RIVER RESEARCH AND APPLICATIONS

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ADDITION OF SPAWNING GRAVEL—A MEANS TO RESTORE SPAWNING HABITAT OF ATLANTIC SALMON (*Salmo salar* L.), AND ANADROMOUS AND RESIDENT BROWN TROUT (*Salmo trutta* L.) IN REGULATED RIVERS

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ABSTRACT

In regulated rivers, canalization and reduced water discharge may lead to loss or impairment of salmonid spawning areas, and thereby negative effects on stock recruitment. We discuss the possibility of mitigating such effects through establishing new spawning areas by addition of gravel. We monitored the occurrence of nests in seven gravel deposition sites in five different Norwegian rivers. The total area covered by each of the depositions spanned from 25 m^2 to 300 m^2. The areas were examined for nests during a 2–5 year period following the addition of gravel, that is, a total of 27 spawning periods. The fish were found to spawn at all localities and years with the exception of two occasions when gravel was lost during floods. Spawning success measured as egg survival was generally high (>80%). These results show that the additions met the criteria for successful spawning. Nests of Atlantic salmon were found to be aggregated in the area with the highest water current. However, successful nests were also found in areas with added gravel where the water current was much reduced. This unusual selection of spawning site most likely reflects the lack of other, more favourable spawning areas. The results therefore suggest that gravel additions can be successful even if the only available areas are suboptimal with respect to water flow and water depth. Three of the seven localities were unsuitable as the gravel was partly or totally displaced downstream during floods. At two of these localities, nests were probably lost because the floods occurred after the spawning season. This shows that large floods can be a major drawback. Monitoring of the spawning success and displacement of gravel is therefore essential to evaluate the method. Subsequently, stable areas, favoured by the spawners, can be expanded by supplementary addition of gravel. In sum, the results show that the careful addition of gravel areas can be used to provide suitable spawning locations for salmonids in regulated rivers. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: Atlantic salmon; trout; spawning habitat; nest; recruitment; habitat; restoration

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INTRODUCTION

Atlantic salmon (*Salmo salar* L.) and brown trout (*Salmo trutta* L.) are known to be highly selective in their choice of spawning area. Nests are placed within restricted boundaries of gravel-size, water depth and water velocity (Heggberget *et al*., 1988; Crisp and Carling, 1989; Grost *et al*., 1990; Moir *et al*., 1998). The availability of gravel suitable for spawning will be determined by hydrological processes. In regulated rivers, areas available for spawning may decrease as a result of reduced water discharge or physical changes like canalization. Reduced discharge may leave spawning areas dry or too shallow for spawning, or lead to increases in deposition of sand and silt. Further, reduced discharge and increased deposition of fines may lead to reduced supply of oxygen in the gravel and thereby reduced egg survival (Chapman, 1988). In sum, these negative effects on the quantity and quality of spawning areas may reduce the recruitment to salmonid populations in regulated rivers.

Typical spawning areas are found at the outlet of pools where suitable gravel is found in combination with increased water velocity. The female digs a pit in the gravel by beating her tail. The eggs are then spawned into the pit and fertilized by one or more males. The female then immediately moves upstream and starts to cover the eggs by digging a new pit. The resulting gravel construction is called a redd (White, 1942). A redd can contain a single nest (i.e. the portion of eggs resulting from one spawning act also called an egg pocket) or several nests spawned in

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Table I. The locality, time of addition, target species, surface area and total area of the studied gravel additions

River and locality	Year of gravel addition	Target species	Area of gravel added (m^2)
River Nidelva at weir Rygenefossen	Autumn 2002	Atlantic salmon and seatrout	$24 \times 4\,m^2 + 8 \times 5\,m^2 = 136\,m^2$
River Nidelva at weir Strubru	Autumn 2002	Atlantic salmon and seatrout	$21 \times 10\,m^2 = 210\,m^2$
River Nidelva at weir Kalvehagefossen	Autumn 2002	Atlantic salmon and seatrout	$11 \times 10\,m^2 = 110\,m^2$
River Modalselva at weir Almeli	Autumn 1999	Seatrout	$30 \times 10\,m^2 = 300\,m^2$
River Matreelva at outlet of lake Matrevatn*	Autumn 2001*	Seatrout	$40 \times 6\,m^2 = 240\,m^2$
River Daleelva at weir	Autumn 2002†	Atlantic salmon and seatrout	$10 \times 8\,m^2 = 80\,m^2$
Lake Bjornesfjorden, outlet of lake	Winter 2002	Resident brown trout	$29 \times 17\,m^2 = 493\,m^2$

*Additional supply of gravel added autumn 2002 to maintain original area of added gravel.
†Additional supply of gravel added autumn 2003 to maintain original area of added gravel.

successive pits (Ottaway *et al*., 1981; Crisp and Carling, 1989). Normally the female will spread her offspring in several redds within the river (Webb and Hawkins, 1989; Baglinière *et al*., 1990; Barlaup *et al*., 1994; Garant *et al*., 2001; Taggart *et al*., 2001).

