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MAN-MADE SECONDARY CHANNELS ALONG THE RIVER RHINE (THE NETHERLANDS); RESULTS OF POST-PROJECT MONITORING

JENNIE H.E.J. SIMONS[a,*], CORIAN BAKKER[a], MAX H.I. SCHROPP[a], LUC H. JANS[a], FRANK R. KOK[b] AND ROB E. GRIFT[c]

[a] *Institute for Inland Water Management and Waste Water Treatment RIZA, PO Box 9072, 6800 ED Arnhem, Netherlands*
[b] *Directorate-General for Public Works and Water Management, Eastern Netherlands Division, PO Box 9070, 6800 ED Arnhem, Netherlands*
[c] *Fish Culture and Fisheries Group, Wageningen Institute of Animal Sciences, Wageningen University, PO Box 338, 6700 AH Wageningen, Netherlands*

ABSTRACT

Owing to river regulations in the past and intensive farming, the ecological value of the floodplains of the River Rhine in The Netherlands has decreased dramatically. One way to restore riverine biotopes is to create permanently flowing channels in the floodplain. Along the River Waal, the main branch of the Lower River Rhine, two such secondary channels have been created since 1994. A post-project monitoring programme of 5 years was set up, which included hydrological, morphological and ecological parameters. This article focuses on the monitoring of aquatic macrophytes, aquatic macroinvertebrates, fish and wading-birds.

The results show that man-made, excavated secondary channels function as a biotope for riverine species including the more demanding rheophilic species. The demands for shipping and protection against flooding on the River Waal cause constraints on secondary channels. Despite these constraints there is still enough space for hydromorphological processes to create new habitats in secondary channel 1, near Opijnen. The space for hydromorphological processes is less in secondary channel 2, near Beneden-Leeuwen. The density and the number of (rheophilic) species are for a large part influenced by the water level and frequent inundation caused by the high hydrological connectivity. Man-made secondary channels seem to provide suitable habitat that is currently lacking for a broad range of rheophilic macroinvertebrate and fish species in the Lower River Rhine in The Netherlands. Owing to the lack of suitable habitats for rheophilic macroinvertebrate and fish species before the creation of the secondary channels, the importance of longitudinal and transversal migration could be illustrated by the drift of macroinvertebrates during floods and the seasonal migration of Age-0 and Age-1 + fish species. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: ecology; floodplain restoration; post-project monitoring; river–floodplain; river restoration; side channel

INTRODUCTION

The River Rhine in The Netherlands

The River Rhine rises in the Swiss Alps and flows through Germany, France and The Netherlands towards the North Sea. Its basin covers 185 000 km^2, and the average discharge at its mouth measures 2300 m^3/s. In The Netherlands the River Rhine divides into three branches, Rivers Waal, Nederrijn and IJssel (Figure 1). The largest of these branches is the free-flowing River Waal, which carries about 70% of the total Rhine flow. In addition, the River Waal is an important shipping connection between the port of Rotterdam and Germany, with 160 000 cargo vessels crossing the German–Dutch border every year. The hydrological and morphological characteristics of the River Waal are described in Table I.

Since the river regulation works of the 19th and 20th century, the low-water bed of the River Waal has been fixed by groynes. They create a deep and uniform shipping channel and protect the riverbanks from

* Correspondence to: Institute for Inland Water Management and Waste Water Treatment RIZA, PO Box 9072, 6800 ED Arnhem, Netherlands. E-mail: j.simons@riza.rws.minvenw.nl

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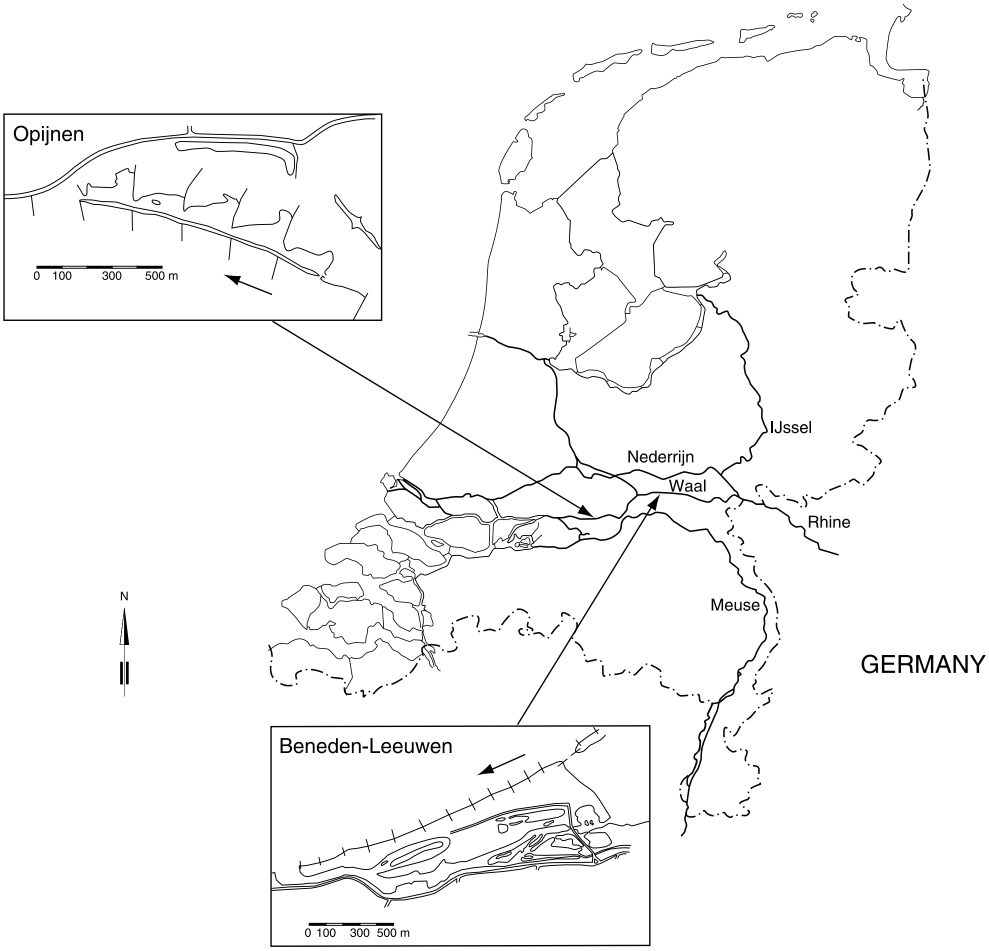

Figure 1. The Rhine branches in The Netherlands, and the location of the two man-made secondary channels along the River Waal

Table I. Characteristics of the River Waal the largest Rhine branch in The Netherlands

Length	83 km
Surface area	123.5 km^2
Mean width main channel	370 m
Mean width winterbed	1470 m
Flow rate	>1.0 m/s
Discharge (1976–1997)	
Average	1480 m^3/s
Highest	7640 m^3/s (January 1995)
Lowest	622 m^3/s
Peak discharge 1993–1999	December 1993/January 1994 January 1995
Discharge within 1 year compared with average year (1901–2000)	1994, 1995, 1999 high 1998 average 1993, 1996, 1997 dry

erosion. Because the groynes prevent the river from meandering freely, no regeneration of the floodplain can take place. As a result, the ground level of the floodplain is rising steadily because of the continuous deposition of river sediments. In addition, most morphological features of the floodplain, such as former channels, have been levelled out, either by man or by the river itself, leaving only little spatial variation in ground level and thus in inundation frequency. These factors, combined with the intensive use of the floodplains for farming, have led to a great loss of characteristic river ecotopes, such as shallow (flowing) water, islands, unprotected banks, floodplain forest and floodplain grasslands (Brink *et al*. 1996; Postma *et al*., 1996; Bakker *et al*., 1998). Secondary channels or channels and oxbow lakes with one open connection with the main channel (parapotamal channels) might improve the ecosystem of the Dutch part of the Rhine since they increase the amount of shallow (flowing) water along the main channel. Shallow water as part of ecologically sound riverbanks is being created in the main channel, but these areas are exposed to high physical loads owing to the navigation that reduces the suitability of this biotope for submerged aquatic vegetation and helophytes, Age-0 fish and some macroinvertebrate species (Boeters *et al*., 1994; Simons and Boeters, 1998). Secondary channels behind a longitudinal dike or in the floodplain are more sheltered from the navigation-induced physical loads and are supposed to provide suitable biotopes for riverine fauna.

