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The impact of small physical obstacles on upstream movements of six species of fish

Synthesis of a 5-year telemetry study in the River Meuse basin

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Abstract

In the course of the 'Meuse Salmon 2000' programme, most weirs and dams (3–8 m in height) in the regulated River Meuse have been progressively equipped with new fishways in order to restore the free circulation of all amphibiotic fish species. Nevertheless, fish entering into major spawning tributaries are still confronted with various kinds of physical obstacles of which the overall impact on fish migration has never been investigated. In order to test their ability to negotiate physical obstacles, 128 individuals of fish (*Salmo trutta*, *Thymallus thymallus*, *Salmo salar*, *Chondrostoma nasus*, *Barbus barbus* and *Esox lucius*) were captured several weeks before their spawning migrations and tagged with radio-transmitters. They were tracked from 30 to 466 days in the River Ourthe and six spawning tributaries over the period October 1995 to June 2001. All obstacles recorded in this study have been classified according to their type and main characteristics (i.e. slope, length and height). Results indicated that most fish migrate during or outside the spawning period and that some small obstacles are not as insignificant as initially thought and can significantly disrupt and/or obstruct their upstream movements. There is a need to harmonize interests in the sustainable conservation of fish populations and the development of small-scale hydropower generation and tourism.

Introduction

In most large rivers, fragmentation of the longitudinal corridors by dams, navigation weirs and hydroelectric power plants has resulted in the drastic range reduction and the extinction of numerous migratory species of fish (Philippart, 1987; Jungwirth, 1998; reviewed in Northcote, 1998). In most cases, the negative effects of these obstructions on fish migration have largely been eclipsed by the influence of overfishing, water pollution or habitat destruction (Jungwirth, 1998; Larinier, 1998). Scientists have attempted to facilitate the passage of fish around or through obstructions using fish passes, bypass channels and fish elevators (Denil, 1938; Clay, 1961, 1995; Jungwirth, 1996; Larinier, 1998). The efficiency of the first such facilities has often been questioned, particularly in terms of the behaviour and swimming capacities of migratory species. However, experience has enabled advances to be made in the choice and design of up- and downstream fish passage facilities, addressing the behavioural ecology of target species, the site-specific flow regime and the unique features of each obstruction (Larinier, 1998). In combination with restocking programmes, recent construction of fish passage facilities have frequently led to the return of anadromous migratory species (particularly salmonids, eels and lampreys) in several rivers basins including the Rhine-Meuse system (Philippart et al., 1994; Marmulla & Ingendahl, 1996; Breukelaar et al., 1998; Gerlier & Roche, 1998; Bij de Vaate & Breukelaar, 1999; Prignon et al., 1999; Philippart et al., 2000; Philippart et al., 2001).

Fish passage facilities have been built predominantly on the main stems of large rivers; however, fish generally use tributaries rather than main stems of large rivers to spawn. The impact of potential obstacles to fish migration into the spawning tributaries has rarely been investigated (Marmulla & In-

Table 1. Main characteristics of the tributaries and sub-tributaries of the R. Meuse. Data in the bottom part of the table relate to the lower course of each stream

Characteristics	Ourthe	Ambleve[a]	Aisne[a]	Neblon[a]	Mehaigne	Oxhe	Berwinne
Elevation–source (m)	507	586	600	255	180	260	270
Elevation–confluence (m)	63	102	135	120	68	65	53
Length (km)	175	93	35	18.3	66	13.9	29
Drainage area (km^2)	3672	1083	184	78.7	360	45.3	131
Average slope (p/1000)	2.54	5.20	13.29	7.7	1.70	14.0	7.48
Width in lower course (m)	30–50	30–50	5–10	5	5–10	5	5–10
Average annual discharge 1999 (m^3/s)	67.4	21.7	2.6	0.9	3.0	<0.5	2.4
Water temperature in July 1999 (°C)	19.9	19.4	15.3	15.0	17.6	16.7	18.6
Alcalinity (mg/l $CaCo_3$)	6–110	21–50	6–50	>130	>130	>130	>130
Dominant Huet's fish zone	barbel	grayling	trout/grayl	trout	gray/barb	trout	trout/gray
Dominant fish species (kg)	barbel	barbel	trout	trout/grayl	roach/chub	trout	chub
Level of global water quality	high	high	excellent	high	medium	high	medium

[a] Tributaries of the R. Ourthe.

[b] Lower and upper limit of typological classes. Natural increase from the upper to the lower course.

gendahl, 1996; Ovidio et al., 1996; Croze & Larinier, 2000; Ovidio et al., 2000b). Furthermore, recent telemetry studies have demonstrated that fish, such as thymallids, cyprinids, esocids and percids will migrate over long distances within a river basin to reach their spawning grounds or for ontogenetic and trophic reasons (Baras & Philippart, 1989; Baras, 1992; Beaumont et al., 1997; Lucas & Batley, 1997; Lucas & Frear, 1997; Donnely et al., 1998; Hubert & Kirchofer, 1998; Parkinson et al., 1999; Koed et al., 2000). These considerations reinforce the importance of restoring the free circulation of fish throughout a river basin.

Since a decree taken in 1996 to support the 'Meuse Salmon 2000 project' (Philippart et al.,1994), the Benelux countries (Belgium, the Netherlands and Luxembourg) are constrained to restore the free circulation of fish (Atlantic Salmon, sea trout and eel) in their river basins (Benelux, 1996). In order to legalise their situations, the Walloon and Flemish regional governments in Belgium have initiated a program to register and characterise the obstacles in rivers in the South and North of the country, respectively (Monden et al., 2000; Ovidio et al., 2000b). Currently, in the South, the program involves 30 tributaries and sub-tributaries of the river Meuse. So far, the main problem has been to determine the impact of these obstacles on the free circulation of salmonids, as well as cyprinids, thymallids, esocids, percids and eels. This information is essential to identify problematic sites that should be improved (destruction or modification of obstacles, construction of fish passes) in accordance with the Benelux decree. Some data are available on salmonids (Stuart, 1962; Marmulla & Ingendahl, 1996; Chanseau et al., 1999a; Chanseau & Larinier, 1999), but research programmes on other species and on small rivers and streams are very limited (Lucas & Batley, 1997).

