in the lower Yellow River (Li, 2005; Li et al., 2007).

While the lower reaches of the Yellow River are undoubtedly impacted most by land use change and water-resource development, a variety of other impacts are also relevant throughout the catchment. The construction of large dams and smaller weirs has interrupted the natural transport of sediments, the movement of migratory fish species and the transport of organics that may be important in subsidizing downstream food-webs (Vannote et al., 1980; Ru et al., 2010). In addition, there have been significant changes to water quality including increases in nutrients, inorganic (heavy metals) and organic constituents (Sun et al., 2008).

Recognition of the important links between ecological function, economic and social services that the river supplies has led to significant interest in the implementation of environmental management strategies including monitoring ecological condition, or “ecosystem health” (sensu Karr, 1999). Since 2001, environmental water and sediment releases have been provided from major impoundments to protect ecosystem health in the lower reaches (Li et al., 2007). These flows have resulted in reestablishment of perennial flows and benefits to channel and deltaic morphology. Although some valuable fish species have returned to the river, the response of other ecological components and processes remains unclear (Li et al., 2007). Furthermore, ecosystem health upstream of the major impoundments is currently poorly understood. While some information on water quality and river discharge has been collected in the Yellow River catchment, knowledge of ecological communities is contrastingly scarce. This is especially true for aquatic macroinvertebrates, that otherwise may provide important information on which to base future assessments of river health (Chessman, 1995; Parsons and Norris, 1996; Ormerod and Edwards, 1987).

To address this knowledge gap, two comprehensive surveys of benthic macroinvertebrate assemblages were undertaken at sites located in main channel of the Yellow River. These surveys aimed to quantitatively describe the distribution, diversity and abundance of macroinvertebrates within the catchment and provide a basis for monitoring of ecosystem health. Preliminary investigation of the relationships between macroinvertebrate communities and environmental conditions, especially the influence of altered sediment dynamics, will provide a basis for studying mechanisms and processes of ecological response to future management activities (sensu Underwood et al., 2000). We briefly discuss the use of this information as a benchmark for assessing the future health of the river, especially in terms of the recent focus on managing the sediment-water balance in the lower reaches, and the implementation of more holistic environmental flow management that is currently being investigated.

2 Materials and methods

2.1 Study area

The Yellow River (32º-42ºN, 96º-119ºE) is the second largest river in China: a total mainstream length of 5,464 km drains a catchment of 7.52×10^5 km^2. The region is characterized by a continental climate, with a mean annual temperature of 9°C (range: -14-17°C). Rainfall and runoff are seasonal, with most occurring during the summer months (June-September). Mean annual precipitation and evaporation are 478 mm (150-800 mm) and 1,390 mm (437-2,226 mm) respectively. The mean annual discharge of the river is 58 billion m^3 and river flows are strongly seasonal: highest in autumn and lowest in winter. The annual distribution of sediment discharge is concentrated in the summer-flood season with a historical maximum load of 1,600 kg m^{-3} (1958, recorded at Wenjiachuan) and mean annual sediment transport of 1,600 million tones (Shu and Fei, 2008). The mean annual sediment concentration is 35 kg m^{-3} (recorded at Sanmenxia).

The upper reaches of the river drain high-intensity agriculture and industrial land uses. While floodplain connectivity in these reaches remains unaltered, the lower reaches of the river channel (downstream of Xiaolangdi, see Fig. 1) are confined within a series of inner and outer dykes and levees that confine the channel within a much-reduced floodplain (0.5-20 km wide).

The construction of eleven major reservoirs and numerous smaller weirs (to supply hydro-electric generation) in the mid reaches have extensively modified flow regimes and sediment characteristics in the lower reaches of the river (Sun et al., 2008). Of these, Liujiaxia, Qingtongxia and Sanmenxia dams were built before 1970s and Xiaolangdi dam was built in 1997 (Fig. 1). As a consequence of water resource development, until 2001 the lower reaches of the Yellow River had been modified from a perennial floodplain system to an ephemeral chain of pools. The most significant flow alteration included an increase in the frequency and duration of cease to flow days and the extent (river length) of zero-flow conditions (maximum recorded river length 687 km extending upstream from the river mouth) (Sun et al., 2008). Sediment loads were also reduced to one-tenth of natural which resulted in substantial changes to substrate composition in sedimentary environments of the delta (Wang et al., 2008). In downstream riverine reaches, changes to the sediment-water balance led to substantial sedimentation which reduced channel cross-sectional area, the magnitude of bank-full flows and flood discharge capacity, and increased water stage heights (Ru et al., 2003).

2.2 Physiochemical data

At each site, altitude (Alt: Garmin GPS, model eTrex H), water temperature (T: SATO, model SK-250WP), water depth (Z: Speedtech, model SM-5), and surface water velocity (U: Model LS 1206B) were recorded. Surface water samples collected from each site were analyzed in the laboratory for pH (Leici, Model PHS-2F); conductivity (Cond: Pengshun, Model PDS 307B); total nitrogen (TN: alkaline potassium persulfate digestion-UV spectrophotometry); total phosphorus (TP: ammonium molybdate method), and; chlorophyll *a* concentration (Chl *a*: absorbance at 665 nm and 750 nm using Unico UV-2000 spectrophotometer). Mean river discharge (Dis: $m^3 s^{-1}$) and sediment concentration (SC: kg m^{-3}) collected from each site between 1950 and 2005 were provided by Hydrological Bureau, Yellow River Conservancy Commission. Sediment type (ST) was classified using a six-point scale following the methods of Wang et al. (2006) as: 6, boulder and large cobble (>20 mm); 5, vegetation; 4, sand and silt (<0.02 mm); 3, gravel (>20 mm); 2, small cobble (2-20 mm); 1, fine sand (0.02-0.2 mm); 0, medium sand (0.2-2 mm).