Since the 1970s, the water quality of the Rhine has improved significantly. The 'Rhine Action Programme' in particular, which was agreed upon by the Rhine Bank States in 1987, has accelerated existing programmes to improve and protect the water quality. A second important objective of the 'Rhine Action Programme' was the restoration of lost river ecosystems. In The Netherlands this concept was further elaborated in the Third National Policy Document on Water Management (Netherlands Ministry of Transport, Public Works and Water Management, 1989). In this document secondary channels are one of the measures that were recommended for the ecological rehabilitation of the Rivers Rhine and Meuse. This policy has been continued in the Fourth National Policy Document on Water Management (Netherlands Ministry of Transport, Public Works and Water Management, 1998).

Secondary channels

Originally the River Waal was a meandering river with multiple channels, some of which were abandoned. The variety of flow velocities and water depths produced a great number of different riverine biotopes. Unfortunately, this situation is not likely to return by itself. The economic interests of inland shipping on the River Waal preclude the removal of groynes and other artificial controls on channel morphology. Moreover, freely meandering river channels would pose a threat to the stability of dykes.

Reconnecting existing channels to the river is undesirable because the ecological value of the isolated former river channels is relatively high since for the larger part, the floodplains are being used for intensive farming. The largest gain in ecological terms, therefore, could be achieved by converting farmland to nature reserves. This is in contrast to the strategy of restoring secondary channels, for instance, along the River Danube in Austria (Schiemer *et al*., 1999) and Hungary (Marchand *et al*., 1994) and the River Rhone in France (Henry *et al*., 1995). An alternative to natural secondary channels is to excavate artificial secondary channels in the floodplains of the River Waal. Strict conditions, with regard to shipping and protection against flooding, need to be applied to any such development. A secondary channel has a permanent flow, shallow water depth and natural banks on which the macrophyte association is directly controlled by the river stage (Schoor and Sorber, 1999). Apart from high hydrological connectivity, secondary channels are also characterized by morphodynamic processes, with erosion and sedimentation as major driving factors in habitat formation.

Since 1989, the possibilities for man-made secondary channels in the floodplains of Dutch rivers have been explored by means of literature studies and model studies. Schropp (1995) and Schropp and Bakker (1998) describe some of this research. Diverting flow towards a secondary channel reduces the sediment-carrying capacity of the main channel, and will lead to sedimentation in the main channel. In view of the economic importance of inland shipping, only little aggradation of the main channel bed can be allowed, and thus the secondary channel flow has to be limited to only a few percent of the total river discharge. In addition, the sediment load of the River Waal makes it hard to create a secondary channel that is morphologically active, yet does not get blocked quickly. Siltation of a secondary channel can be slowed down by measures such as a sediment trap or a bottom sill, to keep the sediment load away from the secondary channel.

In 1994, the first two permanently flowing secondary channels in The Netherlands were created at Opijnen (Secondary channel 1) and Beneden-Leeuwen (Secondary channel 2) along the River Waal (Figure 1). Their discharge capacities (respectively, maximum 1.2 and 0.5% of the discharge of the River Waal) are such that no noticeable morphological effect on the main channel is to be expected. This assumption has been confirmed by post-project depth measurements. In secondary channel 1, only little erosion and sedimentation takes place in the secondary channel itself, probably because of the location in an outer bend of the river and a bottom sill at the intake (Figure 2). In secondary channel 2, erosion and sedimentation in the secondary channel are nearly absent, because of a large sediment trap at the intake and very low flow velocities in the channel itself.

Both secondary channels serve as pilot projects to explore the morphodynamic possibilities and the ecological value of secondary channels, within the constraints of safety against flooding and commercial navigation in the main channel. To this end a post-project monitoring plan with hydrological, morphological and ecological parameters was set up initially for the period of 1993–1998. In this article, we focus on the post-project monitoring of the ecological parameters only. Since a presentation of all ecological parameters measured under the post-project monitoring programme would be too extensive for this article, the ecological value of secondary channels will be illustrated by the monitoring results of submerged macrophytes, aquatic macroinvertebrates, fish and wading birds. The results will be presented by describing the two secondary channels as separate cases.

METHODS

Ecological post-project monitoring programme

The main ecological research questions is:

> Do man-made secondary channels fulfil their task as a substitute for a biotope that no longer exist in the Lower River Rhine ecosystem?

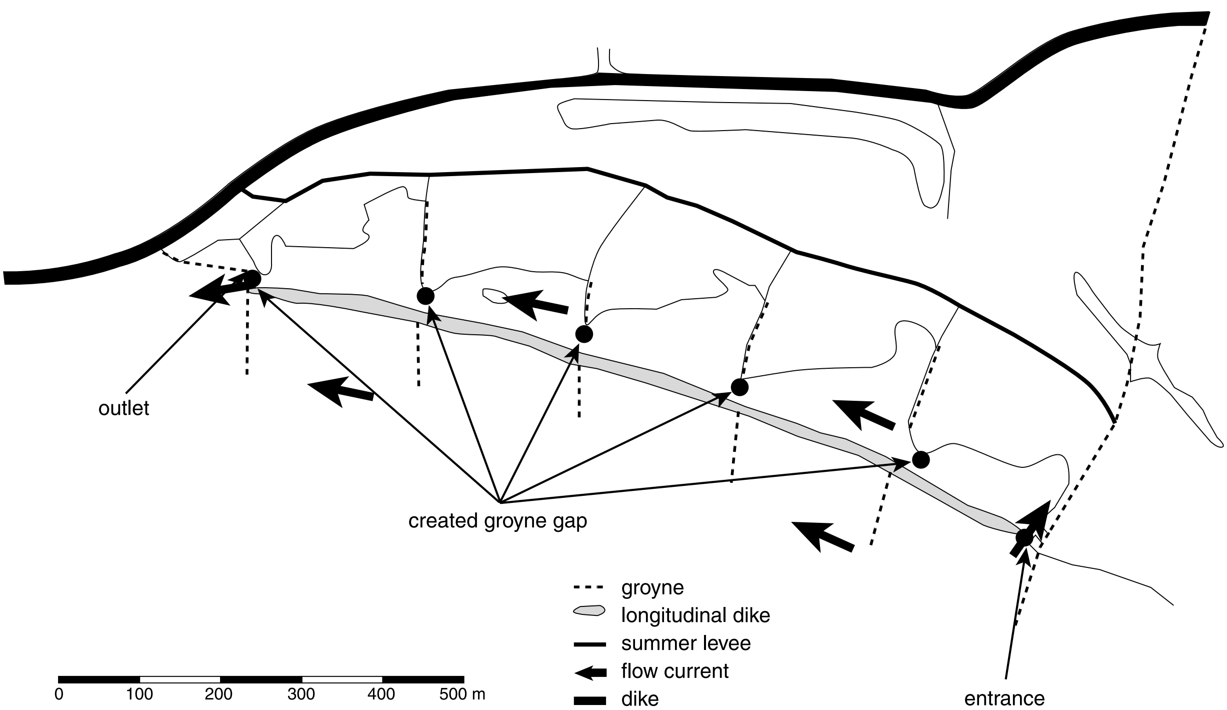

Figure 2. Design of secondary channel 1 (SC1)

For answering this question the following secondary questions were formulated:

(a) Is there, despite the constraints, still enough space for hydromorphological processes to create suitable habitat characteristic for secondary channels?
(b) Do characteristic riverine species such as rheophilic macrophyte, macroinvertebrates, fish species and wading birds benefit from the created biotopes?

These questions led to the post-project monitoring programme for the ecological parameters described in Table II. At first, the post-project monitoring goal for both secondary channels was the evaluation of ecological development of the project areas in general. A monitoring strategy for rivers in The Netherlands (Buijse *et al.*, 1998) led to a shift in the targets for the monitoring programme, comparable to the strategy for the Kissimmee River (Dahm *et al.*, 1995). The monitoring programme for signalling trends was converted into gaining in-depth information for improving ecological knowledge and information to improve development of design tools and guidelines for secondary channels.

Aquatic macroinvertebrates, fish (Table III) and wading birds are indicative of the quality of secondary channels. The results of the other ecological parameters of the post-project monitoring (e.g. macrophyte association, breeding birds, wintering birds, grasshoppers (Orthoptera) and amphibians) are less directly linked to the secondary channel itself, but rather to the increased inundation frequency and the decreased management influence on the banks of the secondary channel. They will be described only when necessary for the understanding of the macroinvertebrates, fish and wading birds.