In order to test their clearing capacities (ability to clear the obstacles), we radio-tagged six species ($n = 128$ individuals) of fish (Atlantic salmon, brown trout, grayling, nase, pike, barbel) below obstacles and before their spawning period in seven rivers and streams in southern Belgium. The present paper synthesizes this study carried out from October 1995 to June 2001. Details on movements and behavioural ecology of some of the tracked fish species have been presented in other publications (Baras, 1992, 1995; Caffrey et al., 1995; Fredrich, 1995; Ovidio et al., 1998; Ovidio, 1999a,b; Parkinson et al., 1999).

Description of sites studied

Fish were tracked in seven watercourses of the river Meuse basin (Fig. 1). The main characteristics of these sites are presented in Table 1. Obstacles studied by radio-tracking are represented by spots and identified by an alphanumeric code in Figure 1 and individually presented on Table 2 (characteristics) and Figure 2 (photos). Other obstacles on the same watercourses are not represented.

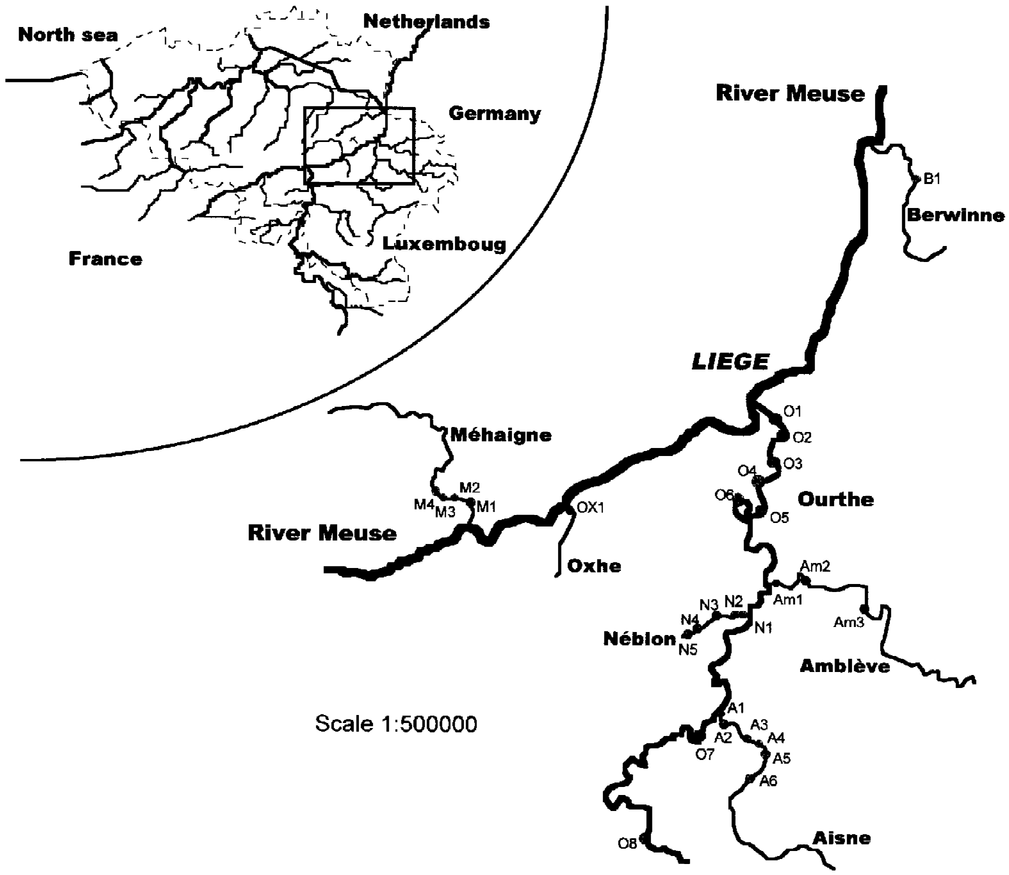


Figure 1. Location of the River Meuse catchment with the locations of the obstacles in the seven tributaries and sub-tributaries of the River Meuse where fish of six species were radio-tracked, October 1995–June 2001.