2.3 Sample collection

In 2008, macroinvertebrates were collected on two occasions from 21 mainstream sites, of which four were located in reservoirs (Liujiaxia, Qingtongxia, Sanmenxia and Xiaolangdi): May-June (12 non-reservoir sites and 3 reservoir sites) and September- October (17 non-reservoir sites and 4 reservoir sites). The six additional sites were sampled on the second occasion to include a wider representation of site characteristics that occur in the Yellow River catchment. These additional sites were located throughout the catchment. Sampling locations spanned a river length of approximately 3,400 km between Kenli in the lower reaches to Liujiaxia in the upper reaches of the catchment (Fig. 1). Sampling sites were located at hydrographic stations; it should be noted that hydrographic stations on the Yellow River are not associated with control structures e.g. weirs, and therefore no additional hydraulic or habitat disturbances are present at these sites. Sites were assigned to apriori reaches based on their position in the catchment.

At each site, between six and eight samples of sediment were collected from the representative habitats (e.g. edge, run, pool, riffle and macrophyte). Samples were collected with a weighted Peterson Grab sampler (0.063 m^2) from sites with shallow water depths and low water velocity, and with a horizontal sediment sampler (3 m pole, 1L volume) from deeper sites with higher water velocity. Sediment samples were sieved in situ and macroinvertebrates were live-picked from the 420 µm fraction and preserved in 10% formalin. Sorted samples (tissue dry mass for Mollusca) were weighed (wet weight, nearest 0.0001 g) with an electronic balance (Sartorius, Model BS224 S) for calculations of biomass.

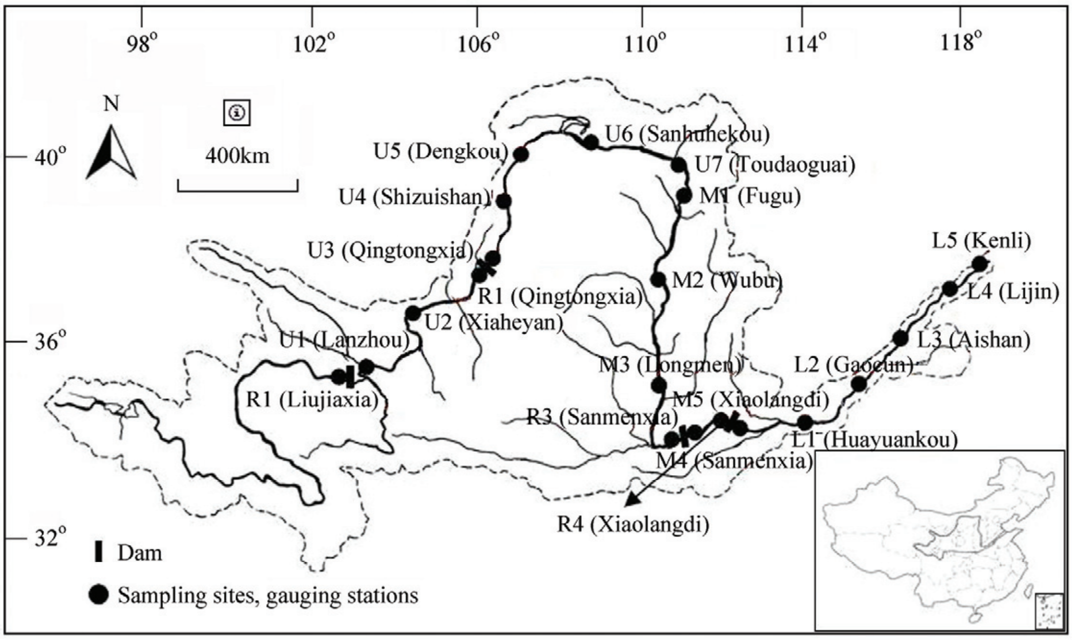

Fig. 1 Distribution of the sampling sites, stream gauges and major reservoirs on the mainstream of the Yellow River, China

Macroinvertebrates were identified in the laboratory with the aid of a dissecting microscope to the lowest possible taxon using identification keys (Brinkhurst and Jamieson, 1971; Morse et al., 1994; Liu et al., 1979). All identified taxa were assigned to functional feeding groups (shredders, collector-gatherers, collector-filterers, scrapers and predators) following the definitions of Morse et al. (1994). For taxa with several possible feeding activities, functional designations were equally proportioned.

2.4 Data analysis

Shannon-Weaver diversity index, Margalef's richness index and Pielou's evenness indices were calculated to investigate general differences in benthic macroinvertebrate assemblages among sites. Density (individuals m^{-2}) and biomass (g m^{-2}) of macroinvertebrates within each site and each reach (upper, middle and lower) were calculated using the arithmetic average from all samples. Sampling sites were classified on the basis of macroinvertebrate presence/absence using Two Way Indicator Species Analysis (TWINSPAN, Hill, 1979). Only species that were present in more than one sample were included in data analyses (50 species total). Relationships between macroinvertebrate assemblages (presence/absence and density) and environmental conditions were investigated using Canonical Correspondence Analysis (CCA; CANOCO 4.5) following the methods of Ter Braak and Smilauer (1998). Twelve environmental parameters (Alt, ST, T, Z, U, pH, Cond, TN, TP, Dis, SC and Chl *a*) and 50 macroinvertebrate taxa were used in the analysis. The most important environmental variables were identified by forward selection. Only statistically significant factors were selected for the final analysis. The statistical significance of Axes 1 and 2 was tested by using a Monte Carlo permutation test with 499 permutations under the full model. Environmental parameters were log transformed and density data were $\log_{10}(x+1)$ transformed prior to analyses to stabilize variances.