The inundation frequency is the long-term (1901–2000) average duration (days per year) the floodplain is inundated and has been divided into six classes: less than 2, 2–20, 20–50, 50–150, 150–364 and more than 364 days of inundation per year (Rademakers and Wolfert, 1994).

CASE SECONDARY CHANNEL 1

Description of secondary channel 1

In 1984, a longitudinal dike with elongated groynes was made on the right bank of the River Waal close to the village of Opijnen, river km 929.430–930.370 (Figure 1). This was meant to improve conditions for commercial navigation by deepening the left part of the main channel. The longitudinal dike closed off the former groyne fields from the main channel. As a result of the national policy to create ecologically sound riverbanks and floodplains, a small, artificial, secondary channel was created in 1994 (Figure 2). The bed level and the bottom sill at the entrance of the channel guarantee flow of water during 99% of the year. The hydrological, morphological and management characteristics of this secondary channel are described in Table IV.

The right bank of the channel is highly influenced by the water level of the main channel because of the very gradual slope and by the grazing activity of cows. This results in a zonation of the plant communities that differ in area annually according to the inundation frequency (Figure 3). The zonation consists of shallow water with very low densities of submerged waterplants like *Potamogeton pectinatus*. The sandy or silted shores, with an inundation frequency of more than 150 days a year, are sparsely vegetated and dominated by species like *Limosella aquatica*, *Eleocharis acicularis* and *Chenopodium rubrum*, *Plantago major* subsp *major* and the co-dominant species *Pulicaria vulgaris*. In the upstream part and along the longitudinal dike some *Populus nigra* and *Salix* species have germinated and are developing. The frequently inundated zone (that is inundated 50–150 days a year) is dominated by *Potentilla anserina*, *P. reptans*, *Rorippa sylvestris* and *Phalaris arundinacea*. Highly characteristic species like *Juncus compressus* and *Inula brittanica* are also found. The occasionally inundated zone (<50 days a year) is dominated by *Agrostis stolonifera*, *Lolium perenne*, *Leontodon autumnalis* and *Urtica dioica*. Characteristic species like *Trifolium fragiferum*, *Cuscuta europaea* and *Eryngium campestre* are found at low densities.

Table II. Post-project monitoring program for SC1 and SC2 for macroinvertebrates, fish and wading birds

	SC1 year and month	SC1 sample points and/ or frequency	SC2 year and month	SC2 sample points and/ or frequency	SC1 and SC2 method
Species composition	1993 11	27	1994 5/6; 10	35	Fishing net; brushing
aquatic			1995 2/5/6; 8	29	stones and wood; sieve
macroinvertebrates[a]	1996 4/5; 8/9	35	1996 4/5; 8/9	24	500 μm
			1997 5; 8	19	
	1998 5/6; 9	36			
Adult Odonates	1094 5–8	5 surveys	1994 6–8	5 surveys	Survey on calm, sunny
species composition		5 surveys	1995 6–8	5 surveys	day
and reproduction	1996 6–8	4 surveys		5 surveys	
activity[b]			1997 6–9		
	1998 6–8				
Species composition	1993 11	1 survey			Fike mesh 12/13 mm;
fish[c]	1994 5; 8; 11	3 surveys	1994 5; 8	2 surveys	Electro fishing 5 kWh;
			1995 8	1 survey	Seine mesh 20 mm;
	1996 5; 8; 11	3 surveys			Fishing net 10 mm
Age-0 fish	1997 5–9	7 surveys	1997 5–9	7 surveys	Seine meshes 1.5; 7.5 mm
composition[d]	1998 5–8	6 surveys	1998 5–8	6 surveys	Trawl meshes 1.5; 4 mm
					Electro fishing 5 kWh
Age-1+ fish	1997 3–12	7 surveys	1997 3–12	7 surveys	Seine mesh 14 mm
composition[d]	1998 3–12	7 surveys	1998 3–12	7 surveys	Trawl meshes 4; 17 mm
					Electro fishing 5 kWh
Submerged	1993 9	1 survey	1993 9	1 survey	Tansley method
macrophytes and	1994 8	1 survey		1 survey	
bank vegetation[e]	1995 8	1 survey	1995 8	1 survey	
Macrophytes association[e]	1995 8	1 survey	1995 6	1 survey	Tansley method (SC1) Landscape guided vegetation survey (SC2)
Wading-birds during			1994 7–9	13 surveys	
autumnal migration[f]	1995 7–9	12 surveys	1995 7–9	12 surveys	
	1996 7–9	13 surveys			
	1997 7–9	11 surveys			
	1998 7–10	14 surveys			

[a] Biotopes sampled 1993–1998 (number of samples): SC1 (98); flowing part of SC2 (21), parapotamal channel SC2 (28), clay excavation pits SC2 (12), isolated channel SC2 (19), temporal waters SC2 (19), sand-excavation pit SC2 (8); sampling of sand, clay, stones; woody debris and vegetation if available.
[b] Biotopes sampled 1993–1998; SC1 and SC2 total study area.
[c] Biotopes sampled 1993–1998; SC1; SC2 flowing part of SC2 1995, parapotamal channel SC2 1994 and 1995, clay excavation pits SC2 1994, isolated channel SC2 1994 and 1995, sand-excavation pit SC2 1994 and 1995.
[d] Biotopes sampled 1993–1998; SC1; SC2 flowing part of SC2, clay excavation pits SC2.
[e] Biotopes sampled 1993–1998; SC1 and SC2 total study area.
[f] Biotopes sampled 1993–1998; SC1; SC2 total study area.

The decreased grazing intensity from 1993 onwards, has allowed the floodplain meadow to develop into richly structured grassland by 1999. The willows and poplars that germinated in 1994 reached heights up to 3–4 m.

Results of post-project monitoring

Aquatic macroinvertebrates. The total number of aquatic macroinvertebrate taxa increased between 1996 and 1998 (Table V). The number of taxa in 1998 (122) was comparable with 1993 (126), before the opening of the secondary channel. The number of taxa specific to a single year was relatively high in 1993,

Table III. Classification of fish species observed in both secondary channels from 1993–1998[a]

Rheophilic A	Rheophilic B	Eurytopic	Limnophilic
Barbus barbus	*Aspius aspius*	*Abramis bjoerkna*	*Carassius carassius*
Chondrostoma nasus	*Cobitis taenia*	*Abramis brama*	*Leucaspius delineatus*
Cottus gobio	*Gobio gobio*	*Alburnus alburnus*	*Misgurnis fossilus*
Lampetra fluviatilis	*Leuciscus idus*	*Anguilla anguilla*	*Rhodeus sericeus*
Leuciscus cephalus		*Ctenopharyngodon idella*	*Tinca tinca*
Leuciscus leuciscus		*Cyprinus carpio*	
		Esox lucius	
		Gasterosteus aculeatus	
	Rheophilic C	*Gymnocephalus cernuus*	
	Osmerus eperlanus	*Perca fluviatilis*	
	Platichtus flesus	*Pseudorasbora parva*	
		Pungitius pungitius	
		Rutilus erythrophthalmus	
		Rutilus rutilus	
		Stizostedion lucioperca	

[a] Classification according to Schiemer and Waidbacher (1992). Of Rheophilic A species, all stages of life history are bound to flowing water; of Rheophilic B species, some stages are confined to low flow conditions. Rheophilic C species are diadromic species that migrate between rivers, estuaries and the sea. Eurytopic species occur in both flowing and stagnant water, Limnophilic species are bound to stagnant water in isolated floodplain lakes.

Table IV. Characteristics of secondary channel 1 (SC1)

	Value	Years measured
Discharge (Q)		1994–1999 ($n = 27$)
Maximum Q SC1	29.5 m^3/s	
Maximum Q SC1/Q main channel	1.2%	
Number of flow days based on bedlevel of secondary channel in 1999		Based on discharge and bed level
% average year (1901–2000)	87% (1994 99%; 1995 98%; 1997 93%)	
% actual waterlevel in 1999	99%	
Flow velocity		1994–1999 ($n = 27$)
Range secondary channel	0–0.8 m/s	
Mean at groyne opening	0.3–0.4 m/s	
Range former groyne field	0–0.3 m/s	
Bed level		1995, 1996, 1997, 1999
Maximum sedimentation	0.3 m/year	
Mean slope of banks	Right bank 1:50 Left bank 1:5–1:10	
Depth during low discharge (Q95%)	0–1 m	
Management		Since 1993
Grazing by cows	1.5–2 adult cow/ha	

mainly because of the subsequent disappearance of those taxa characteristic of stagnant water and vegetation. Exotic taxa, mainly from the Danube, constituted a large part of the new taxa in 1996 and 1998.

