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Field protocol for assessing small obstacles to migration of brown trout *Salmo trutta,* and European grayling *Thymallus thymallus*: a contribution to the management of free movement in rivers

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Abstract Between 1996 and 2004, adult brown trout, *Salmo trutta* L. ($n = 40$) and European grayling, *Thymallus thymallus* (L.) ($n = 39$) were radio-tracked in three southern Belgium rivers to assess their capabilities to bypass various obstacles. During their upstream migrations individuals encountered different types of physical obstacles and successfully passed some under variable environmental conditions. The obstacles cleared by the fish were characterised based on a simple topographical description protocol and compared with tracking data. The ability of trout and grayling to pass different typologies of physical obstacles in natural river systems is discussed in the context of enabling their free movement in rivers.

KEYWORDS: fragmentation, jumping, migration, obstacles, telemetry.

Introduction

Fragmentation of rivers by physical obstacles has resulted in the drastic range reduction or extinction of numerous diadromous and potadromous species of fish worldwide (Dynesius & Nilsson 1994; Jungwirth 1998; reviewed in Northcote 1998). To partially or completely re-establish the free migration of fish in their watercourses, various national and regional governments have initiated restoration projects. The recording of obstacles that can interfere with longitudinal connectivity is critical information to plan river restoration (Belgium: Benelux 1996; Ovidio & Philippart 2002; France: Souchon & Trocherie 1990; Area, Eau-Environnement 2002; Malavoi 2003). To date the main problem has been to determine the potential effect of each obstacle and to select the problematic sites that should be improved to restore longitudinal connectivity (construction of fish passage facilities, removal or modification of the obstacles). This selection is too often biased because managers lack information on the fishes' capabilities to leap physical obstacles.

The concept of obstruction to fish migration is often associated with the height of the obstacle, but very small weirs may also be major obstructions (Ovidio &

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Philippart 2002). Fish passage success about an obstacle depends on the hydraulic conditions over and at the foot of the obstacle in relation to swimming and leaping capabilities of the fish species concerned (Stuart 1962; Larinier 2001; Ovidio & Philippart 2002; Holthe, Lund, Finstad, Thorstad & McKinley 2005). The swimming and leaping capacities depend on the species, the size of individuals, their physiological condition and water-quality factors (Wardle 1975; Beamish 1978; Blake 1983; Beach 1984). Many studies have been conducted in artificial environments to determine the swimming performance of migratory species (e.g. Jones, Kiceniuk & Bamford 1974; Stahlberg & Peckmann 1987; Videler 1993; Peake, McKinley & Scruton 1997). Some have also tested the capacity of fish to leap over vertical sills in experimental rivers and channels (Powers & Orsborn 1985; Holthe *et al.* 2005). More recently Lauritzen, Hertel & Gordon (2005) performed behavioural and kinematic analysis of the jumping capacities of the sockeye salmon, *Oncorhynchus nerka* (Walbaum), in natural environments.

However, as hydraulic conditions over obstacles in rivers are often complex, heterogeneous and dependent on flow conditions, their potential effects on fish movements cannot be determined easily using theoretical curves of swimming and leaping performance. Ideally, the successful passage of each obstacle must be tested in the field, by studying the leaping and clearing capabilities of endemic species for different water flow conditions. Unfortunately, the abundance of obstacles in most river basins [e.g. one obstacle every 5.3 km of river stretch in the Seine-Normandie basin – Area, Eau-Environnement 2002; 45 weirs on a 26-km river stretch of the river Nea in central Norway – Arnekleiv & Rønning 2004)] and the time and cost necessary for such studies preclude individual testing of each obstacle. Nevertheless, river managers require such concrete information for the appropriate conservation and management of a large variety of species.