3 Results

3.1 Physiochemical parameters

Sites ranged in altitude from 1,723 to 6 m above sea level. Discharge was highest (> 1,250 m s^{-3}) at sites located in the lower reaches, downstream of site M4, and in the upper reaches (sites U1-U3–1,000 m s^{-3}). Discharge at most sites located in the mid-reaches (sites U4-M2) ranged from 822-965 m s^{-3}. Water temperatures were highest (range 22-24°C) at sites located in the mid and lower-catchment (sites M4-L1), lowest (range: 11-15°C) in the upper reaches between sites M2 and U1, and ranged from 15-19° C downstream of site L1. The water depths and velocity varied among sites depending on local conditions and ranged from 0.3-36.6 m and 0-0.85 m s^{-1} respectively. Chlorophyll *a* and sediment concentrations were variable although were generally highest in the mid to lower-reaches of the catchment. Sediment type varied among sites depending on their distance downstream from reservoirs; sites located immediately downstream of reservoirs were characterized by coarser substrates (cobbles and sands) whereas the sediments at all other sites comprised sands, some of which were vegetated. Conductivity and pH exhibited slight variation among sites although pH was highest in the upper-reaches and conductivity was highest in the mid-reaches. Total nitrogen and total phosphorus were highest in the upper-reaches (especially in U1 and M4) and lowest in the lower-reaches (Table 1).

Table 1 Environmental conditions measured at the sampling sites located on the main channel of the Yellow River and associated major reservoirs

Sites	Alt (m)	Dis ($m^3 s^{-1}$)	T (℃)	Z (m)	V ($m s^{-1}$)	TN ($mg L^{-1}$)	TP ($mg L^{-1}$)	Chl *a* ($\mu g L^{-1}$)	pH	Cond ($mS cm^{-1}$)	SC ($kg m^{-3}$)	ST
R1	1,723	–	15.2	10.9	0	0.430	0.251	0.728	9.23	0.431	–	Silt
U1	1,508	1,030	13.7	0.6	0.45	0.408	0.244	1.014	9.40	0.472	1.888	Cobble/gravel/sand
U2	1,227	1,040	14.4	0.5	0.34	0.464	0.433	2.912	9.25	0.575	2.080	Cobble/sand
R2	1,128	–	13.7	2.4	0.21	0.476	0.161	0.910	9.40	0.626	–	Silt/sand
U3	1,150	1,050	14.0	0.9	0.78	0.501	0.249	1.092	9.40	0.615	3.914	Cobble/sand
U4	1,084	965	14.6	0.5	0.25	1.200	1.073	1.820	9.33	1.000	1.878	Sand
U5	1,044	935	15.2	0.3	0.25	0.358	0.412	1.820	8.96	0.741	1.761	Sand/vegetation
U6	1,020	880	11.4	0.3	0.60	0.381	0.411	1.638	8.72	1.270	1.555	Sand
U7	1,039	834	15.1	1.3	0.78	0.025	0.348	1.941	8.53	1.143	1.099	Sand
M1	669	822	15.8	0.3	0.34	0.519	0.059	1.601	9.05	0.866	5.520	Cobble/sand
M2	636	951	14.6	0.6	0.68	0.978	0.257	1.698	8.08	0.783	9.408	Cobble/sand
M3	380	1,012	19.1	0.8	0.14	0.025	0.250	1.274	7.62	0.878	22.600	Sand/vegetation
R3	296	–	22.0	1.6	0.15	0.025	0.247	6.551	8.89	0.920	–	Silt
M4	289	1,330	22.2	0.4	0.40	0.549	0.285	4.368	8.91	0.902	19.750	Cobble/gravel/sand
R4	238	–	24.4	36.6	0.10	0.586	0.017	3.617	7.42	0.969	–	Silt
M5	120	1,342	22.8	0.4	0.36	0.577	0.013	1.248	7.41	0.926	23.050	Cobble/gravel/sand
L1	89	1,482	24.3	1.6	0.85	0.303	0.043	7.331	8.57	0.985	12.110	Sand/vegetation
L2	58	1,318	19.0	0.6	0.12	0.388	0.144	5.823	9.08	0.845	9.845	Sand
L3	33	1,311	18.6	0.4	0.10	0.025	0.149	5.095	9.47	0.851	1.640	Sand
L4	9	1,264	17.4	0.3	0.68	0.227	0.008	2.366	8.76	0.831	1.744	Sand
L5	6	–	14.9	0.3	0.10	0.025	0.103	1.893	9.62	0.816	–	Sand

3.2 Macroinvertebrate community structure

A total of 149 macroinvertebrate samples collected during the study contained 74 taxa belonging to 28 families and 56 genera. Insects represented the most diverse group and comprised 48 taxa. Oligochaeta comprised 17 taxa, molluscs comprised 5 taxa while other groups (Nematoda, Hirudinea and Crustacea) were represented by 4 taxa (Fig. 2a). The most abundant groups collected were the oligochaetes and insects, together representing 89.0% of all taxa collected. Diptera was the dominant group (70.5%) of insects (Fig. 2b). Macroinvertebrate assemblages were dominated (43.8%) by collector-gatherers, which included 32 taxa (Fig. 2c). Predators (22.6%) and scrapers (21.9%) were also relatively abundant and comprised 17 and 16 taxa, respectively. Shredders and collector-filterers only represented approximately 10% of the taxa collected (Fig. 2c).

Oligochaetes contributed most to macroinvertebrate density (58.1%) and biomass (36.3%) throughout the river (Figs. 3a-b). Collector-gatherers were the dominant functional feeding group contributing 44.6% and 43.1% to the density and biomass of taxa collected respectively (Figs. 3c-d).

3.3 Spatial variation in macroinvertebrate community structure

The number of macroinvertebrate taxa varied among sites (F =8.34, P<0.05), however not among reaches or reservoirs (Fig. 4a). Taxa richness ranged from 28 (HYK) to two (KL). Thirty-six taxa were collected in upper reaches, 42 taxa in mid reaches, 35 taxa in lower reaches and 38 taxa in reservoirs. Collector-gatherers and scrapers dominated macroinvertebrate assemblages in all reaches, except the upper reaches, where collector-gatherers and predators were the dominant feeding groups (Fig. 4b). The Shannon-Weaver and Margalef's richness indices were higher in middle reaches compared with both upper and lower reaches and reservoirs (Fig. 5).