In 1993, rheophilic taxa made up 4% of the total number of taxa. This percentage increased to 14–21% after the creation of the secondary channel in 1994. For the rheophilic species, no specific preference for stones/wood, sand or silt or preference of flow velocities within the channel was found. No rare rheophilic species were observed.

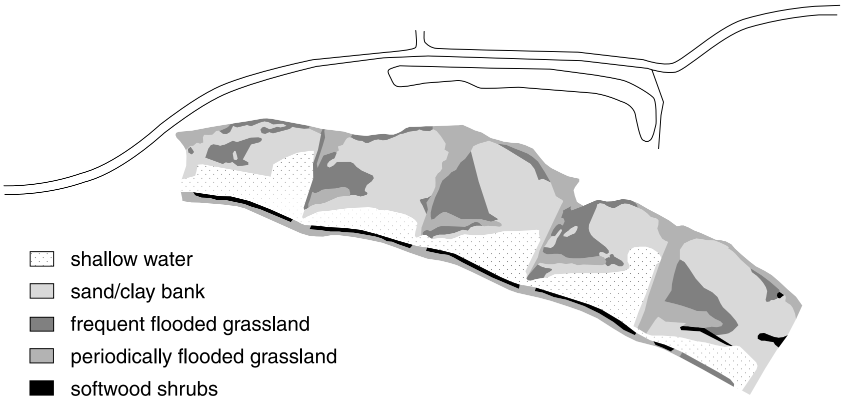

Figure 3. Macrophyte association of SC1 in 1995

Table V. Species composition of aquatic macroinvertebrate taxa (almost all species are identified at species level) for SC1 and SC2

	SC1			SC2 whole study area			
	1993	1996	1998	1994	1995	1996	1997
Total number of taxa	122	113	126	200	257	200	181
Rheophilic taxa	5	24	18	20	30	19	11
Specific for the year	70	31	37	66	79	49	45

The mean density (numbers per square meter) of rheophilic individuals increased after the creation of the secondary channel in 1994 (Figure 4(a)). The ratio of densities of rheophilic taxa from 1993, 1996 and 1998 was 1:2:40. *Corophium curvispinum*, an exotic species from the River Danube, comprised 44–48% in terms of numbers of individuals of the rheophilic species in 1996 and 1998 and even 80% in 1993.

Age-0 fish. Since the creation of the secondary channel, rheophilic Age-0 fish were present every year (Table VI(a)), even Rheophilic A species like *Lampetra fluviatilis*, *Barbus barbus*, *Leuciscus cephalus*, *L. leuciscus* and *Chondrostoma nasus* (Table III), which are rare in the River Rhine in The Netherlands. Of the Rheophilic B species, *Leuciscus idus* was numerically dominant in all years and in 1998 *Aspius aspius* was dominant as well. The largest part, however, was made up by Eurytopic species of which *Rutilus rutilus*, *Abramis brama*, *Alburnus alburnus* and *Gymnocephalus cernua* dominated in most years. The total number of species had increased since 1994, mainly because of the addition of rheophilic species.

A part of the total density (number of individuals per 1000 m^2) consisted of individuals of species from the Rheophilic A and B guilds. They were present in almost every year after opening of the channel (Figure 5(a)), but Eurytopic species clearly dominated the number of individuals per 1000 m^2. Large fluctuations between and within years occurred for the total density and the density per guild. Rheophilic species were present during the whole sampling period from May through September (Figure 6). The maximum total density occurred between June and August in both 1997 and 1998. The difference in densities between the gear types within a sampling period was mainly caused by the biotope the gear types were used in; seine nets were used for the shallow parts in the shore zone and trawls for the deeper thalweg.

Age-1+ fish. Eurytopic fishes also dominated the density (number of individuals per 1000 m^2) of the Age-1+ group of fish (Figure 7(a)). The number of rheophilic individuals was dominated by Rheophilic

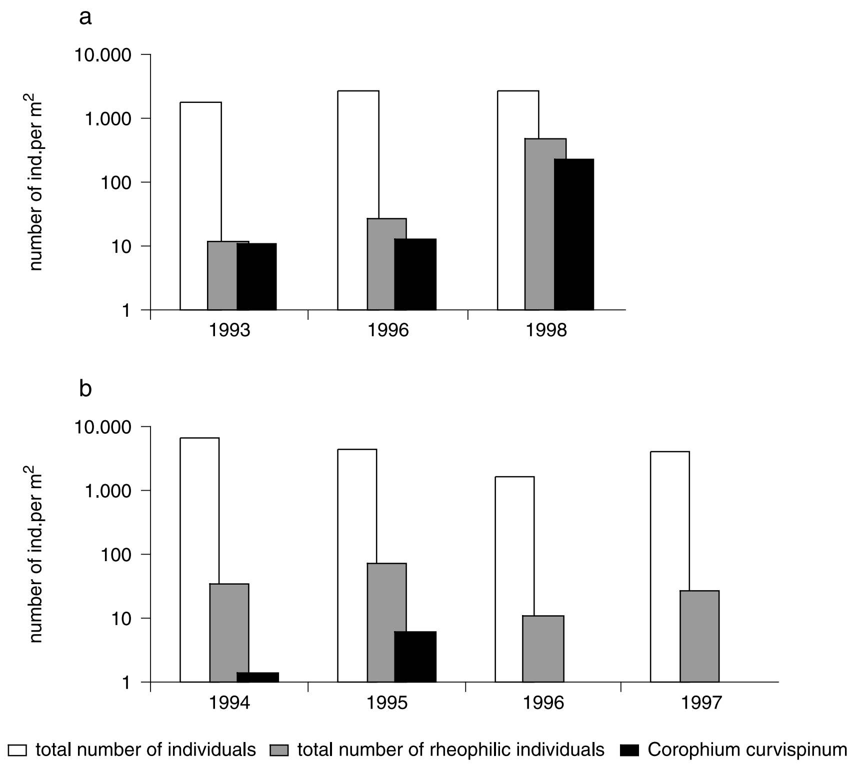

Figure 4. Mean density of aquatic macroinvertebrates per sample. The density of rheophilic individuals and *Corophium curvispinum* is presented as part of the total number. The standard deviation is often two to three-times the mean number of individuals per sample. (a) In SC1 (number of samples in 1993, 1996, 1998 is 27, 35 and 34, respectively); (b) in total study area of SC2 (number of samples in 1994, 1995, 1996, 1997 is 35, 31, 24, 19, respectively)

Table VI. Total number of species within the age-0 fish assemblage in (a) SC1 and (b) SC2 in August[a]

(a)	SC1				(b)	SC2 flowing part			SC2 clay pits		
	1994	1996	1997	1998		1995	1997	1998	1994	1997	1998
Eurytopic	6	6	9	6		2	5	4	5	9	7
Rheophilic A	0	3	3	2		1	1	1	0	0	0
Rheophilic B	1	2	3	3		2	2	2	1	2	2
Rheophilic C	0	0	0	1		0	0	0	0	0	0
limnophilic	0	0	1	0		0	0	0	–	1	0

[a] Results from samples with seine nets (mesh size 20 mm stretched).

B species, Rheophilic A individuals were almost absent. Notice the number of Limnophilic individuals per 1000 m^2 in 1994, just after the opening of the secondary channel. They were dominated mainly by *Scardinius erythrophthalmus* and to a lesser extent *Tinca tinca*. Limnophilic individuals were seldomly observed the years after and will not be addressed further.

Variation in density between years was even larger than for the Age-0 fish. Fluctuations in biomass were also very large within years; the total biomass peaked in April and June of both years (Figure 8). The number of Age-1 + fish during the period July–October was, however, low. During December 1998, a large group of approximately 800 adult bream (*Abramis brama*) and 80 adult ide (*Leuciscus idus*) was found. Throughout the year, the biomass was heavily dominated by bream.