The migrations of brown trout, *Salmo trutta* L. and European grayling, *Thymallus thymallus* (L.) have been intensively studied using radiotelemetry in streams in Southern Belgium (more than 4000 fish locations, Ovidio, Baras, Goffaux, Birtles & Philippart 1998; Ovidio 1999; Ovidio, Parkinson, Sonny & Philippart 2004). During their upstream migrations, individuals encounter numerous different small physical obstacles and successfully pass them. Passage data provide an opportunity to define a simple descriptive protocol for characterising the obstacles cleared by brown trout and European grayling. Furthermore, physical measurements relating to the obstacle may allow classification into an obstacle typology that may facilitate improved obstacle passage by both species.

Materials and methods

The study was conducted in the rivers Aisne, Néblon, and Lhomme, three salmonid sub-tributaries of the river Meuse basin that run through southern Belgium (Fig. 1; Table 1).

Fish tracking and environmental records

Trout and grayling were captured by electric fishing or caught in fish traps for the tracking studies. Transmitters were implanted in the intra-peritoneal cavity following Ovidio *et al.* (1998, 2004), ensuring that the transmitter to fish body weight ratio in air did not exceed 2.5%. Fish were released precisely at their place

Figure 1. Location of the study areas in Belgium.

Table 1. Main characteristics of the three rivers where fish were radio-tracked

Characteristics	Aisne	Néblon	Lhomme
Elevation source (m)	600	255	475
Length (km)	35	18.3	50.6
Drainage area (km^2)	184	78.7	479
Average slope (m 1000 m^{-1})	13.3	7.7	63.7
With in lower course (m)	5–10	5–10	10–15
Average annual discharge (m^3 s^{-1})	2.6	0.5	2.7
Average annual temperature (°C)	9.4	10.4	10.0
Dominant Huet (1949) fish zone	Grayling	Trout	Grayling
Dominant fish species (kg)	Trout	Trout	Trout
Level of global water quality	Excellent	High	High
Fish tracked			
Brown trout	31	4	5
European grayling	20	11	8

of capture (or upstream of the fish pass where they were caught) as soon as they recovered posture and spontaneous swimming (about 5 min after surgery). The methodology minimises possible biases originating from long-term postoperative care. A total of 40 brown trout and 39 European grayling were tracked in the Aisne from 1996 to 2000, in the Néblon in 2000 and in the Lhomme from 2003 to 2004 (Table 1).

Water temperature (electronic data loggers, TidBit Onset Corp.®) and discharge (data from DGRNE-Water Division) were recorded hourly in the three rivers. Temperature and discharge recorders were located in the downstream part of the catchments of each river. Data were used to estimate temperature and discharge conditions during successful obstacle passage and to evaluate the frequency of occurrence of such conditions over the whole study period.

Physical description of the obstacles

Key topographical variables (e.g. drop height, plunge pool depth) have been used to describe simple obstacles and to evaluate their passage potential under controlled conditions (Powers & Orsborn 1985). However, no simple protocol exists that permits calculation of key topographical variables in a standardise fashion. Moreover, certain values are a direct function of river discharge (e.g. drop height; Fig. 2). To overcome this limitation, it was necessary to either model the response of key variables as a function of discharge or take measurements at a given, easily identifiable discharge. Hydraulic turbulence cannot be modelled and the description of the obstacle at a precise passage discharge would require substantial logistical resources for monitoring the instantaneous discharge in the river. The minimum annual discharge was chosen as the reference discharge to establish the topographical description protocol for obstacles because it is easy to identify, generally stable over several days, and allows easier working conditions in the river.

The protocol developed for this study was intended: (1) to report on the topographical heterogeneity of a river barrier; and (2) to calculate values of key topographical variables for obstacles.

Each obstacle was described according to a simple spatially based protocol.