Material and methods

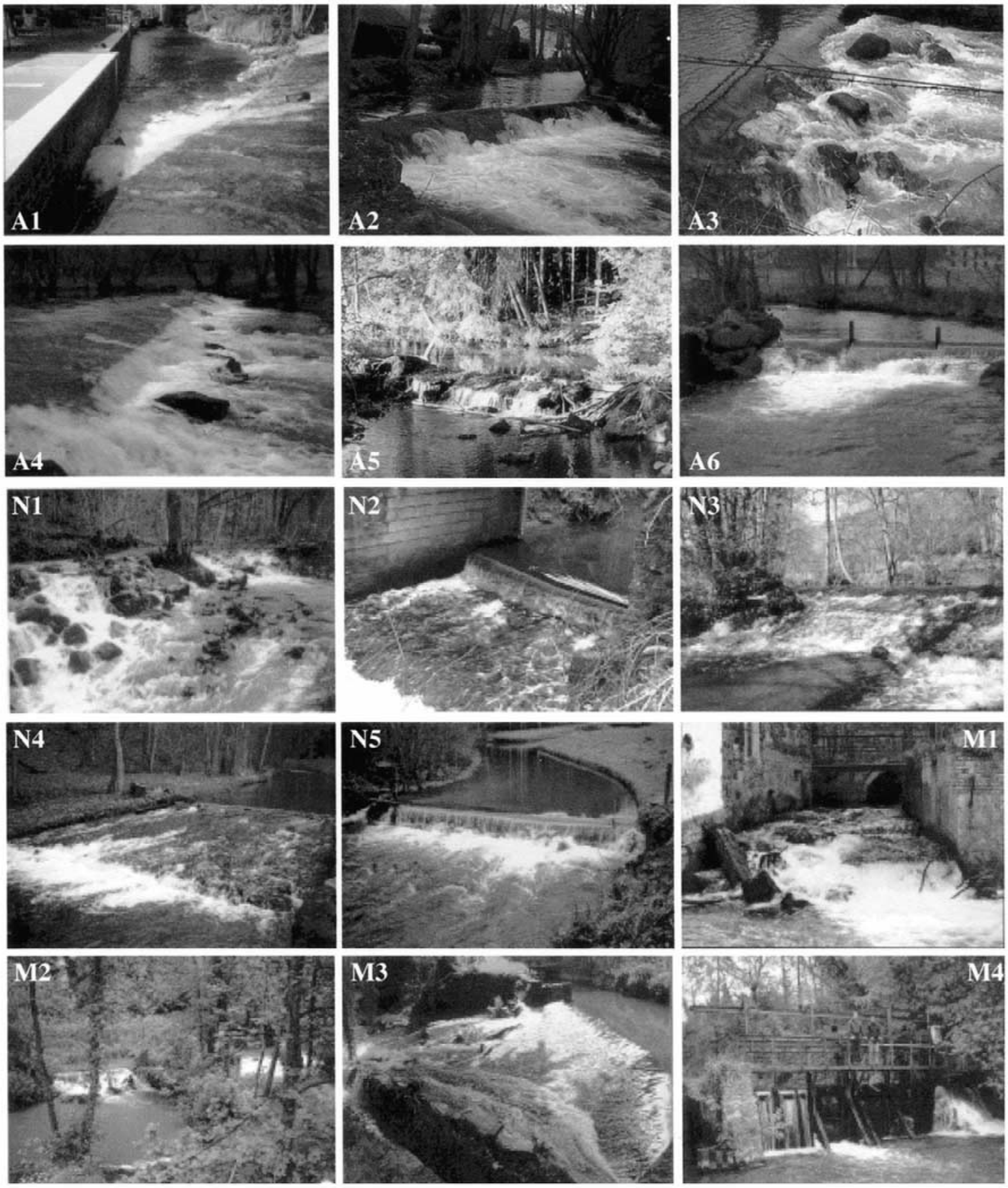
Characterisation of obstacles

Obstacles ($n = 28$) and their environments were characterised in the field in terms of slope, height, depth below the obstacle, matter, existence of ripeness, mean temperature of the water in July, water height on the obstacle, length of the obstacle and fish association in the concerned part of the river (Table 2). These characteristics were measured on a single day during specific flow conditions. Logically, most of these variables would change with water flow. In order to take this imprecision into account, some variables were grouped into several categories (see Table 2). In the Ourthe and Amblève, measurements were sometimes too dangerous to take and some variables (length, depth below the obstacle and slope) were estimated on the basis of photos and/or comparisons with other well-known obstacles.

Water temperature was recorded in each river and stream using data loggers (TidBit Onset Corp.®). In some rivers, two loggers were placed in the upper and lower part of the study site to increase the accuracy of the estimate (<1 °C from one obstacle to another). Water flow was recorded continuously in each watercourse (data from SETHY-MET).