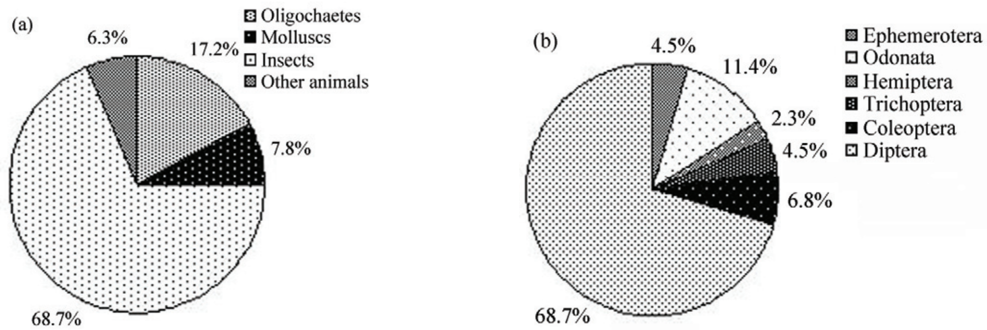

Fig. 2 Percentage of macroinvertebrate taxa in a) broad taxonomic groups, b) order of insects and c) functional feeding groups in the Yellow River

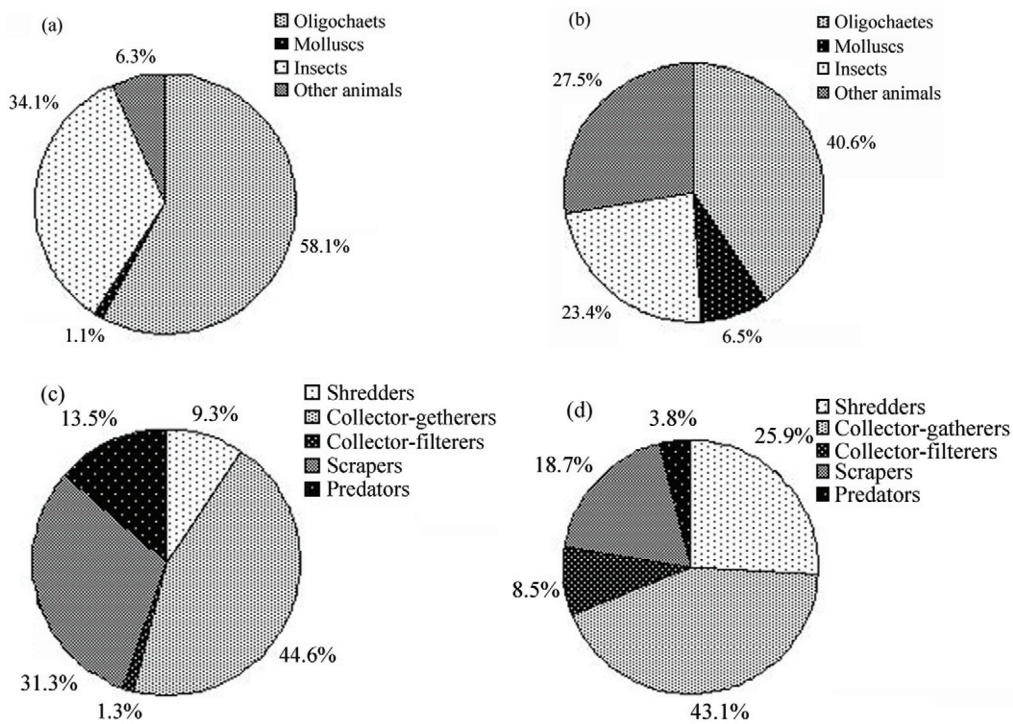

Fig. 3 Percentage of density (ind m^{-2}), biomass (g m^{-2}) of each taxonomic group (a, density; b, biomass) and functional feeding groups (c, density; d, biomass) of macroinvertebrates in the Yellow River

Macroinvertebrate density and biomass were greater in reservoirs compared with the river; average density and biomass in riverine sites was 599 individuals m^{-2} and 0.626 g m^{-2} respectively and in reservoir sites was 945 individuals m^{-2} and 0.918 g m^{-2} respectively. Fourteen species accounted for 85.1% and 83.2% of the total density and biomass (respectively) from riverine sites, and 13 species accounted for 86.7% and 88.3% from reservoir sites (Table 2). Density and biomass were dominated by few species in each area. *Nais communis* and *Acalcarella* sp. dominated total macroinvertebrate density in riverine sites, together contributing 40.5% of the total density, and *Branchiura sowerbyi* and *Exopalaemon modestus* contributed 43.6% to total biomass in the same sites. *Nais communis*, *Tubifex tubifex* and *Culicoides* sp. together contributed 45.2% of total density in reservoir sites and *Radix lagotis* and Glossiphonidae sp.

combined to contribute 42.8% of total biomass in the same sites (Table 2).