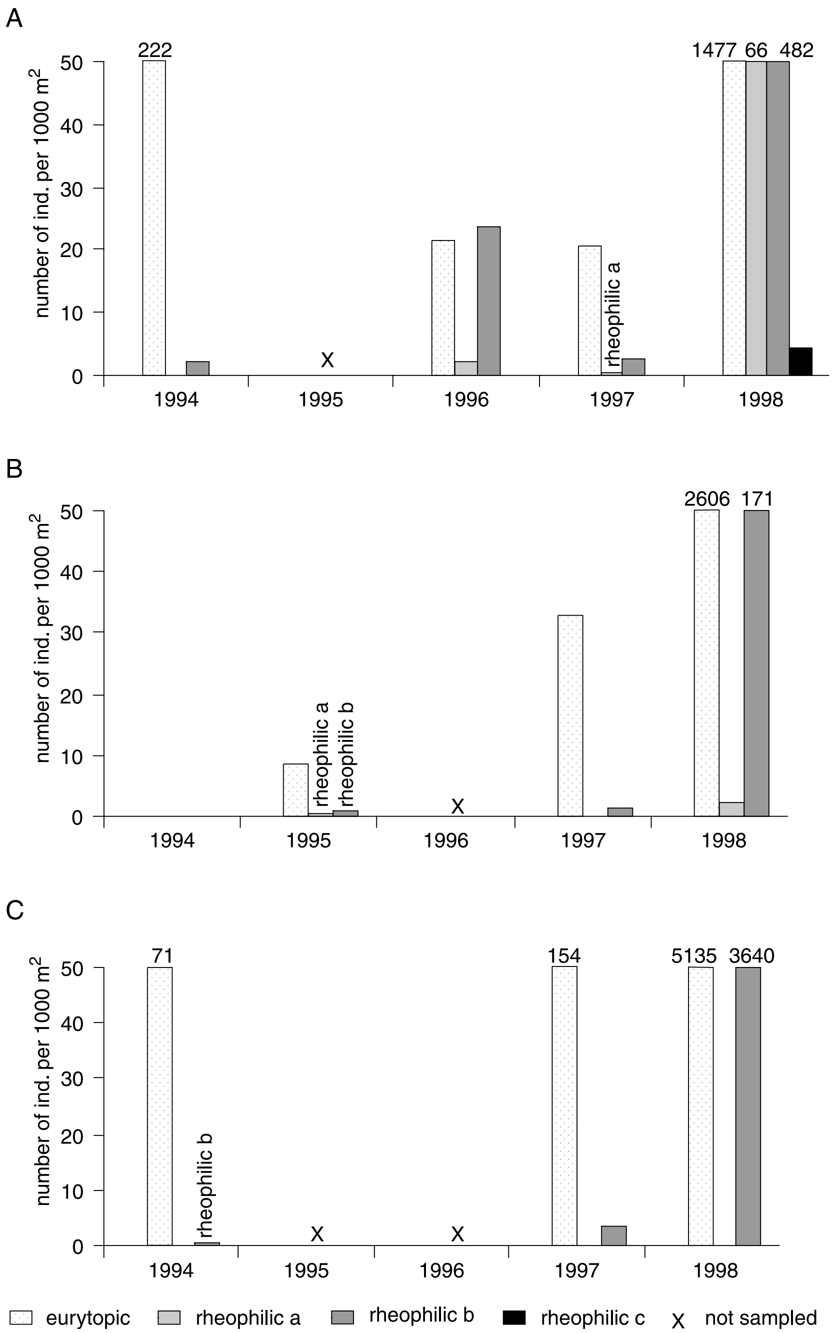

Figure 5. Density of Age-0 fish in August caught with seine mesh 20 mm, (a) in SC1; (b) in flowing part of SC2; (c) in clay pits in contact with CS2

Wading birds. The combination of very shallow water and gradually sloped banks can serve as an important feeding and resting place for wading birds during autumnal migration. The number of waders was subject to high annual fluctuations (Figure 9(a,b)). The number of species (9–16) was highest in 1995 and lowest in 1996. *Vanellus vanellus*, *Limosa limosa*, *Nurmenius arquata*, *Tringa totanus*, *Philomachus pugnax* were observed in July. In August, species like *Actitis hypoleucos*, *Tringa ochropus* and *Gallinago*

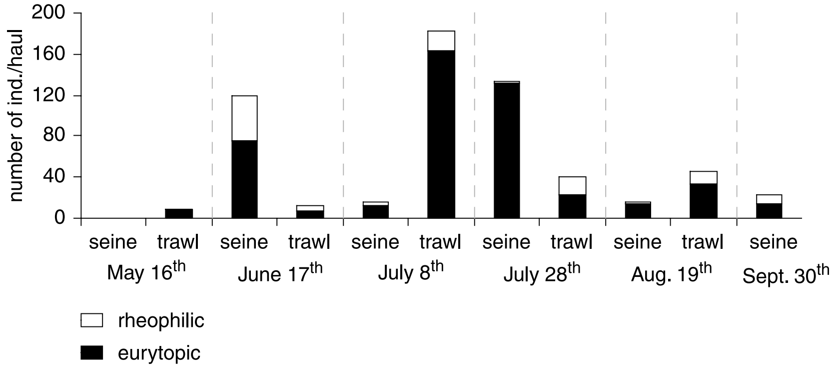

Figure 6. Number of Age-0 individuals per haul in 1997 in SC1 caught with seine and trawl

gallinago were dominant. For *V. vanellus*, *L. limmosa* and *T. totanus* and for *A. hypoleucos*, *T. ochropus* and *G. gallinago* abundance levels corresponded to the migration peak for these species (Bekhuis, 1997).

SECONDARY CHANNEL 2

Description of secondary channel 2

Excavation of secondary channel 2, on the left bank of the River Waal near the village of Beneden-Leeuwen, river km 929.430–930.370, was completed in 1997. The first excavations started in the autumn of 1994, when the connection between a deep sand-excavation pit and a clay-pit was made. At high water levels, the clay pit was connected with a former riverbend. From 1995 to 1997, three branches of the secondary channel and some clay pits were excavated (Figure 10). The clay was used for raising dikes that were not yet up to the required standard. In this case, the actions for safety against flooding were successfully combined with ecological development. This project is the first field-experiment as result of 'Living Rivers' (WWF, 1993). At low water levels, the sill between the sandpit and the main channel of the River Waal reduces the flow in the secondary channel during 5% of the year. The hydrological, morphological and management characteristics of the secondary channel are described in Table VII.

Owing to the relatively steep banks of the flowing part of SC2 and the clay pits connected with SC2, the vegetation on the banks does not show a zonation which is caused by the whole range of inundation frequencies that occurred in SC1. The bands of bare sand and clay with pioneer plants (inundated more than 150 days a year) and the lower part of the frequently (50–150 days a year) inundated zone are very small. In the shallow water of the flowing parts of the secondary channel and the stagnant clay pits, permanently or frequently connected with the secondary channel, no submerged waterplants were found in 1993 and 1995. The small, clay and sand zones (more than 150 days of inundation) were sparsely covered by species like *Limosella aquatica* and *Eleocharis acicularis*. The larger part of the 50–150 and < 50 days a year inundation zones along the flowing secondary channel and most of the clay pits were covered mainly with *Salix alba*, *S. viminalis* and *S. triandra*, with a species-poor undergrowth. The low-hanging branches of the shrubs serve as substrate for aquatic macroinvertebrates. The other part is covered by species-poor herbs dominated by species like *Phalaris arundinacea*, *Cirsium arvense*, *Rubus caesius*, *Elytrigia repens*, *Urtica dioica* and locally by *Brassica nigra* and *Calystegia sepium*. The upstream banks, between sandpit and clay pit, consists of grassland dominated by species like *Agrostis stolonifera*, *Lolium perenne* and *Elytrigia repens*.