- Delimitation of different transversal barrier parts to account for transversal heterogeneity of the obstacle (red lines on Fig. 3). These representative components were identified as a fall, a chute, or a succession of both types to consider significant topographical diversity.
- Each transversal obstacle part was longitudinally described with measurement points (XY location, elevation and depth) selected on three main cross-sections (Fig. 2), to describe topography and water level upstream on and downstream of the obstacle. One or a few measurement points were selected to be representative (the mean value was calculated if more

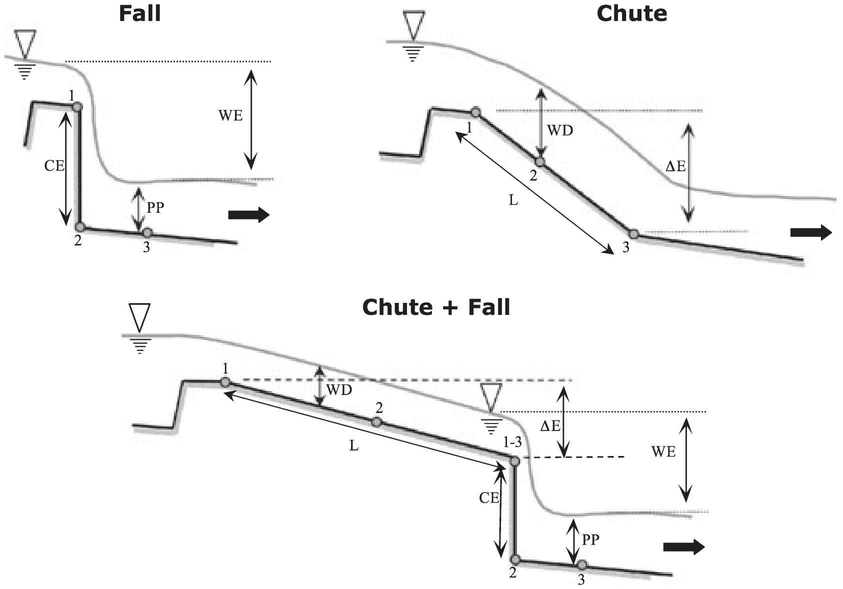

Figure 2. Description of morphological characteristics of obstacles (longitudinal view). Measurement points have to be located on three main transversal sections (points 1–3 on the longitudinal view) to measure water elevation (WE), crest elevation (CE) and plunge pool depth (PP) for falls and water depth (WD), length (L) and elevation (ΔE, used to calculate slope) for chutes. One or more measurement points were chosen to describe heterogeneity of each transversal part (see Fig. 2 and Table 3).

Figure 3. Pictures of each study obstacle in the river Aisne (A1–A6), in the river Néblon (N1–N3) and in the Lhomme (L1). Different transversal parts (I–VI per obstacle, from the left bank to the right bank) were delimited by lines and identified by their number (see Table 3 for physical characteristics) on each picture.

than one point was selected) of the heterogeneity of the obstacle.

- The main descriptive variables indicated as representative by Powers & Orsborn (1985) were calculated according to Figure 2.
- When the longitudinal succession of different obstacle types (e.g. fall + chute; Fig. 2) occur in a transversal part, each type was described successively and separately.

Analysis combined the radiotelemetric data (threshold passed, date, species and characteristics of the fish), discharge conditions and temperature when clearing the obstacle, and the topographical measurements for each transversal part.

Results

From 1996 to 2004, a total of 56 obstacle passages were recorded in the rivers Aisne, Néblon and Lhomme (Table 2). In the Aisne, 100% of fish (trout and grayling) were able to bypass the obstacles during upstream migration. Fish generally succeeded in passing the obstacles between two locations 24 h apart, except on two occasions when obstacles A4 and A5 were passed in 2 and 3 days. Although A1 was equipped with a high-performance fish pass, some individuals bypassed the obstacle without using the pass. Most of the obstacles were cleared by both male and female fish. In the Néblon, obstacle N1 was cleared by one individual in 3 days, two individuals failed to clear it. A grayling easily cleared obstacle N2 on two occasions. Obstacle N3 was bypassed by a trout, but a grayling located downstream during migration failed to negotiate it. In the Lhomme, one trout was confronted with obstacle L1 and negotiated it in 2 days.