The main purpose of the present study is to discuss criteria for increasing the successful egg deposition and incubation of salmonid fish in regulated rivers. Results from seven different deposits aimed at Atlantic salmon, anadromous brown trout (hereafter called seatrout) or resident brown trout in regulated Norwegian rivers are used as a basis for evaluating this strategy of habitat restoration.

MATERIAL AND METHODS

Data were collected from seven localities within five watersheds where gravel was added to establish new spawning areas. The chosen watersheds are all affected by river regulation and the deposits were part of river-specific habitat restoration programmes. Based on assessment of juvenile densities found by electrofishing, salmonid reproduction occurs from natural spawning grounds in all the studied watersheds. At four localities, gravel was added in association with artificial weirs (Table I).

At all areas spawning success was monitored by sampling nests and egg survival during winter or spring when the embryos had developed to eyed eggs, or in some instances to yolk-sac fry. Individual nests were located by scuba diving or wading. From each nest a sample of eggs was collected by a pointed shovel and a net. Eggs were identified to species by genetic analysis (Mork and Heggberget, 1984; Vuorinen and Piironen, 1984). From each area, the following data were recorded from all or a subsample of the nests: waterdepth (distance from gravel surface to water surface), average water velocity of the water column, egg survival (number of live eggs vs. dead eggs) and burial depth (distance from gravel surface to top of egg pocket). Mean egg survival was calculated for all sampled nests specified for each addition and year. Gravel samples were taken from a subsample of nests by use of a shovel and a net with a 250 μm mesh size. At one area with added gravel in river Nidelva, the locality of individual nests was recorded to study spawning preferences in relation to distance from weir, water velocity and water depth. In this river the water discharge is kept constant at 1 $m^3\,s^{-1}$ throughout the spawning season and during the ensuing winter when sampling was conducted.

RESULTS AND DISCUSSION

At all seven localities, the fish spawned during the first spawning season the added gravel was available (Table II). These results show that the additions met the criteria for successful spawning. A general lack of natural spawning areas most likely contributed to this immediate response. Similar quick responses have also been reported from

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Table II. Number of nests located at the areas with added gravel during the years following the additions

River and locality	Year after addition of gravel				
	1	2	3	4	5
River Nidelva at weir Rygenefossen	13 (9 As)	5 (5 As)	4 (3 As) (1 St)	0*	†
River Nidelva at weir Strubru	11 (9 As)	37 (29 As)	34 (32 As)	32 (31 As)	†
River Nidelva at weir Kalvehagefossen	17 (17 As)	10 (9 As)	23 (22 As) (1 St)	21 (19 As)	†
River Modalselva at weir Almeli	7	†	13	10* (9 St)	15* (11 St)
River Matreelva at outlet of lake Matrevatn	5 (5 St)	26 (26 St)	†	49 (15 St)	48 (St)
River Daleelva at weir	43 (42 St)	30	0*	†	†
Lake Bjornesfjorden, outlet of lake	9 (Rt)	7 (Rt)	31 (Rt)	29 (Rt)	†

The total number of nests is given whereas the numbers of nest identified to species (As = Atlantic salmon, St = Seatrout, Rt = resident brown trout) are shown in brackets.

*Washout of gravel.

†Not sampled.

other studies with addition of spawning gravel for both Atlantic salmon (White, 1942) and brown trout (Rubin *et al.*, 2004).

The results in Table II show that nests were found in all additions and in all years studied after the additions with the exception of two occasions when gravel was lost during floods. Although not all nests have been recorded, the number of nests most likely reflects the between year variation in spawning activity. Some of this variation was most likely caused by physical changes leading to between-year changes in the available gravel area suited for spawning. At the outlet of lake Matrevatn the recorded increase in number of nests can be attributed to modification of the particle size of the added gravel. The first year the added gravel had a composition dominated by 64–124 mm, which during scuba inspection was considered too coarse for spawning. Modification by adding gravel with particle size 16–64 mm the following year was most likely the cause of the substantial increase (from 5 to 26 nests) recorded at this locality. In lake Bjornesfjorden, moving some of the gravel about 5–10 m downstream to an area with faster running water closer to the outlet, most likely contributed to the observed increase in number of nests (from 7 to 31) found at this site.