Results of post-project monitoring

Aquatic macroinvertebrates. The total number of aquatic macroinvertebrate taxa sampled in all waterbodies remained almost the same during the post-project monitoring period (Table V). The density of individual species per sample seemed to have slightly decreased since 1994 (Figure 4(b)). All

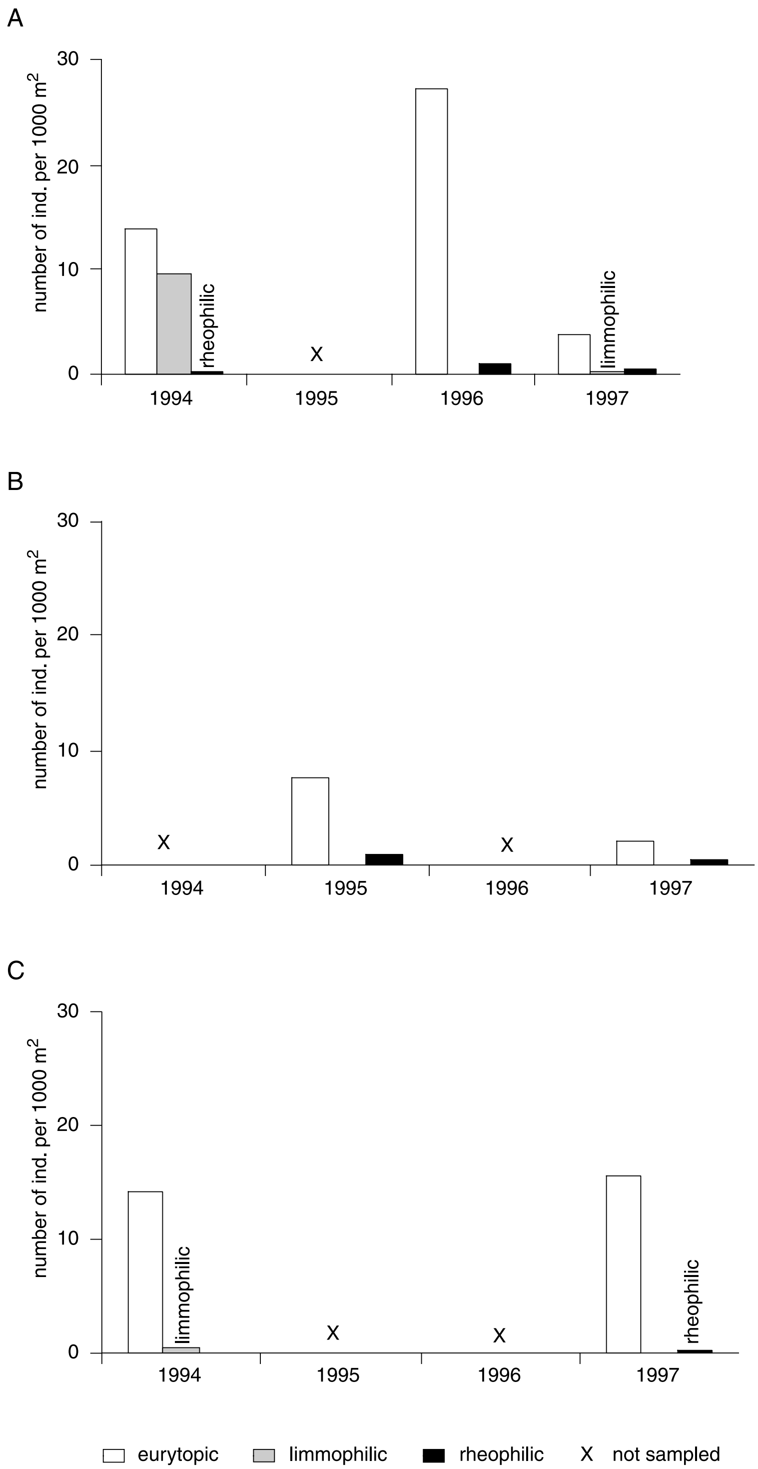

Figure 7. Density Age-1 + fish in August caught with seine mesh 20 mm, (a) in SC1; (b) in flowing part of SC2; (c) in clay pits in contact with CS2

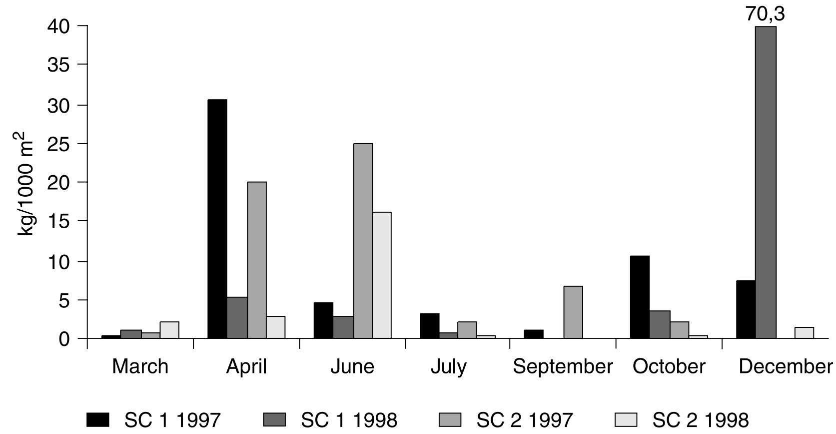

Figure 8. Biomass per 1000 m^2 of Age-1 + fish during 1997 and 1998 in SC1 and SC2

waterbodies of SC2 were stagnant for a small or larger period every year, depending on the river stage. The high total number of taxa and density of rheophilic taxa in 1995, and to a lesser extend in 1994, is very likely to be caused by the peak discharges that occurred in both years. Aquatic macroinvertebrates might have drifted towards The Netherlands from the upstream part of the River Rhine. This can also be seen from the high number of species specific for the year in 1994 and 1995 (Table V). The percentage of rheophilic taxa per 1 m^2 remained stable, ranging from 6% (1997) to 12% (1995), during the monitoring period.

The total taxa composition of the isolated river channel, temporal waters and clay pits was similar. Species with a preference for vegetation, like *Corixidae* and *Asellus aquaticus* were found only here. The deep sandpit is important for species of *Pisidium* and *Corbicula*. The flowing secondary channel held no unique species. The mean density of all invertebrate taxa was similar for all waterbodies; lowest densities were found in the 12 m deep sand-excavation pit and the highest in the isolated waterbodies (shallow clay excavation pits).

The number of rheophilic taxa was high in the flowing part of the secondary channel and in temporal ponds and isolated waterbodies (Figure 11(a)). The rare rheophilic *Simuliidae*-like *Wilhelmina* spp and *Boophtera erythrochephala* were not able to settle permanently at that time in SC2. *Ephemeroptera*, like *Potamanthus luteus* and *Caenis macrura* were also found at lower densities in 1996 and 1997. The highest mean density (number of individuals per m^2) was measured in the oxbow lake (parapotamal channel), the lowest in the sand-excavation pit (Figure 11(b)). The major substrate for rheophilic species is a combination of solid material like stones and wood. A large amount of *Dikerogammarus villosus*, an exotic species, is found there. In 1994 and 1995, more vegetation was usable as substrate, because of the high river stage, so the density was relatively high.

Age-0 fish. In both the flowing part of SC2 and in the stagnant connected clay pits, two Rheophilic B species were found (Table VI(b)). The Rheophilic A species were only found in the flowing part, represented by different species every year. In the flowing part of SC2, the same species occurred as in SC1 but the species diversity was lower in SC2. Most species and most of the abundance (individuals per 1000 m^2) was made up by Eurytopic species (Figure 5(b,c)). In the flowing part of SC2 *Alburnus alburnus* was dominant and, in 1995, also *Gymnocephalus cernua*. The clay pits were dominated by the same species as in SC1, apart from the Rheophilic A species and the total species diversity was also comparable. The number of species evidently increased after 1994/1995 mainly because of the addition of Eurytopic species.

The density (number of individuals per 1000 m^2) of Rheophilic A species was very low in both biotopes of SC2. The total density followed the same pattern in both biotopes in 1997 and 1998. Densities of Eurytopic and Rheophillic B species were highest in the clay pits. In both SC2 biotopes, the density of Eurytopic species was higher than in SC1 (Figure 5). However, the opposite was true for the rheophilic species. Among years, the total densities and the densities per guild varied strongly.