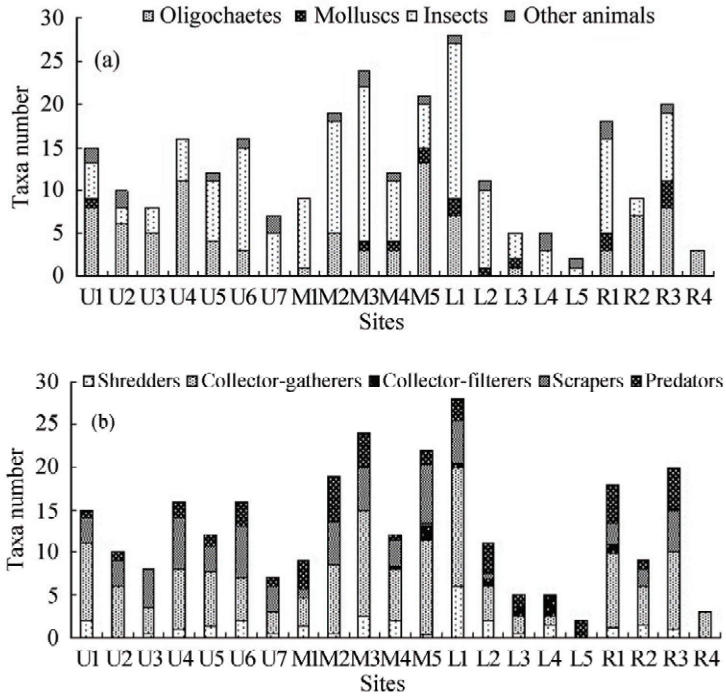

Fig. 4 Macroinvertebrate taxa number of each taxonomic group (a) and functional feeding group (b) collected from sampling sites in the Yellow River

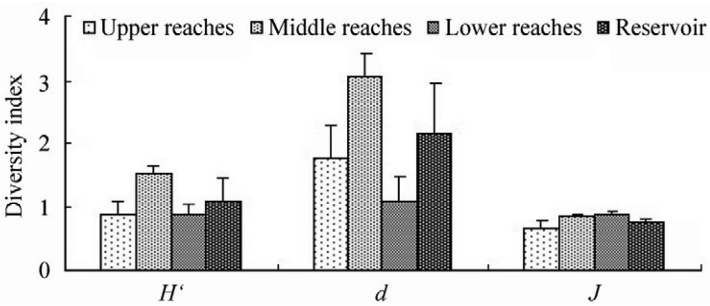

Fig. 5 Mean Shannon-Weaver (*H'*), Margalef's richness (*d*) and Pielou's evenness (*J*) indices for macroinvertebrate assemblages in the upper, middle, lower reaches and reservoirs of the Yellow River

Mean macroinvertebrate densities were highest in the upper reaches (952 ± 323 individuals m^{-2}) compared with both the mid (462 ± 143 individuals m^{-2}) and lower (252 ± 92 individuals m^{-2}) reaches (Fig. 6). In contrast, biomass was higher at sites in the lower (0.702 ± 0.383 g m^{-2}) and mid (0.404 ± 0.178 g m^{-2}) reaches compared with sites in the upper reaches (0.801 ± 0.235 g m^{-2}). Taxa that contributed most to macroinvertebrate density varied spatially: oligochaetes dominated assemblages at sites in the upper reaches, insects dominated assemblages at sites in the middle reaches and other animals (eg. Crustacea) dominated sites in the lower reaches.

The contribution of each functional feeding group to the density and biomass of macroinvertebrates collected at each site also varied spatially (Fig. 7a-b). Scrapers and collector-gatherers were dominant in upper reaches (49.1%, 39.2% and 6.5%, 78.3% of density and biomass respectively). In the mid reaches and reservoirs, collector-gatherers were dominant (50.0%, 47.5% and 57.3%, 42.7% of density and biomass respectively). In contrast, predators and shredders dominated macroinvertebrate assemblages at sites in the lower reaches (50.8%, 19.8% and 8.6%, 81.5% of density and biomass respectively).

Table 2 Percentage of dominant (% of density or biomass ≥ 5%) macroinvertebrate taxa in the Yellow River.

Species	Mainstream		Reservoirs	
	Density (%)	Biomass (%)	Density (%)	Biomass (%)
Oligochaeta				
Nais communis	29.5	1.7	17.6	0.9
Paranais frici	6.4	0.4	6.7	1.6
Tubifex tubifex	6	8.1	11.5	9.1
Branchiura sowerbyi	7.3	13.5	3.2	5.0
Limnodrilus sp.	7.8	8.8	8.3	10.4
Limnodrilus udekemianus	2.4	4.2	7.5	6.2
Molluscs				
Radix lagotis	0.2	1.5	1.3	20.2
Corbicula fluminea	0	0	0.7	9.8
Limnoperna lacustris	0.4	5.6	0	0
Insects				
Culicoides sp.	0.7	0.3	16.1	0.6
Acalcarella sp.	11.1	2.2	6.1	0.2
Polypedilum flavum	6.8	1.4	5.2	1.6
Other animals				
Trichonematidae sp.	5.5	0.3	2.1	0.1
Exopalaemon modestus	0.6	30.1	0	0
Gammaridae sp.	0.4	5.1	0	0
Glossiphoniidae sp.	0	0	0.4	22.6
Total No. dominant species	14	14	13	13
Proportion (%) of total	85.1	83.2	86.7	88.3

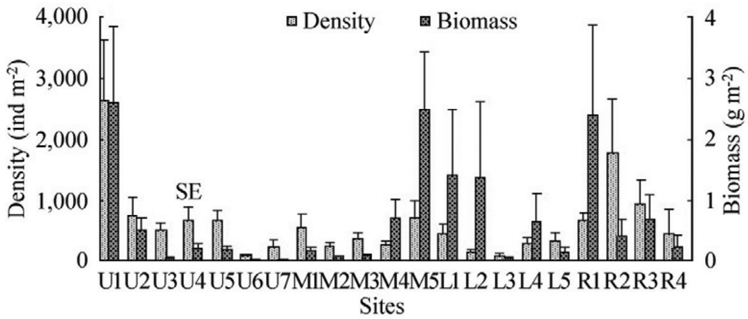

Fig. 6 Density (ind m^{-2}) and biomass (g m^{-2}) of macroinvertebrate groups collected from sampling sites in the Yellow River

3.4 Classification of sampling sites

Classification analysis identified six site-groups based on macroinvertebrate assemblage structure (Fig. 8). Further examination revealed groups five and six were similar in species richness and were therefore combined to form one group, resulting in the final classification of five, clearly-identified groups (A, B, C, D, and E). Indicator species important in each of the five site-groups were identified as; *Micropsectra* sp. (Group A and B), *Polypedilum* sp. (Group C and D) and *Acalcarella* sp. (Group E). Site groups also showed distinct environmental conditions. Group A comprised sites located downstream of reservoirs where the sediment was dominated by coarser particle sizes including boulder, cobble and coarse sand. Group B comprised sites with various degrees of riparian vegetation. Group C comprised only sites located in the reservoirs, all of which displayed greater water depths and lower water velocity compared with riverine sites. Group D comprised sites where point source pollutants were high and assemblages were dominated by relatively tolerant macroinvertebrate taxa (e.g. oligochaetes). Group E comprised sites located in the lower reaches of the catchment where river discharge was higher and sediments were dominated by finer particle sizes including fine sands.