Obstacles identified as falls had a crest elevations from 0.39 to 1.89 m and a plunge pool ranging from 0.07 to 0.77 m. Lengths of obstacles ranged from 0.54 to 8 m with slopes between 4% and 74%. The main characteristics of potential parts used by brown trout and European grayling to bypass the various obstacles are graphically presented in Figure 4 and the detailed topographical measures of each accessible part in Table 3. Some obstacles or transversal parts of obstacles comprised a succession of falls and chutes (or inversely). For each obstacle, the hypothetical easiest passageway was identified. For A1, A5 and N3, some individuals were observed clearing the obstacle using this hypothetically easiest passageway. Based on these considerations, it appears that brown trout of 260 mm fork length (FL) jumped at least to a crest of approximately 0.59 m in height with a plunge pool of 0.63 m depth (pool crest ratio: 107%) at a minimum water temperature of 9.2 °C. Trout of 295 mm FL jumped to a crest of 1.81 m with a plunge pool of 0.77 m (pool crest ratio: 42%) at a minimum water temperature of 6.5 °C. Grayling of 272 mm FL passed at least a crest of 0.96 m using a plunge pool of 0.35 m (pool–crest ratio: 37%) at a minimum water temperature of 5.2 °C.

Trout of 266 mm FL crossed at least slopes of 26% and 2.98 m in length at a minimum water temperature of 7.7 °C and of 16.5% and 5.13 m in length at 8.5 °C. Grayling of 300 mm FL crossed at least slopes of 12% and 6.21 m in length at a temperature of 10.1 °C. Trout and grayling cleared slopes of 10% over 8 m after having jumped a 0.59-m crest.

In the Aisne, obstacles were cleared at a water temperature ranging from 4.6 to 14.0 °C, but particularly between 10 and 14 °C (33% of the time from 1996 to 2000; this percentage ranged from 25% to 35% across years, and from 7% to 64% among obstacles). When considering the discharge during passage, it appears that obstacles on the Aisne would have been

Table 2. Number of passages of each obstacle by trout and grayling (note that one obstacle could be passed more than once by the same individual). Minimum (Min.) and maximum (Max.) of fork length (FL in mm) and weight (in g) of fish (male, female or both) which passed obstacles are presented in comparison with the temperature and discharge ranges for the days of passage. The time taken for fish to pass one obstacle was estimated (days) between its arrival in front of the obstacle until the fish passed the obstacle

			Time spent (day)		Fork length (mm)		Weight (g)			Discharge ($m^3 s^{-1}$)		Temperature (°C)	
Obstacle	Species	Number clearing	Min.	Max.	Min.	Max.	Min.	Max.	Sexes	Min.	Max.	Min.	Max.
A1	Trout	5	1	1	260	291	206	312	M & F	0.76	2.45	9.2	14.0
A1	Grayling	2	1	1	288	374	297	520	M	1.14	2.45	7.7	12.4
A2	Trout	6	1	1	295	489	287	1357	M & F	0.41	7.01	6.5	13.5
A3	Trout	15	1	1	263	570	206	1685	M & F	0.24	4.16	4.6	13.3
A3	Grayling	3	1	1	272	455	216	349	M & F	1.14	4.89	5.2	12.4
A4	Trout	11	1	3	266	347	233	460	M & F	0.32	4.3	7.7	12.9
A5	Trout	7	1	2	266	347	233	460	M & F	1.04	4.44	7.4	11.1
A6	Trout	2	1	1	266	315	233	350	F	1.04	3.6	9.2	10.5
N1	Grayling	1	3	–	300	–	315	–	F	0.783	0.783	10.1	10.1
N2	Grayling	2	1	1	329	329	393	393	M	1.03	1.35	9.4	9.4
N3	Trout	1	1	–	290	–	285	–	Unknown	1.3	1.3	9.6	9.6
L1	Trout	1	2	–	294	–	258	–	F	0.228	–	8.5	–