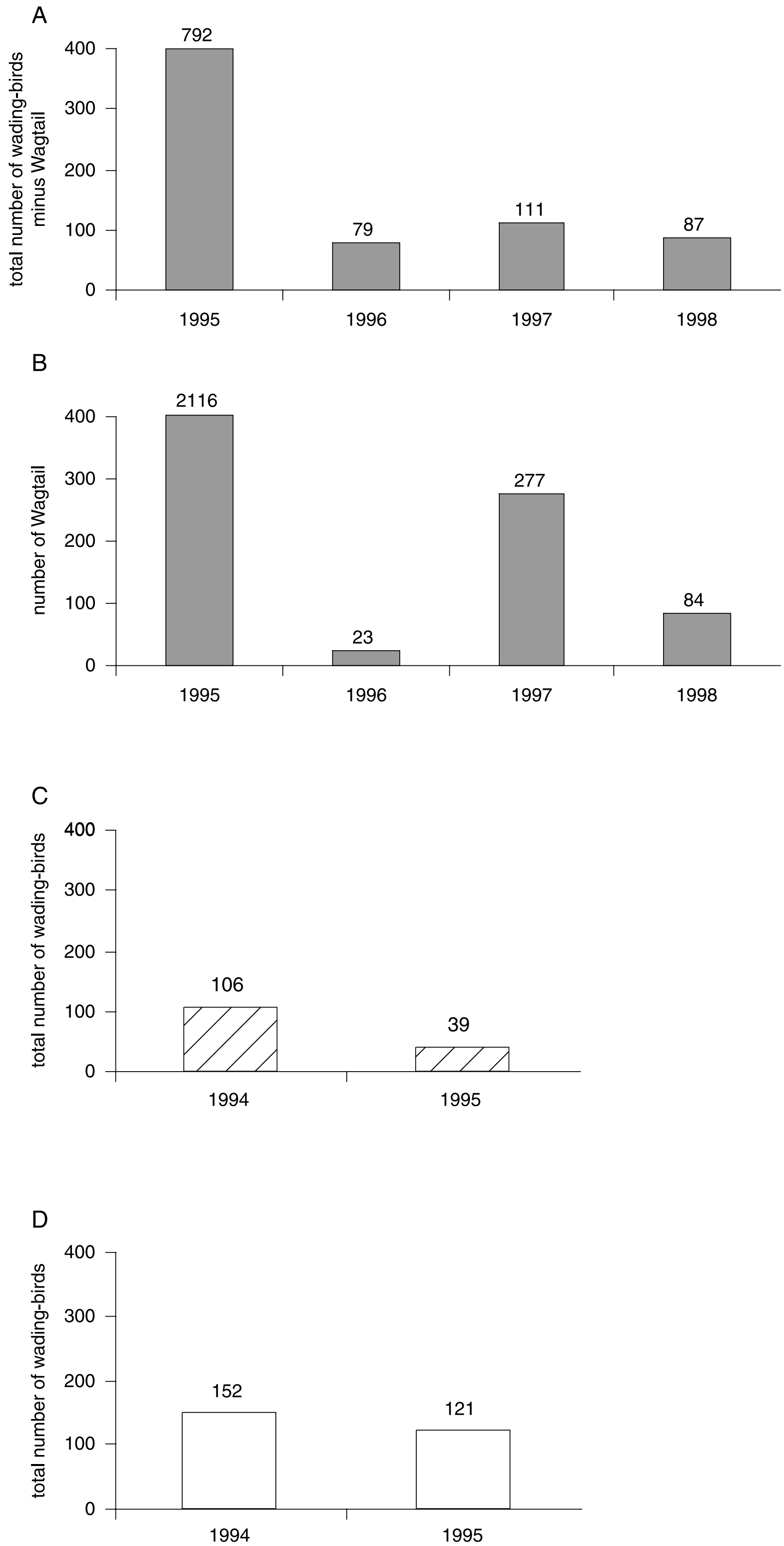

Figure 9. Number of wading birds during autumnal migration, (a) total number of wading birds minus lapwing (*Vanellus vanellus*) in SC1; (b) number of lapwing during autumnal migration in SC1; (c) total number of wading birds around the flowing part of SC2; (d) total number of wading birds around the clay pits and parapotamal channel associated with SC2

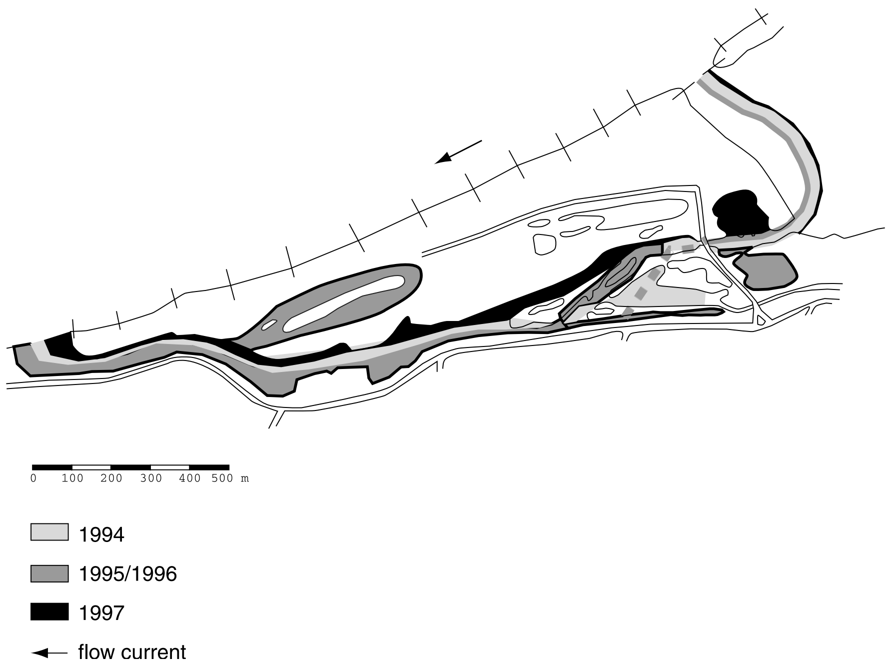

Figure 10. Design of SC2. In 1994 the creation of the channel started and they are finished in 1997. The different colours are associated with the stream flow in the year(s) concerned

Table VII. Characteristics of flowing part of SC2[a]

	Value	Years measured
Discharge (Q)		1996–1998 ($n = 10$)
Maximum Q SC1	9 m^3/s	
Maximum Q SC1/Q main channel	0.5%	
Number of flow days from 1994–1998		Based on discharge and sill at entrance of sand-pit
% average year (1901–2000)	95%	
Flow velocity		1996–1998 ($n = 10$)
Range secondary channel	0–0.3 m/s	
Maximum at culvert	1.5 m/s	
Bed level		1995, 1996, 1997, 1998
Maximum sedimentation	Nil	
Mean slope of banks	Right bank 1:10 Left bank 1:10	
Depth during low discharge (Q95%)	0.5–1.5 m	
Management		1994–May 1996 and since 1997
Grazing by cows (Galloways) and horses (Koniks)	One adult cow or horse per 4 ha	

[a] The characteristics of the large sandpit, the clay pits and the former river channel are not included.

Age-1+ fish. As in SC1, the density (number of individuals per 1000 m^2) of Eurytopic fishes in SC2 was by far the highest, compared to rheophilic and limnophilic fish (Figure 7(b,c)). Rheophilic fish were almost absent. A comparison of the densities of Age-1+ fish for the waterbodies of SC2 could only be made for 1997. The highest densities of fish occurred in the stagnant clay pits in 1997. Density in the flowing part of SC2 appeared to be comparable with SC1. The within-year fluctuations in biomass were also large for SC2, with a maximum in April and June (Figure 8). The biomass of Age-1+ fish seems to

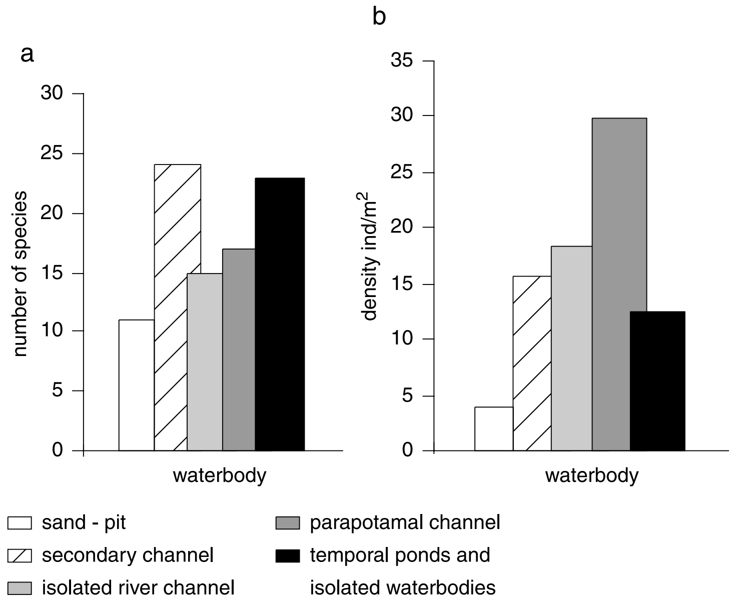

Figure 11. Rheophilic macroinvertebrates in the different waterbodies of SC2, (a) number of rheophilic species; (b) mean density of rheophilic species

be low from July to March. As in SC1, in SC2 the total fish biomass was almost exclusively made up by bream.