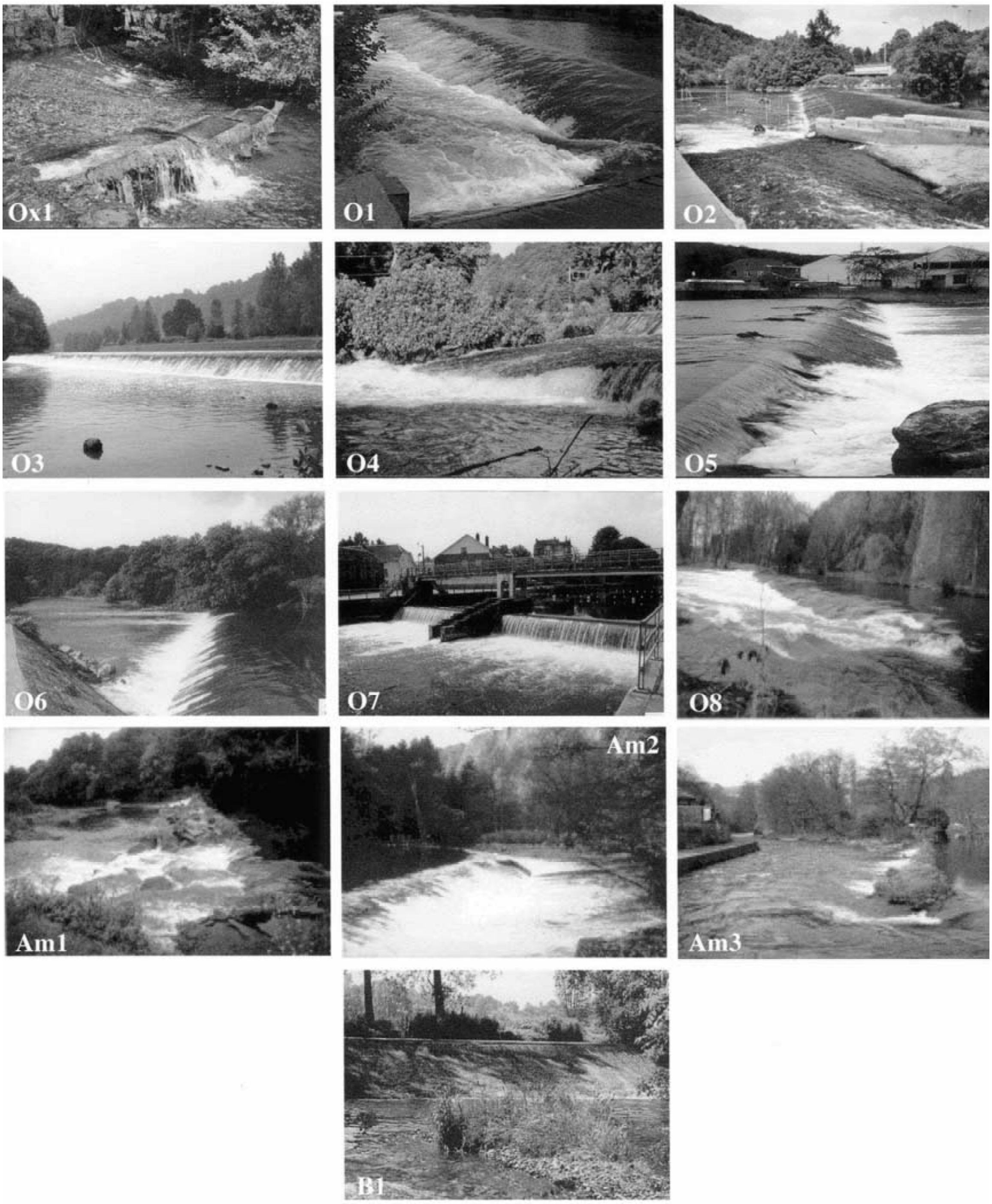
Capture and tagging

Fish were captured by electric fishing (DEKA, 2.5 kVA) downstream of obstacles or caught in fish traps during or just before their spawning period. Fish were anaesthetised in a 0.2–0.4 ml l^{-1} solution of 2-phenoxy ethanol (depending on species) then placed ventral side up into a V-shaped support adjusted to their morphology. A mid-ventral incision was made between the pelvic girdle and the anus and an alcohol sterilised transmitter (40 MHz, internal coiled antenna) was inserted into the body cavity. The weight



(a)

Figure 2. View of the different obstacles studied. The alphanumeric codes refer to the locations of the obstacles in Figure 1.



(b)

Figure 2. Continued

Table 2. Characteristics of the 28 obstacles studied. Obstacles are classified by watercourses. The code of the obstacles relates to their position on the river Meuse basin (Fig. 1) and their photos (Fig. 2). In the type column, -SLO- and -STR- respectively, represent a sloping or a straight obstacle. In the matter column -C-, -R-, -M- and -W- respectively, signify concrete, rocks, metal and wood

Obstacle	Type	Slope (%)	Height (cm)	Max. depth below (cm)	Matter	Ripeness	Mean T° in July (°C)	Water Height (cm)	Length (cm)	Fish association (Huet, 1949)	Fish pass
A1	SLO	40	–	20–40	C–R	–	<16	4–8	352	grayling	Y
A2	STR	–	98	>100	C	1	<16	8–12	200	grayling	N
A3	STR	–	85	20–40	C–R	3	<16	8–12	220	grayling	N
A4	SLO	51	–	<20	C–R	1	<16	4–8	380	trout	N
A5	STR	–	87	40–60	C–R	1	<16	4–8	130	trout	N
A6	STR	–	77	60–80	C–W	1	<16	4–8	10	trout	N
N1	STR	–	58	<20	C–R	–	<16	4–8	90	grayling	N
N2	STR	–	45	<20	C	–	<16	–	–	grayling	N
N3	SLO	22	–	<20	C	–	<16	4–8	490	grayling	N
N4	SLO	8	–	20–40	C	–	<16	4–8	640	grayling	N
N5	STR	–	65	40–60	C–R	–	<16	–	5	grayling	N
M1	SLO	8	>100	40–60	C–R	1	16–18	8–12	1500	barbel	N
M2	SLO	8	–	20–40	C	–	16–18	4–8	2300	barbel	Y
M3	STR	–	109	20–40	C–R	–	16–18	–	15	barbel	N
M4	STR	–	200	20–40	W–M	–	16–18	–	–	barbel	N
Ox1	SLO	24	–	20–40	C	–	16-18	<4	560	trout	N
B1	SLO	>50	–	20–40	C	–	>18	<4	450	barbel	N
O1	SLO	30–45	–	>60	C–R	2	>18	>12	>450	barbel	N
O2	SLO	30–45	–	>60	C–R	1	>18	>12	>450	barbel	N
O3	SLO	>45	–	40–60	C	1	>18	8–12	>450	barbel	N
O4	SLO	15–30	–	40–60	C	–	>18	8–12	>450	barbel	N
O5	SLO	30–45	–	40–60	C	–	>18	8–12	>450	barbel	N
O6	SLO	30–45	–	40–60	C	–	>18	8–12	>450	barbel	N
O7	STR	–	200	40–60	C–M	–	>18	8–12	>150	barbel	Y
O8	SLO	30–45	–	40–60	C	1	>18	8–12	>450	barbel	N
Am1	SLO	15–30	–	40–60	R	1	>18	8–12	>450	barbel	N
Am2	SLO	15–30	–	40–60	C–R	1	>18	8–12	>450	barbel	N
Am3	SLO	15–30	–	40–60	C–R	1	>18	8–12	>450	barbel	N

of the transmitter ranged from 4 to 20 g depending on fish body weight, making sure that the transmitter to fish body weight ratio in air would not exceed 2.0%. The incision was closed by two to five separate stitches, 9–10 mm apart, using sterile plain catgut or vicryl on cutting needles. Fish were released precisely at their capture site (or upstream of the fish pass where they were caught) as soon as they had recovered posture and spontaneous swimming (about 5 min after surgery). This methodology minimises the possible biases originating from long term post-operative care.

One hundred and twenty-eight fish belonging to six species (*Salmo trutta*, *Salmo salar*, *Thymallus thymallus*, *Barbus barbus*, *Chondrostoma nasus* and

Table 3. Characteristics of the tradio-tracked fish from October 1995 to June 2001 and summary of their movements

Species and rivers	*n*	FL±SD (mm)	W±SD (g)	Tracking period	% of upstream migrants	Distance travelled by upstream migrants in km (mean±SD)	Post spawning downstream migration
S. trutta							
Aisne	19	332±72	428±44	Oct. 1995 to Dec. 1998	88	8.8±2.0	yes
Méhaigne	9	404±71	884±524	Sept. 2000 to Feb. 2001	75	2.0±3.7	yes
Néblon	4	311±11	342±60	Oct. to Dec. 1999	25	0.8	yes
Oxhe	6	332±56	420±198	Sept. 2000 to Jan. 2001	17	0.25	yes
Ourthe	9	480±78	1354±474	Nov. 1995 to Sept. 2000	78	23.2±11.2	yes
S. salar							
Berwinne	1	670	2707	Nov. 1999 to May 2000	100	6.9	–
T. thymallus							
Aisne	23	326±42	381±114	Feb. to Jun. (1998 to 2000)	85	1.48±1.41	yes
Néblon	11	308±22	354±71	Feb. to May 2000	36	3.9±2.8	no
C. nasus							
Ourthe	5	478±28	1672±237	Feb. to June 2001	20	2.4	–
E. lucius							
Ourthe-Ambl.	6	641±60	2381±910	Dec. 2000 to June 2001	100	7.7±6.67	yes
B. barbus							
Méhaigne	5	396±62	935±434	April to June 2001	80	1.3±0.5	yes
Ourthe (upper)	9	437±21	1026±167	Apr. 1998 to June 2000	100	6.1±7.7	yes
Ourthe (med.)	5	442±14	1430±147	March to June 2001	100	1.8±8.1	no
Berwinne	1	555	2740	May to Feb. 2001	0	–	–

Esox lucius) were tracked for different periods of time (Table 3). Fish were located at least five times a week until the end of the transmitter battery life or loss of the signal. Locations were made by triangulation using a mobile FieldMaster radio receiver and a loop antenna (ATS). Locations were made with an accuracy of 1–10 m^2, depending on river size and distance between the fish and the observer.