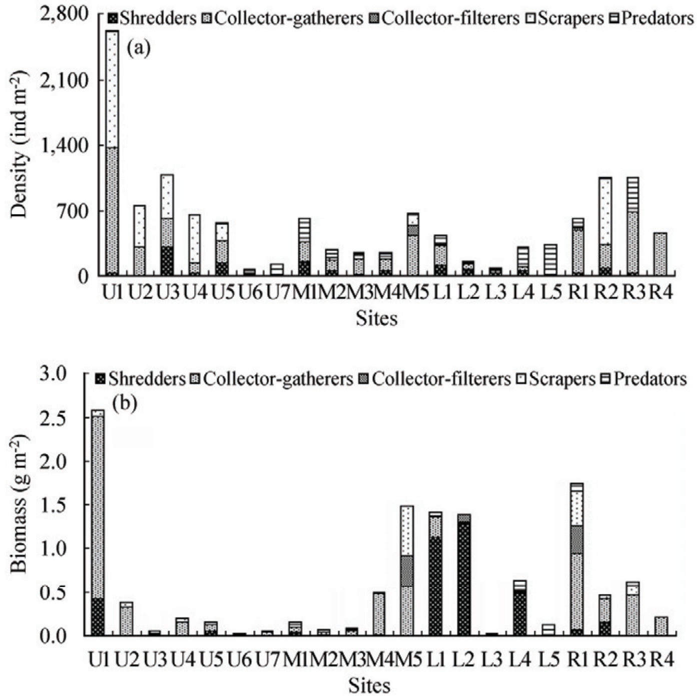

Fig. 7 Density (a) (ind m^{-2}) and biomass (b) (g m^{-2}) of functional feeding groups collected from sampling sites in the Yellow River

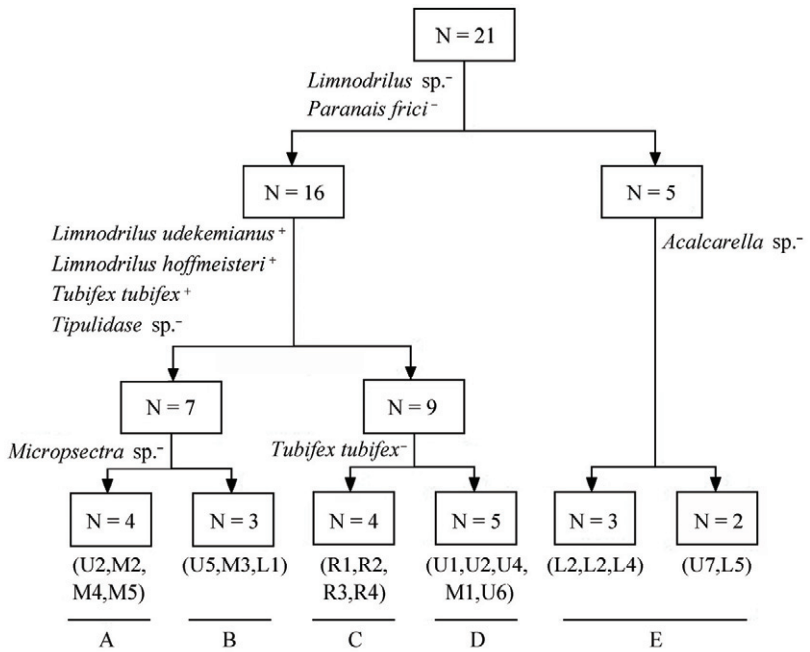

Fig. 8 Dendrogram of macroinvertebrate presence/absence. Taxa name are the indicators for each of the dichotomies

3.5 Environmental influence on macroinvertebrate assemblages

Analyses of forward selection and Monte Carlo permutation test revealed altitude, pH, total nitrogen and total phosphorus as the important environmental factors influencing the presence/absence of macroinvertebrates (Fig. 9a; Table 3), The first two CCA axes accounted for 20.6% and 64.1% of the cumulative macroinvertebrate species presence and species-environment relationship respectively. Similarly, altitude, pH, total nitrogen, total phosphorus and sediment concentration were important environmental factors influencing the density of macroinvertebrates (Fig. 9b; Table 3). The first two CCA axes accounted for 21.3%, and 56.1% of the cumulative macroinvertebrate species density and species-environment relationship respectively.