Wading birds. The number of waders during autumn migration in 1995 was relatively low as compared to SC1 (Figure 9). The yearly pattern for both biotopes of SC2 was comparable. The number of species was low for the flowing part of the secondary channel, 8 and 4, respectively, in 1994 and 1995, but also for the clay pits and parapotamal channel, 8 and 12 of which 6 species were represented by only one individual. *Actitis hypoleucos* was dominant followed by species like *Tringa ochropus* and *Gallinago gallinago*. In 1994 *Vanellus vanellus*, *Limosa limosa* and *Tringa totanus* were also present, with a peak migration in July.

DISCUSSION

Characteristic riverine species and especially rheophilic macroinvertebrates, fish and macrophyte species and waders benefited almost immediately after the opening of the secondary channels as a result of the presence of flowing, shallow water. Man-made secondary channels were used as habitat by riverine and sometimes by rare rheophilic species in a similar way to a less regulated main channel or naturally formed secondary channels (van Dessel, 1989; Duel *et al*., 1994), and have thus enhanced this section of the River Rhine ecosystem in The Netherlands.

The high number and density of rheophilic macroinvertebrate taxa in SC1 is mainly because of the creation of flowing water in 1994. The density of rheophilic fish species in this secondary channel is high as compared with SC2.

The large number of rheophilic macroinvertebrate taxa in 1995 and 1994 at SC2 show that the industrial Ruhrgebiet in Germany can be passed by drifting macroinvertebrate species during very high discharges. Thus, potentially suitable biotopes in The Netherlands could be occupied by rare or locally extinct rheophilic species from the more ecologically sound upstream parts of the Rhine. Rare rheophilic species were found after the high discharges, but did not settle permanently in the secondary channels. They were not observed during the monitoring in 1996, 1997 and 1998.

The high number of exotic species in the secondary channels is not surprising because 15% of the total number of aquatic, macroinvertebrate taxa of the Rhine branches in The Netherlands consists of non-native species. The percentage of exotic species of the total number of individuals is as high as 92% (bij de Vaate *et al*., 1998).

Both secondary channels were used as a nursery habitat for Eurytopic and Rheophilic B Age-0 fish species and SC1 in particular was used by the Rheophilic A species. Owing to the low densities of rheophilic species, fluctuations among years for the rheophilic guilds were very obvious. As expected, the presence of flowing water proved to be an important factor for the Rheophilic A species. This can be concluded from the comparison of SC1 with the flowing part of SC2 and the stagnant clay pits (Table VI(a,b) and Figure 5). In SC1, where higher flow velocities were recorded (Table IV), than in the flowing part of SC2 (Table VII), both the density and the number of Rheophilic A, Age-0 fish species were higher. In the stagnant clay pits that are connected with SC2, no Rheophilic A species were found. Rheophilic A, Age-0 fish species were also found in low densities in an almost stagnant oxbow lake in the floodplains with one downstream connection with the main channel (Grift *et al*., 2001).

No Rheophilic A, Age-1 + fish, and thus no adults of these species, were observed in both secondary channels. The sandy and sometimes also silted secondary channels, characteristic for the Waal branch of the River Rhine, seems to lack suitable spawning habitat for most Rheophilic A species that deposit eggs on gravel bottoms where their embryos and larvae develop (Balon, 1975). Their Age-0 + fish might enter the secondary channels at early stages by passive transport from upstream spawning locations. In drift nets that were positioned at the entrance of secondary channel 1, 157 *Barbus barbus* (barbel) larvae (sizes 12–17 mm) were caught in May and June 1999, which might confirm the larval drift of barbel from upstream parts of the River Rhine into the secondary channels (R. Grift, unpubl data). In many rivers, larvae drift from upstream spawning sites to inshore nursery areas and retention of these larvae in low flow zones in secondary channels will be advantageous for recruitment (Schiemer *et al*., 2001).

The high biomass of Age-1 + fish during April and June was nearly exclusively made up by the Eurytopic bream (Figure 8) that had probably entered the floodplain to spawn. The Age-0 bream was one of the dominant species in both SC1 and the clay pits of SC2

The low density of Age-1 + fish in most years (Figure 7), and the low biomass during the period from July to October could be caused by the low water levels, and thus very shallow water, during this period. The low numbers of Age-1 + fish in August may be responsible for the large fluctuations seen in Figure 8. In 1996 and 1997, both dry years compared with the average year (Table I), the Age-0 density, especially for the rheophilic guilds, was also low in August (Figures 5 and 6). During this period the water was very shallow and periodically stagnant in both secondary channels (Simons *et al*., 2000). The high densities of Age-0 species in the clay pits might be caused by the greater water depths.

Since 1994, asp (*Aspius aspius*), an exotic Rheophilic B species, has been reported from the Rhine in The Netherlands with increasing numbers (Buijse and Cazemier, 1998). From that year onwards, asp was also found both in SC1 and SC2. Next to exotic macroinvertebrate species, exotic fish species also seem to inhabit these newly created secondary channels.

The very gradual slope of banks in the zone that flooded for more than 150 days a year in SC1, with shallow water and emergent sand or clay banks, could be an important feature of secondary channels. The shallow water and wet soils are used as foraging habitat by waders during autumn migration. The differences between SC1 and SC2 for wading birds are caused by the very gradual slopes of the banks of the channel in SC1 in contrast with the relatively steep slopes of SC2. Owing to the steep banks and, therefore, the low amount of emergent sand and clay banks, the number of waders during autumn migration is relatively low compared with SC1. The presence of wading birds seems to be largely dependent on bare sand and clay during the migration period in combination with the changes in water level just before and during the migration period. In 1995 and 1997, just before the peak of migration in July, the water level dropped. In 1995, it increased a little at the end of July and the beginning of August and then dropped again. The flow of fresh water and food must have caused a large food availability, mainly macroinvertebrates, for this bird group. From the end of June 1997 onwards the water level dropped quickly and was very low with periodically stagnant water in SC1 until November. In 1996 and

1998, the water level was already low from June. This resulted in emergent sand and silt well before the migration period and, therefore, lack of food availability.

Compared with the aquatic macroinvertebrate data of the main channel of all River Rhine branches in The Netherlands in 1995, 23% of the taxa were only found in the secondary channels. Also the density of aquatic macroinvertebrates and Age-1 + fish is higher in both secondary channels than in the main channel (Simons *et al.*, 2000). The density of Age-0 fish in SC1 seems much higher than in the groyne fields of the main channel (R. Grift, unpubl data).

CONCLUSIONS

Man-made secondary channels function as a biotope for riverine, including the more demanding rheophilic, species. Despite the constraints caused by the demands for shipping and protection against flooding on the River Waal, there is still enough space for hydromorphological processes to create new habitats in secondary channel 1, but not in secondary channel 2. Only a few years after their creation, secondary channels were inhabited by a broad array of riverine fauna. Secondary channels seem to provide habitats that are essential for the ecology of rheophilic macroinvertebrate and fish species. The number and density of (rheophilic) species is to a large extent influenced by the water level and frequent inundation caused by the high hydrological connectivity.

Owing to the lack of habitats for rheophilic macroinvertebrate and fish species in the Rhine in The Netherlands at present, the importance of longitudinal migration, described by e.g. Junk *et al.* (1989) and transversal migration described by e.g. Ward *et al.* (1999), could be illustrated by the drift of macroinvertebrates during floods, and the seasonal migration of Age-0 and Age-1 + fish species.

Most parameters of secondary channel 1 will be monitored for several more years in a comparable way. In secondary channel 2, some ecological parameters will be followed as the result of an Environment Assessment Study for the filling of the sand-excavation pit with removed (contaminated) topsoils from the floodplain. In a more downstream location along the River Waal, a third secondary channel 'Gameren' with an average discharge of 3% of the River Waal was finished in October 1999 (Schropp and Jans, 2000). Here also morphological and ecological parameters have been closely monitored since 1997. The knowledge on the importance of secondary channels for the ecology of a large lowland river supports and guides the creation of future secondary channels.

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