Results

Analysis of movements by species

The distances travelled by fish during their spawning migrations substantially varied between species, rivers and individuals (Table 3). The proportion of upstream migrants and the distances travelled by brown trout (*S. trutta*) are particularly important in the Ourthe and Aisne where obstacles rarely impeded movements of the fish (e.g. Fig. 3). The proportion of upstream migrants was greater in the Aisne than in the Néblon ($\chi^2 = 8.074$; $p = 0.0045$) and Oxhe ($\chi^2 = 13.576$; $p = 0.0002$). In the Ourthe, the proportion of upstream migrants was higher than in the Oxhe ($\chi^2 = 6.349$; $p = 0.0117$). The proportion of upstream migrants was also higher in the Méhaigne than in the Oxhe ($\chi^2 = 6.349$; $p = 0.0117$), but most fish were blocked below obstacles during their upstream migrations (e.g. Fig. 4). In disturbed salmonid streams (Oxhe and Néblon), none of the trout, excepted one, migrated and thus never confronted with obstacles.

The same phenomenon was observed in the grayling (*T. thymallus*). The proportion of upstream migrants was higher in the Aisne than in Néblon ($\chi^2 = 7.271$; $p = 0.0076$). In the Néblon, some obstacles probably impeded fish migrations (Table 4). The only Atlantic salmon (*S. salar*) studied was blocked below

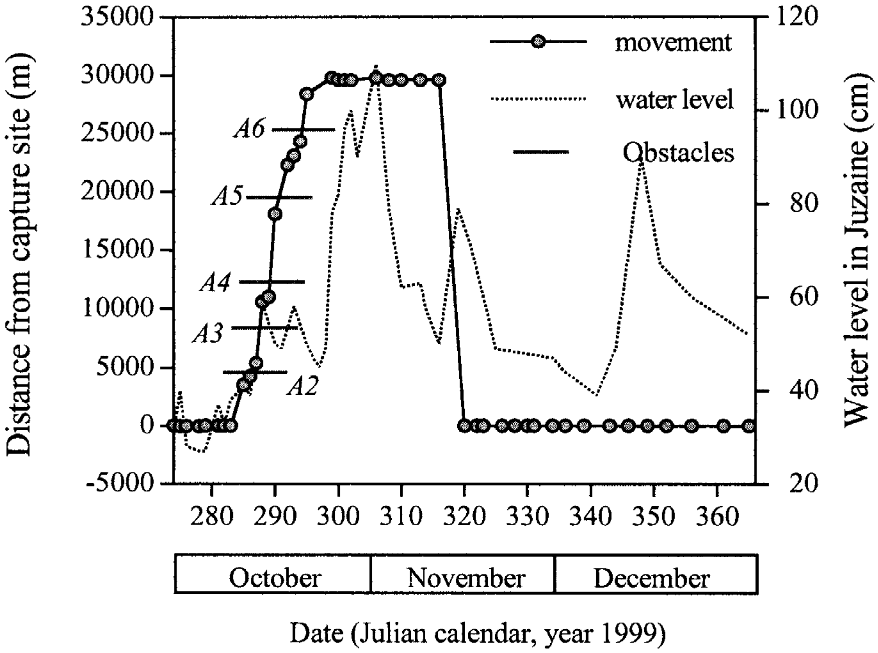


Figure 3. Spawning migration of a female brown trout (250 mm FL) and water flow in the Aisne Stream, Meuse River catchment 1 October 1999–31 December 1999. The alphanumeric codes refer to the five obstacles that this fish cleared. Juzaine is situated in between obstacle A1 and A2. See also Table 2 and Figure 2 for the description of the obstacles. This is a typical migratory behaviour of wild trout in an equilibrated stream (low level of anthropisation).

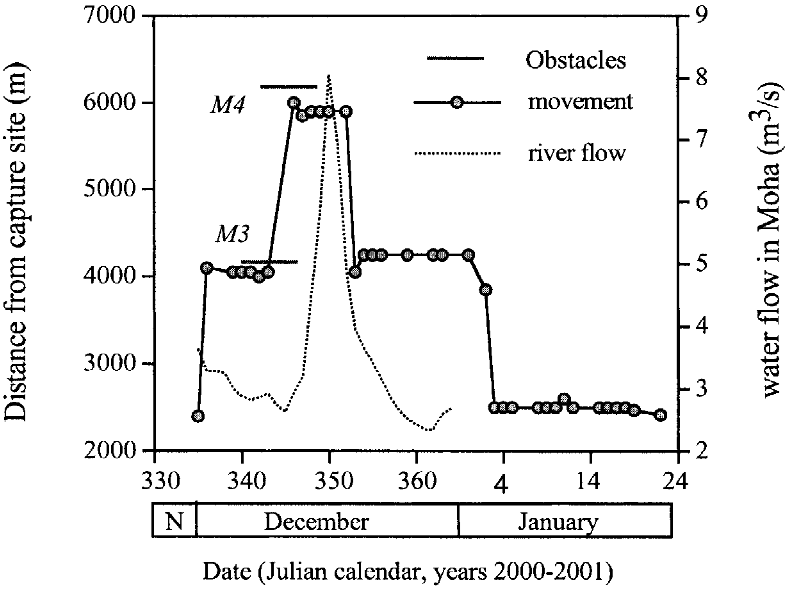


Figure 4. Spawning migration of a male brown trout (511 mm FL) and water flow in the Méhaigne Stream, Meuse River catchment 25 November 2000–24 January 2001. The alphanumeric code M3 refers to the obstacles that this fish cleared. The fish never pass through the obstacle M4. Moha is situated in between obstacles M1 and M2 (Fig. 1). See also Table 2 and Figure 2 for the description of the obstacles. This is a typical migratory behaviour of wild trout in a disturbed stream (high level of anthropisation).