The successive reduction from 13 to no nests found during the four-year period after the addition at weir Rygenefossen in Nidelva was caused by washout of gravel. The gravel removed by the flood was redistributed to an area with low water velocity where the salmon did not spawn. In river Daleelva, most of the gravel was taken by a flood during the first year after the addition. More gravel was added during the second autumn but this was lost during a major flood occurring two years later. Also, in river Modalen, a substantial part of the added gravel has been lost during floods over the four-year period after the addition. In sum, loss of the whole or a major part of the added gravel has occurred at three of the seven studied sites (i.e. 43%). At two of these localities, nests were probably lost because washout of gravel occurred after the spawning season. Over a longer period of time the additions will be exposed to a higher number of floods. Consequently, washout of additions of gravel material is likely a general problem and can be a major drawback for these types of additions.

To maintain a spawning area over time it is important to record both spawning activity and redistribution of gravel associated with floods. Thereafter, the areas that are both used for spawning and are stable during major floods can be strengthened and expanded. In general, knowledge of topography and the hydrological regime is important to avoid failure caused by washout of gravel during floods.

The egg survival found in nests at the various sites was generally high (i.e. >80%) and suggests normal conditions for survival when the fish spawn in added gravel (Figure 1). However, a reduced egg survival was repeatedly recorded for the additions in river Nidelva. The cause of this is not known, but may be associated with acidification or a relative high sedimentation rate of organic debris observed at the spawning areas.

To succeed with gravel additions it is important to consider gravel size, water depth and water velocity relative to the size of the spawning fish. As seen from Figure 2, Atlantic salmon and seatrout were found to spawn in more

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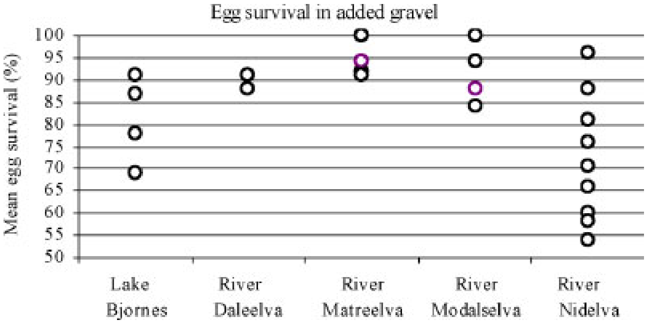

Figure 1. Mean egg survival in nests at the different localities with added gravel. Each point represents mean survival found in nests after one spawning season. Nests of Atlantic salmon are represented with white symbols, seatrout with black, and resident brown trout with grey symbols. The number of nests recorded at each locality and year is given in Table II. One record of low egg survival (18.8%) from river Nidelva is not included in the figure. This figure is available in colour online at www.interscience.wiley.com/journal/rra

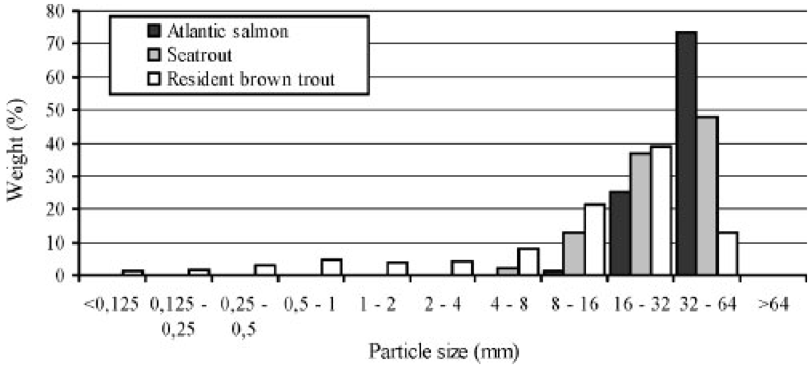

Figure 2. Weight distribution of gravel samples taken from a typical nest spawned in added gravel by Atlantic salmon in river Nidelva, seatrout in river Daleelva and for comparison, a nest spawned by a smaller, resident brown trout

coarse gravel (32–64 mm) compared to smaller resident brown trout (16–32 mm). These results typically reflect the general size-specific spawning preferences of salmonids (Kondolf and Wolman, 1993).