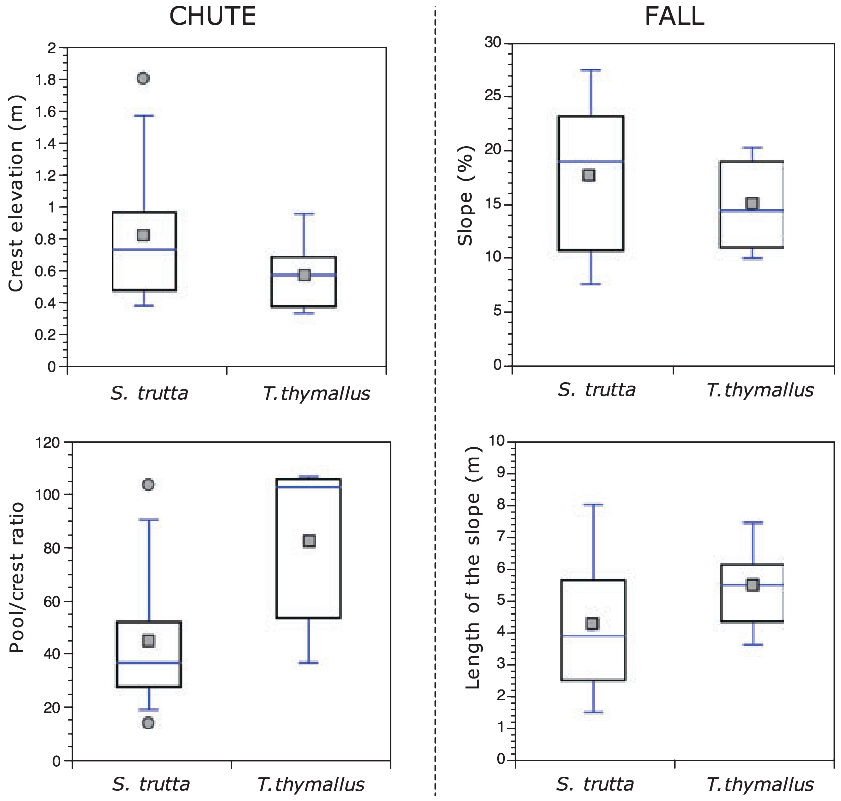

Figure 4. Physical characteristics of the main descriptive variables of the obstacles cleared by brown trout and European grayling. Values are median, percentiles 5, 25, 75 and 95. Circles indicate outlier values.

potentially passable by the trout between 0.24 and 7.01 $m^3\ s^{-1}$ (87% of the time from 1996 to 2000; this percentage ranged from 71% to 96% across years, and from 37% to 83% among obstacles). For the grayling, obstacles A1 and A3 would have been passable 30% and 52% of the time, respectively, in 2000 considering temperature, and 25% and 48% of the time, respectively, considering discharge availability in 2000. In the Néblon, obstacles were cleared at temperatures ranging from 9.4 to 10.1 °C (6% of time in 2000) for trout and grayling and during conditions of relatively higher flows (0.78–1.35 $m^3\ s^{-1}$; i.e. 16% of the time in 2000) compared with mean annual flow of the Néblon (0.58 $m^3\ s^{-1}$). This analysis was not possible in the Lhomme as just one obstacle was cleared.

Discussion

This study characterised typologies of small obstacles cleared by brown trout and European grayling. The approach, in the context of life cycle, complements theoretical knowledge on trajectory calculations (Evans & Johnston 1980; Powers & Orsborn 1985) and research in controlled environments (Slatik 1970). Radiotelemetry is effective in observing obstacle passage, but acquiring individual data over a wide range of environmental conditions is tedious, given it demands continual presence in the field and requires a large number of fish. Conversely, this methodology guarantees that clearing obstacles was a natural event (e.g. reproductive migration, habitat changes). Individuals followed by radio-tracking were generally larger than the adult population in place so the results should not be extended to the entire population. This limitation of having to follow individuals larger than average reflects the need to minimise the weight of the transmitter in relation to weight of the fish and reduce the potential biases of marking on the results.