Table 4. Synthesis of the impact of 28 physical obstacles on the migration of the six tracked species

Obstacle	Species located downstream of the obstacle (number)	% of fish moving upstream of the obstacle (FL±SD; cm)	Time for clearing (days)	Flow at clearing in m^3/s; mean±SD and (min value)
A1	brown trout (5)	100% (283±15)	<1	1.71±0.75 (0.76)
	grayling (2)	100% (353±30)	<1	1.8±0.93 (1.14)
A2	brown trout (6)	100% (351±73)	<1	2.76±2.60 (0.40)
A3	brown trout (15)	100% (367±116)	<1	1.73±1.24 (0.24)
	grayling (3)	100% (334±104)	<1	3.35±1.96 (1.14)
A4	brown trout (11)	100% (300±30)	<1 to 3	1.44±1.3 (1.31)
A5	brown trout ($n = 6$)	100% (300±34)	<1 to 2	2.47±1.43 (1.04)
A6	brown trout ($n = 2$)	100% (290±35)	<1	2.32±1.81 (1.04)
N1	brown trout–grayling 2+2	0%	–	–
N2	brown trout (1)	–	–	–
N3	grayling (2)	50% (300)	3	0.783
N4	grayling (3)	66% (329)	<1	1.19±0.22 (1.04)
N5	brown trout (1)	100%	<1	1.3
	grayling (1)	0%	–	–
M1	brown trout (3)	33% (299)	<1	1.17
	Barbel (1)	0%	–	–
M2	brown trout (2)	100% (354±78)	<1	3.91±0.37 (3.64)
M3	brown trout (5)	40% (500±13)	4±4	3.1±0.25 (2.92
	barbel (2)	0%		
M4	brown trout (2)	0%	–	–
Ox1	brown trout (3)	33% (376)	<1 day	–
B1	a. salmon/barbel (1+1)	0%	–	–
O1	brown trout (1)	100% (506)	<1	9.6
O2	brown trout (1)	100% (506)	5	10.2
O3	brown trout (1)	100% (506)	<1	10.2
O4	brown trout (1)	100% (506)	51	28.5
O5	brown trout (4)	50% (478±39)	3.5±3.5	127.9±152 (20.3)
O6	brown trout (2)	100% (478±39)	1.5±0.7	85.2±96.9 (16.7)
O7	brown trout/barbel (5+2)	0%	–	–
O8	brown trout (1)	0%	–	–
Am1	pike (1)	100% (580)	3	26.2
Am2	pike (1)	100% (580)	3	36.7
Am3	pike (1)	100% (580)	6	70.594

obstacle B1 in the Berwinne after a 7-km upstream migration. Nases (*Chondrostoma nasus*) were never confronted with obstacles in the Ourthe. All, but one, moved downstream after a flood (250 m^3 S^{-1}) in Spring, 2001 and never returned to their previous locations.

One-hundred percent of the radio-tagged pike (*E. lucius*) in the Ourthe moved upstream to reach their spawning places. One fish was confronted with three obstacles in the Amblève (Am1 to Am3, Fig. 1), which it succeeded in clearing (Fig. 5). Paradoxically, pike moved greater distances than several other species in

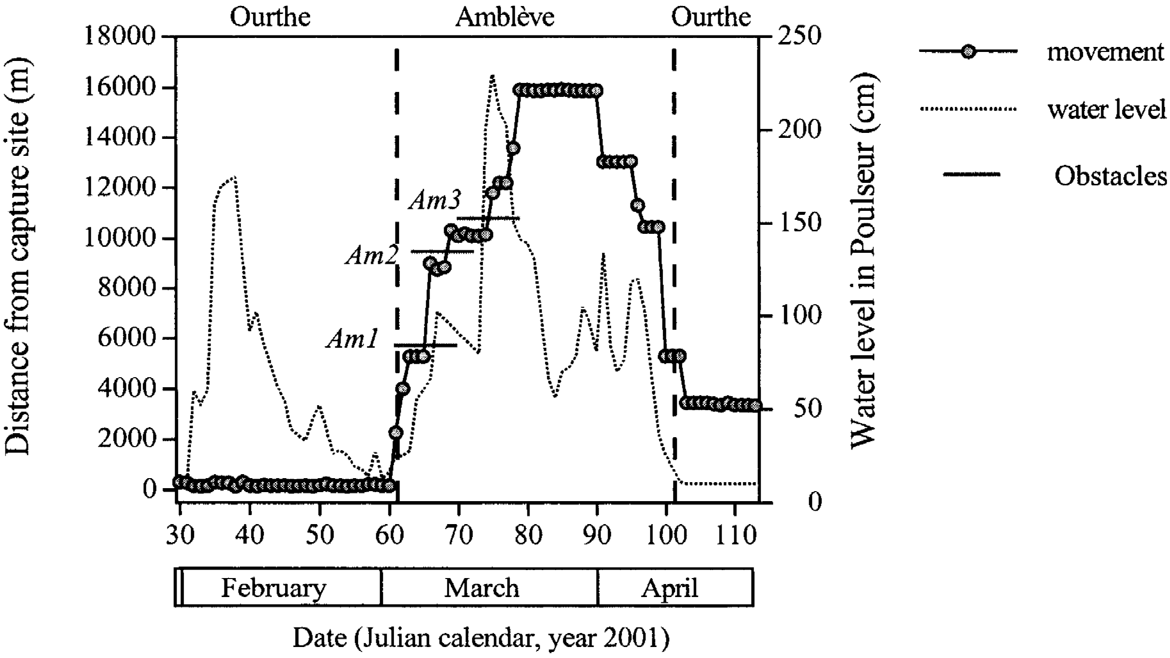


Figure 5. Spawning migration of a pike (580 mm LF) and water flow in the Rivers Ourthe and Amblève, Meuse River catchment 30 January 2001–21 April 2001. The alphanumeric codes refer to the three obstacles that this fish cleared. Poulseur is situated in between obstacle O5 and O6 (Fig. 1). See also Table 2 and Figure 2 for the description of the obstacles.

other watercourses. A hundred percent of the Barbel (*B. barbus*) in the Ourthe migrated and travelled over distances ranging from several hundred meters to several kilometers. In the Méhaigne, most barbels spawned near their place of capture (confirmed by direct observation from the stream bank), but, as observed in trout, some were impeded by obstacle M3 (see Table 3). In the Berwinne, the tagged barbel never migrated.