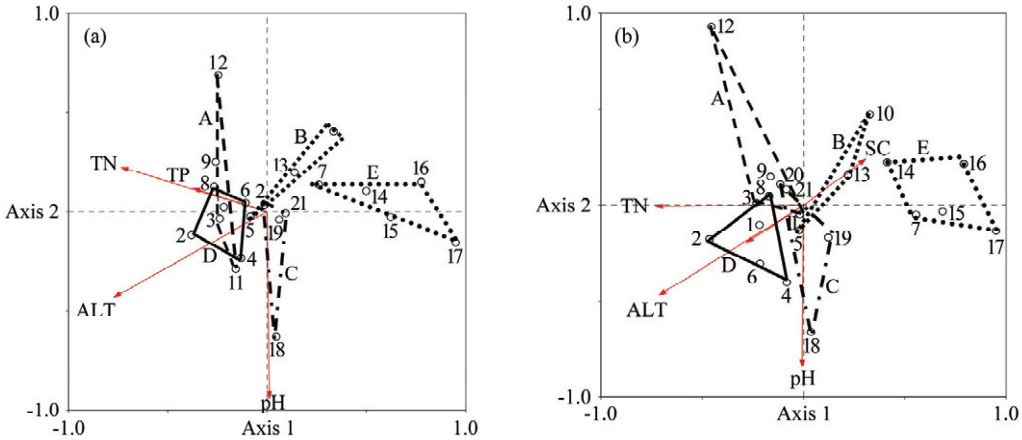

Fig. 9 CCA bipots for presence/absence (a) and density (b) of macroinvertebrate and environmental factors. Environmental factors include: ALT, altitude (m); pH; TN, total nitrogen (mg L^{-1}); TP, total phosphorus (mg L^{-1}); SC, sediment concentration (kg m^{-3}). A-E represent groups 1 to group 5 identified in TWINSPAN; The number 1-21 represent sampling sites: 1, U1; 2, U2; 3, U3; 4, U4; 5, U5; 6, U6; 7, U7; 8, M1; 9, M2; 10, M3; 11, M4; 12, M5; 13, L1; 14, L2; 15, L3; 16, L4; 17, L5; 18, R1; 19, R2; 20, R3; 21, R4 (c.f. Fig. 1 for locations)

Table 3 Eigenvalues and cumulative percent variation for two CCA axes, and significant environmental attributes influencing macroinvertebrate presence/absence and density in the Yellow River

	Present/absence		Density	
	Axis1	Axis2	Axis1	Axis2
Eigenvalues	0.46	0.37	0.50	0.38
Species-environment correlations	0.95	0.97	0.96	0.96
Cumulative percentage variance				
of species data	11.4	20.6	12	21.3
of species-environment relation	35.6	64.1	31.7	56.1
Altitude (m)	-0.69	0.41	-0.67	-0.24
pH	-0.73	-0.17	-0.62	-0.50
Total nitrogen (mg L^{-1})	-0.35	-0.02	-0.71	-0.09
Total phosphorus (mg L^{-1})	0.05	0.77	0.26	-0.25
Sediment concentration (kg m^{-3})			0.31	0.53

4 Discussion

Before this study, only limited information was available on the aquatic macroinvertebrate assemblages in the Yellow River. These data had limited spatial resolution and were based on the incidental collection of macroinvertebrates during fisheries surveys conducted in 1959 and 1986 in large reservoirs. A total of 25 and 71 taxa were recorded in 1959 and 1986 respectively (Institute of Zoology, Chinese Academy of Sciences, 1959; Investigation group of fishery resources of the Yellow River System, 1986). Data from surveys conducted in 1986 between Lanzhou to Kenli identified 42 taxa of insects as the most dominant group as well as 3 taxa of oligochaetes, 6 taxa of molluscs and 6 taxa of other animals. A comparison of these data with those reported here indicates a substantial increase in taxa richness except for the gastropoda and crustacea (Fig. 10). Many of the species recorded in the Yellow River during this study are common in Chinese freshwaters and are distributed throughout river catchments (Morse et al., 1994).

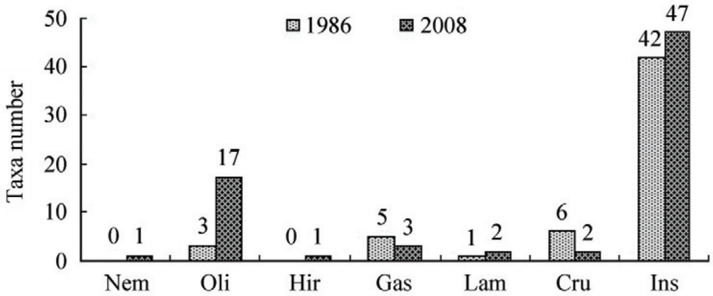

Fig. 10 Macroinvertebrates taxa number between 2008 (this study) and 1986 (Investigation group of fishery resources of the Yellow River system. 1986) in the Yellow River

Differences in sampling regime and collection techniques undoubtedly contributed to the difference in macroinvertebrate assemblages between 1986 and this study. Nonetheless, the primary influences on macroinvertebrate assemblages in the Yellow River (identified in this study) were pollution, stability of sediment and sediment concentration. Extensive agricultural and industrial development the middle and lower reaches of the Yellow River have extensively modified the sediment, integrity of riparian vegetation, and water quality (Ni and Han, 2005). To supply increasing demands for agricultural and industrial water supply 21 large-scale and 136 smaller dams and regulatory structures have been constructed. The floodplain of the lower Yellow River supports both intensive agricultural activities and rural farming communities and a complex system of dykes and levees have been constructed to manage flooding of these areas (Shi and Ye, 1997). The combination of river regulation and the levee system has resulted in substantial sediment aggregation and a reduction in discharge capacity, loss of lateral (with the floodplain) and longitudinal connectivity (increase frequency and duration of cease to flow events) in the downstream reaches (Liu, 2005). Previous surveys of macroinvertebrate assemblages were conducted under these substantially modified environmental regimes.

Since 2001, sediment-water releases from Xiaolangdi dam have been implemented to manage the effects of the sediment-water imbalance and the extent (temporal and spatial) of cease-to-flow conditions (Xu et al., 2005). These sediment-water releases have had substantial benefit for some geomorphological features and the increase in macroinvertebrate taxa richness may also provide some preliminary indication of ecological response (Zhang et al., 2007; Xu et al., 2005). Interpretation of this response remains difficult due to the comparability of 1986 (pre-water releases) data with that of the present study.