Most fish were able to negotiate all the obstacles along their migration route under existing conditions of water temperature and discharge. As a consequence of this high success rate, it was not possible to determine between individuals that succeeded in negotiating the obstacles or not. Care must also be taken not to consider fish that did not attempt to negotiate the obstacles with failure, because the downstream side of a dam can be favourable for brown trout that, for example, can develop a dam residential strategy that

Table 3. Physical characteristics of each transversal part defined for each obstacle. Each transversal part represents a different possible way for fish to pass the obstacle. Each of these parts (I–VI per obstacle) was described as a chute (C), a fall (F) or a mixture of both types, and with different variables measured or calculated according to the protocol presented in the text and in Fig. 2. Bold line represents the apparent easiest passageway. The value of each variable characterising a transversal part represented either one measure or the mean of different measures depending on physical heterogeneity inside the transversal part

		Fall				Chute		
Transversal part	Type	Crest elevation (m)	Water surface elevation (m)	Plunge pool (m)	Pool/crest ratio (%)	Slope (%)	Length (m)	Depth (m)
A1-I	**C + F**	**0.59**	**0.539**	**0.63**	**107**	**10**	**8.00**	
A1-II	C + F	0.39	No water	No water	No water	21	3.62	
A1-III	C + F	0.57	No water	No water	No water	10	5.03	
A2-I	F	1.20	1.04	0.31	26			
A2-II	F	1.57	1.08	0.49	31			
A2-III-1	F	0.63	0.39	0.54	86			
A2-III-2	F	0.87	0.59	0.30	34			
A2-IV	F	1.63	1.00	0.63	39			
A2-V	**F**	**1.81**	**1.04**	**0.77**	**42**			
A2-VI	F	1.15	0.56	0.62	54			
A3-I	**F**	**0.96**	**0.66**	**0.35**	**37**			
A3-II	C					19	3.70	0.04
A4-I	**F**					**26**	**2.98**	**No water**
A4-II	C + F	0.45	0.32	0.13	29	4	2.38	No water
A4-III	C + F	0.64	0.57	0.07	11	13	4.08	0.04
A5-I	**C**	**0.96**	**0.84**	**0.36**	**37**			
A5-II	C	0.16	0.82	0.11	71			
A5-III	C + F	0.40	0.31	0.20	50	74	0.54	0.09
A5-IV	C + F	0.48	0.56	0.46	95	30	1.90	0.10
A6-II	**C**	**0.94**	**0.77**	**0.21**	**23**			
A6-III	C	0.92	No water	No water				
A6-I	C	0.48	0.47	0.23	35			
N1-I	F					17	5.67	0.03
N1-II	F					19	5.31	0.04
N1-III	**F**					**12**	**6.21**	**0.12**
N2-I	**C + F**	**0.33**	**0.25**	**0.34**	**103**	**12**	**6.06**	**0.05**
N3-I	C	0.82	0.60	0.20	25			
N3-II	C	0.97	0.64	0.37	38			
N3-III	**C**	**0.61**	**0.52**	**0.09**	**15**			
L1-I	**F**					**16.5**	**5.13**	**0.13**
L1-II	F					19.6	8.15	0.03
L1-III	F					24	6.17	0.02

allowed very high growth rates while avoiding the risks inherent to long range migrations. Brown trout and European grayling also frequently spawned in gravel bed environments downstream of obstacles (Ovidio *et al.* 2004). Visual observation on fish that attempt to leap obstacles is a better methodology to distinguish successful and unsuccessful attempts (Lauritzen *et al.* 2005).