Effects of obstacles on fish migration

All the obstacles in the Aisne were cleared by 100% of the fish (trout and grayling) within a few days (max.: 3 days for obstacle A4), even under low flow conditions (Table 4; e.g. Fig. 3). Some individuals cleared obstacle A1 without passing through a high-performance basin fish pass. In the Néblon, trout and the grayling never cleared obstacles N1 and N2. Fifty percent and 66% of the grayling cleared obstacles N3 and N4, respectively. Obstacle N5 was cleared by one trout while one grayling failed to pass through, even after several attempts. In the Mehaigne, one trout (33%) cleared obstacle M1, but the barbel never did. Under high flow, the trout cleared obstacle M2 without utilising the fish pass. Obstacle M3 seemed to be only passable by large trout (>49 cm) under relatively high water levels. Other trout and barbel were completely blocked. Obstacle M4 was evidently insurmountable.

In the Oxhe stream, only one trout cleared obstacle Ox 1 under very high flow (Table 4). In the Berwinne, obstacle B1 was insurmountable for both the adult salmon and the barbel during their spawning migration. In the Ourthe, obstacles O1 and O3 were easily cleared in less than 24 h by a trout. The same trout cleared obstacle O2 in 5 days, but was blocked for 51 days by obstacle O4 during low summer flows. Fifty percent and 100% of the trout cleared weirs O5 and O6 in a few days. Trout and barbel never cleared the mobile weir O7 when it was operating in closed position. The fish never found the entrance of the old fish pass. The only brown trout tagged finally cleared the obstacle when it was operating in open position and was later definitively blocked below weir O8. In the Amblève, the pike successively cleared weirs Aml, Am2 and Am3 within 3–6 days (Fig. 5).

Effect of water temperature

Obstacles were cleared when the water temperature ranged from 4.6 to 19.8 °C. Most clearings were observed at temperatures ranging from 8 to 12 °C. Fig-

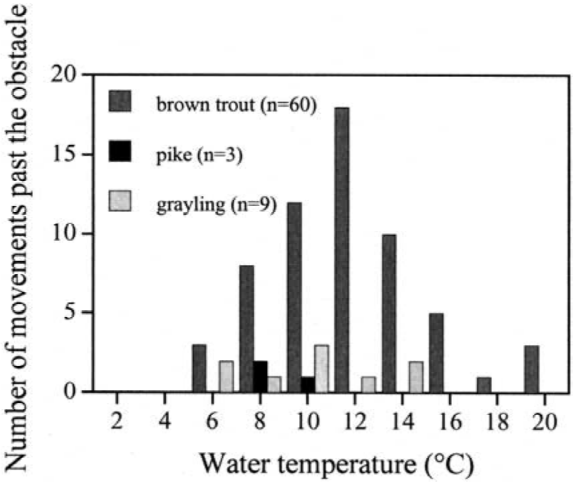


Figure 6. The relationship between water temperature and success in negotiating river obstacles.

ure 6 also indicates that salmonids cleared obstacles in summer when mean water temperature exceeded 16 °C.

Discussion

This study has enabled us to determine the effect of several types of small physical obstacles (height <2 m) on the free circulation of six species (128 individuals) of fish. The results remain preliminary, because the number of observations is too limited to precisely establish the passing capacity of each species studied. However, both the diversity of obstacles and species studied, as well as our individual fish approach provides a better understanding of the problems in restoring longitudinal connectivity in rivers and streams.

It is difficult to determine whether the lack of passage of an obstacle is due to an inability of the fish to surmount the blockage. Zones immediately downstream of blockages are often propitious habitats for several fish species (Ovidio & Baras, 1997), because of the abundance of food, well oxygenated water and presence of gravel beds for the reproduction of lithophilic species (Ovidio, 1999b). This may be why certain fish established their principal resting places in these areas and raises the question whether the removal of such obstacles is always desirable? In order to reduce our margin of error, fish were considered to be impeded only when an obstacle prevented the fish moving upstream by 200 m. This phenomenon is often accompanied by increased activity of the fish at the foot of the obstacle (e.g. clearing attempts, seeking easier passages) (Stuart, 1962).

Several obstacles that appeared to be minor impediments turned out to be to difficult to pass, and even unpassable by one or more of the species. For example, a 45-cm height vertical sill is insurmountable for salmonids if the depth below the dam is not sufficient. Such estimation errors could easily accumulate in a hydrographic network and in the long term, perturb or even prevent the re-establishment of migrating fish. Conversely, some obstacles that appeared difficult or even impossible to pass were cleared with varying degrees of ease by certain species. For example, an obstacle with a vertical slope >50% is passable if the water height on the obstacle is sufficient. In this case, the cost of the biological investigation is largely recuperated, because construction and/or the renovation of fish passes or other pass devices is avoided.

Our observations show that, like salmonids, thymalids, rheophilic cyprinids and pike migrate for several kilometres in rivers (usually upstream) to reach their spawning sites. In the past, most of these species were considered relatively non-migratory because the methodologies used to study their displacements were inadequate (Gowan et al., 1994; Faush & Young, 1995; Baras, 1998; Ovidio et al., 2000a). In recent years, biotelemetry studies of individual fish over time have revealed that many species are affected significantly by river obstacles (Baras, 1992; Lucas & Batley, 1997; Hubert & Kirchofer, 1998; Parkinson et al., 1999; Koed et al., 2000). In the present study, pike (*E. lucius*) were surprisingly mobile, travelling several kilometres (max.: 20 km), and overcoming several consecutive obstacles to reach their spawning grounds. Adult brown trout also showed high mobility, migrating not only during the spawning season (October–February), but also during the summer.