Moreover, although important physical processes have been partially restored, ongoing effects of this regulation include a reduction in the period of maximum sediment discharge and a decrease in the peak river discharges that naturally transport high sediment loads through the lower reaches. Furthermore, climate related changes in rainfall and temperature have resulted in a general warming and drying of the Yellow River catchment (Li, 2005). These modifications are also expected to have a variety of effects on ecological function within the river channel, the ecological response to which is poorly understood.

This study provides important insights into such ecological responses. Altered sediment dynamics resulting from regulation has previously been suggested as the primary control on the low diversity and abundance of macroinvertebrate assemblages in the lower Yellow River (Liu, 2005). Similar conclusions have been identified in other catchments with similar disturbances in which high turbidity and the mobile sediments were identified as primary controls on macroinvertebrate assemblages (Vasconcelos and Melo, 2008). This study reports the mean taxa richness at each site as 13 and assemblages, particularly from the lower reaches, comprised few benthic species. Comparison of the results presented here with those from other large rivers showed a reduced taxa richness, density and biomass in the Yellow River (Table 4). In particular, the taxa richness of molluscs in the Yellow River (6%) was fewer than that previously described for other similarly large rivers (c.f. 50% in the Nile River and 21% in Yangtze River) which usually exhibit greater taxa richness, abundance and biomass (El-Shabrawy and Fishar, 2009; Xie et al.

1999). As bivalves are filter feeders and are dependent on sandy substrates for habitat, and gastropods are scraper feeders and are dependent on organic detritus, alterations to the natural downstream transport of high sediment concentrations, including detrital material, may explain the observed low species richness of both these taxa in the Yellow River (Xiong et al., 2008). These modifications have also consolidated coarse sand sediments, and smothered them with layers of finer sediment. Benthic fauna require unconsolidated substrates that allow them to use interstitial spaces between particles for habitat (Duan et al., 2009). These changes may therefore account for the types of species recorded in the lower Yellow River. In contrast, macroinvertebrate diversity in mid reaches was higher than at sites in other reaches. This may be due to the fact that most of the sites (Fugu, Wubao, Sanmenxia and Xiaolangdi) sampled in mid reaches were located downstream of dams, and therefore characterized by coarser substrates. CCA also showed altitude, sediment concentration, pH, total nitrogen and total phosphorus were main influencing factors.

Table 4 Comparisons of macroinvertebrate density, biomass and dominant taxa between the Yellow River and other large rivers

	The Nile River (El-Shabrawy and Fishar, 2009)	The Yangtze River (Xie et al., 1999)	The Yellow River (This study)	The Yili River (Unpublished data)
MAR (m^3)	840×10^8	$9{,}600\times10^8$	580×10^8	117×10^8
MAP (mm)	1,000-2,000	1,100	478	200-300
SC (kg m^{-3})	1.6 (Aswan)	1.2 (Yichang)	35.0 (Sanmenxia)	0.6 (Mean)
Habitat	Sand-silt, vegetation	Sand-silt, no vegetation	Sand, no vegetation	Sand-silt, gravel, cobble, vegetation
Sampling sites		30	21	17
SN	52	123	73	70
D (ind m^{-2})	1,500	3,468	599	1,400
B (g m^{-2})	142	14.8	0.62	0.46
Dominant group	Molluscs	Oligochaetes	Oligochaetes	Insects

Note: MAR, Mean annual runoff; MAP, Mean annual precipitation; SC, Sediment concentration; SN, Taxa number; D, Density; B, Biomass

Expansion of agricultural activities, especially on the fertile floodplain has resulted in degradation of riparian vegetation and both groundwater and surface water dependant wetland systems (Liang and Ding, 2004). Historical water quality data indicates concentrations of TN, NH_4^+-N and TDS have all increased over the past 40 years in the mainstream of Yellow River (Chen, 2006). The levels of pollution recorded may be expected to select for only tolerant taxa. Indeed, this study has shown that macroinvertebrate assemblages in upper and middle reaches of the Yellow River were generally comprised of pollution-tolerant taxa. Using the macroinvertebrate tolerance range described in Wang and Yang (2004), many of the species collected have values greater than 8 (Maximum 10). Although altitude, and or position in the catchment is known to influence macroinvertebrate assemblages, the dominance of pollution tolerant taxa in the mid to upper reaches of the Yellow River, described here, is probably influence by the high point-source pollution that is present in these reaches of the catchment (Suren, 1994; Jacobsen, 2004; and this study).

The River Continuum Concept hypothesized the size of detrital matter would decrease along a drainage network (Vannote et al., 1980). The distribution of organic matter within catchments influences functional feeding groups such that shredders and collectors dominate upstream assemblages where coarse and fine particulate organics are plentiful, collectors and scrapers dominate in middle reaches and collectors and predators dominate groups in lower reaches (Vannote et al., 1980). Interestingly, the distribution of functional feeding groups in the Yellow River does not fully support these predictions. We identified collectors and scrapers as the dominant feeding groups in upper reaches, collectors and predators in middle reaches, predators and shredders were predominant in lower reaches. We hypothesise that these results are influenced by the high pollution levels characteristic of sites located in the mid and upper catchment (i.e. group D identified by TWINSPAN analysis), and the resultant dominance of Oligochaeta in these reaches.

This study presents, for the first time, spatially-specific data on aquatic macroinvertebrate assemblages in the Yellow River. Assemblages were found to be relatively rich in species based on global standards, however, in comparison to other similar large rivers, macroinvertebrate richness, density and biomass in the Yellow River were found to be relatively low. Pollution and the diversity and stability of sediment were identified as primary controls and macroinvertebrate assemblages. While our data indicates significant difference between previous surveys, interpretation is limited by the lack of long-term data. Nonetheless, the data presented here provides a benchmark for monitoring ecological conditions in the Yellow River, and specifically ecological response to major restoration works, including the development and implementation of environmental flows which represents a key focus of current management activities.

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