Biotelemetric methods make it possible to determine the obstacle clearing date precisely and therefore concurrent environmental conditions (temperature and river discharge). Most of the time obstacles are complex heterogeneous structures and the fish use several potential pathways, but the precise route is rarely identified. In this investigation, the different possible passageways were isolated to identify the easiest route. For some obstacles, visual observations provided information on the pathway taken by tagged or untagged fish in the river. The description of the different routes shows that the pathways used correspond, *a priori*, to the subjectively most favourable passage conditions from a physical perspective. This corroborates Powers & Orsborn (1985), who suggested that fish will be generally attracted to the area of highest momentum (flow × velocity) when migrating upstream; therefore if multiple paths are present the fish may try to ascend the one with the highest attraction, which will be created by the greatest combination of drop, velocity and discharge (Powers & Orsborn 1985). However, it does not exclude some obstacles being negotiated using different passageways and therefore the observations may underestimate the true range of fish capabilities.

Some brown trout leaps observed were superior to theoretical leaping capacity of the species (Beach 1984). These results confirm that the theoretical trajectories do not take into account the actual hydraulic heterogeneity used by fish, such as the velocity at the foot of a drop as well as the additional propulsive force cause by the beating caudal fins at the moment it leaves the surface of the water (Larinier 1992). Furthermore, the theoretical curves do not consider microhabitat conditions that fish probably exploit. In this study, current velocities and turbulence were not taken into consideration in the description of the obstacles because of their variability and complexity at the local scale. This suggests that it is vital to combine theoretical approaches with studies of obstacles actually cleared *in situ* to improve knowledge on fish obstacle clearance capabilities.

Information on the ability of grayling to negotiate obstacles is lacking despite the species being in decline in Western Europe (Philippart & Vranken 1983; Persat 1996). European grayling often live sympatrically with brown trout, but its behavioural plasticity is lower. For example, the grayling's migration period lasts a shorter time and is less flexible, and is therefore more susceptible to being disturbed by physical obstacles that are only passable under certain discharge conditions (Ovidio 1999; Parkinson, Philippart & Baras 1999; Ovidio *et al.* 2004). The results indicate that the grayling succeeded in swimming on a 12% slope for more than 6 m. Adult grayling are also capable of clearing obstacles with a drop height of 0.66 m, suggesting that the species can leap in some instances.

The pool/crest ratio is widely considered as an important characteristic of obstacle jumping by salmonids (Lauritzen *et al.* 2005). The 1.25 ratio has long been suggested as the optimal in fish ladder design, but Lauritzen *et al.* (2005) observed sockeye salmon jumping obstacles with a pool–crest ratio ranging from 0.68 to 1.53. In this study, the physical description of obstacles demonstrated that brown trout and European grayling leapt small falls with a pool/crest always < 1.25. River managers should therefore set the pool/crest ratio to its highest level when modifying obstacles.

Water temperature plays an important role in muscle effort efficiency and thereby on leaping and swimming capacities of fish (Wardle 1975; Evans & Johnston 1980; Beach 1984). Experimental studies have provided a number of empirical expressions giving relations between temperature, swimming velocity, endurance, and fish size and morphology (Wardle 1975; Zhou 1982; Beach 1984). The present study, in an uncontrolled milieu, cannot provide this type of analysis, but it suggests a range of swimming and leaping capabilities of adult trout and grayling that is relatively wide. Trout and grayling managed to clear the different obstacles presented when the water temperature was between 4.6 and 19.5 °C, but within a preferential range of 10–14 °C for brown trout and 6–10 °C for European grayling. This mainly corresponds to thermal conditions that trigger the beginning of their spawning migrations, in association with flow fluctuations, in southern Belgium (Ovidio *et al.* 1998, 2004).

Based on intensive telemetry investigations and simple physical description protocol, this study brings information on obstacle typologies that may be potentially cleared by adult brown trout and grayling during their upstream migrations. The typologies presented are not exhaustive, but considering the lack of information about migration obstacles, the results contribute to a better understanding of clearing capacities of salmonids in small rivers. The study should be followed up to include more species and greater size ranges, including on other types of obstructions.

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