Our results indicate that the ability to successfully pass obstacles differs among species. Brown trout are sometimes capable of clearing vertical sills 1.1 m. in height and swimming over 3.8 m long oblique obstacles with slopes of ca. 50%. They are also capable of clearing long obstacles (up to 23 m) with a slope of ca. 30%. Clearance of vertical obstacles requires sufficient water depth immediately downstream of the obstacle (minimum twice the size of the fish) to enable the fish to gain momentum. For a sloped obstacle, water depth on the obstacle itself is crucial, and should be equal, at least, to the fish's height. This is probably why some brown trout never passed obstacles ca. 40 cm height and the Atlantic salmon was unable to pass a 1.4-m height and 50% sloped obstacle. The water depth below the obstacle, as well as that on the obstruction was too low. On the Gave de Pau (France), Chanseau et al. (1999a) demonstrated that Atlantic salmon during upstream migration is capable of passing obstacles <1.5 m height in less than 24 h. However, we only tracked one salmon and we must be careful of any comparison. We also demonstrated that grayling are able to clear slopes ca. 40%. During our study, its jumping capacity appears slightly weaker (max.: 0.85 m) than that of brown trout. Pike showed an ability to clear obstacles with slopes of ca. 20% and drops of 20 cm. Barbel were systematically blocked at the foot of obstacles and nases never confronted obstacles.

Clearance of an obstacle can be temporary, depending strongly on water flow conditions. Water flow affects hydraulic conditions, including water depth on the obstacle, flow speed, depth downstream, and the nature and direction of turbulence, and water temperature, both of which affect the behaviour of fish facing the obstacle. We have observed that certain obstacles are cleared under almost all flow conditions, while others are only cleared under conditions of medium or high water flows. Because it is laborious to test all obstacles under all possible flow conditions, it becomes imperative to model the range of hydraulic conditions for different types of obstacles and compare this to the capabilities of different fish species to pass them.

Water temperature is also important in the success with which fish pass obstacles because of its effects on a fish's muscular efficiency and thus its swimming and jumping capacities (Wardle, 1980; Beach, 1984). Our observations show that the various obstacles are cleared in a thermal range from 4.6 to 19.8 °C, with a preference for temperatures between 8 and 12 °C.

The effects of flow and water temperature were observed several times. When fish arrive at the foot of an obstacle, they almost always attempt to clear it immediately. If they are unable to do so, they go downstream dozens to several hundreds of metres and wait, sometimes several weeks, for environmental conditions to improve (increase in water level or temperature), which will allow them to clear the obstacle. Chanseau & Larinier (1999) observed 1.5 km downstream migrations of Atlantic salmon in the Gave de Pau. In Scotland, Webb (1990) observed that the salmon that did not clear the fish pass at Pitlochry the first time never returned to the structure. However, other authors (Liscom et al., 1985; Laine, 1995) observed successive penetrations by Atlantic salmon in fishways. This type of behaviour is very costly in terms of energy and the numerous jumping attempts could also result in injury. Moreover, obstacles cause delays that may constrain the fish to reproducing during non-optimal environmental conditions.

Migrations of various fish species are seasonal and closely linked to a combination of environmental conditions (essentially flow and water temperature) that trigger or favour fish displacement and thus their interactions with various obstacles (Jonsson, 1991; Ovidio et al., 1998). Consequently, any policy of obstacle restoration should preferentially comply with an in-depth study of the behavioural ecology of the species present in the river.

Within a given species, clearing capacities can vary from one individual to another. This phenomenon is often observed in individuals of different sizes. Indeed, in function of their structure and characteristics (depth downstream, water height on the obstacle), some obstacles are more easily cleared by fish whose size is within a certain range. For example, the 1.09 m high obstacle M3 was only cleared by trout >49 cm. We have also observed that, for identical environmental conditions, individuals of the same size sometimes remain blocked for different periods of time at the foot of the same obstacle. Such inter-individual differences do not facilitate establishing precise norms for clearing capacities of fish. However, within the context of the Benelux decree, some targets should be set. For example, 90% of migrating fish should be able to pass each obstacle. Inter-individual behavioural differences are not specific to the ability to pass obstacles, they have also been remarked in strategies of space utilisation by river fish, such as brown trout, barbel and grayling (Baras, 1992; Ovidio 1999a,b; Parkinson et al., 1999).

Another important problem revealed by our study concerns post-reproduction downstream migration. In most cases, we observed that fish often return within a few metres to the capture site. This phenomenon was already described by Baras (1992) with barbel (*B. barbus*), Fredrich (1995) with chub (*Leuciscus cephalus*), Ovidio (1999) with brown trout (*S. trutta*) and Parkinson et al. (2000) with grayling (*Thymallus thymallus*). The obstacles are obviously more easily cleared going downstream than upstream. However, one must not underestimate the injuries and mortality caused by the passage over certain artificial obstacles in the direction of the current, especially when these obstacles have electric turbines (Long, 1968; Sorenson et al., 1998; Chanseau et al., 1999b; Larinier & Travade, 1999; Coutant & Whitney, 2000; Lajeone & Monzingo, 2000; Michaud, 2000). Facilities for upstream passage of adult salmonids are reasonably straightforward. However, this is not the case for facilities for safe downstream migration for the postspawners and their progeny.

When an obstacle is revealed to be effectively impassable by migrating fish, one should firstly understand what makes the obstacle impassable, what are the impacts on the fish living upstream and downstream (e.g. are the conditions downstream of the obstacles desirable for some species) and then to question the necessity of the structure. If the structure is not justifiable the best solution would be its complete or partial destruction, so that it no longer constitutes an obstacle to the free circulation of fish. This solution has priority, as it ensures the passage of all species. If removing the obstacle is not feasible, the obstacle should, when possible, be rendered clearable through design adaptation, thus avoiding the construction of a fish pass (Croze & Larinier, 2000). If such a structure cannot be realised, an artificial clearing device should be built. The construction of such a device must be carefully studied and adapted to the targeted species, variations in water levels up- and downstream of the obstacle, slope to be cleared, topographical constraints and solid transport in the river (Croze & Larinier, 2000).

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