The size of the area with added gravel should be adjusted to fish size and the given topography. A redd containing several nests will normally have a length of about 3.5 times the length of the spawning fish (Crisp and Carling, 1989; Crisp, 1996). A resident brown trout (<30 cm in length) will therefore need about 0.5 m^2 of gravel surface to spawn, whereas a larger seatrout or Atlantic salmon will need about 1–5 m^2, or more to make a redd. The advantage of applying large depositions, for instance covering 100 m^2, is that the water velocity and depth will vary and thereby increase the chances of meeting the spawning criteria set by the fish. Alternatively or in combination with larger additions, small additions can be pinpointed to areas where conditions are considered optimal.

Mean burial depth of eggs found in the present study varied from 7 to 11 cm for trout and was 12 cm for Atlantic salmon (Figure 3). Depths measured were for the distance from the surface of the gravel to the top of the egg pocket, and its centre would be buried deeper. In a review, DeVries (1997) found that Atlantic salmon and seatrout would bury their eggs down to about 15–35 cm depth depending on fish size. Based on these results and the present findings of burial depth, it seems that additions do not need to exceed a depth of about 30–40 cm. If the layer of gravel is deeper, this may result in unstable conditions that either can be actively avoided by the spawning fish or that can lead to reduced egg survival due to movement of gravel.

The mean water velocity found for nests from the various spawning areas ranged from about 12 to 33 $cm\,s^{-1}$ (Figure 3), and the mean water depth ranged from 51 to 100 cm (Figure 3). Atlantic salmon and seatrout will normally spawn at areas having a mean water velocity from 20 to 80 $cm\,s^{-1}$ (Heggberget *et al.*, 1988; Crisp and Carling, 1989), whereas smaller resident brown with <30 cm length typically will spawn at water velocities from

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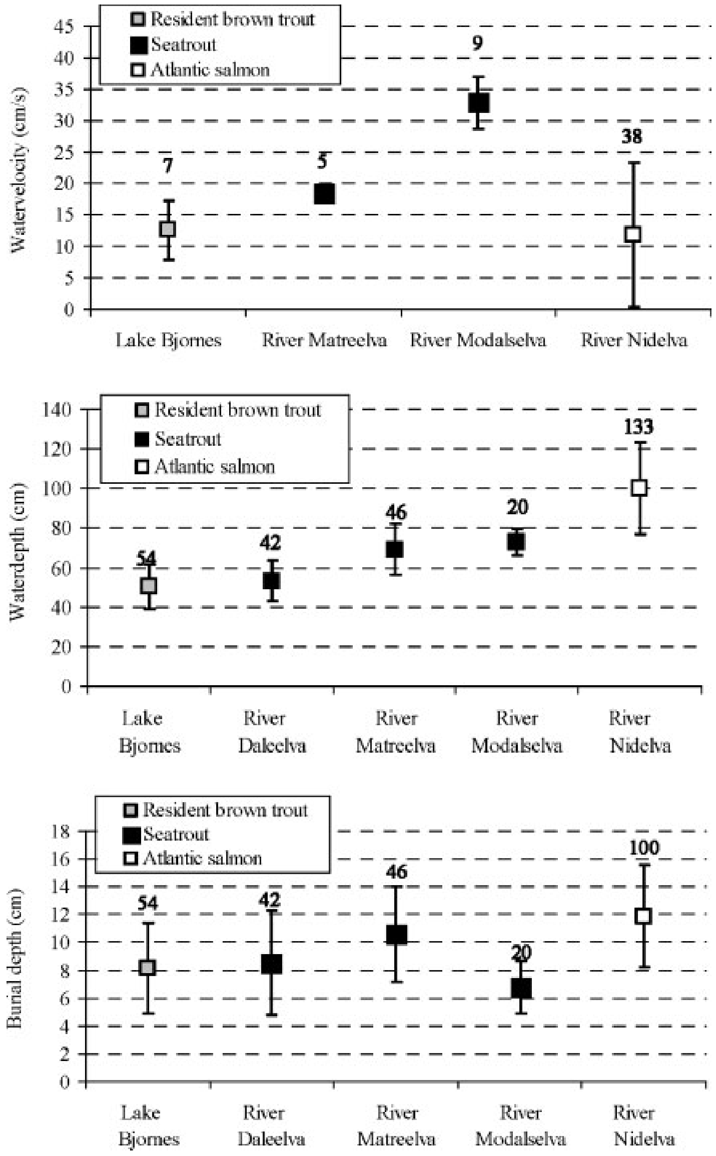

Figure 3. Mean values with standard deviation for burial depth (distance from gravel surface to top of egg pocket), water depth and water velocity recorded from a sample of nests at the studied areas with added gravel. The number of nests examined is given above each point

10 to 40 cm s^{-1} (Smith, 1973; Grost *et al*., 1990). In general, the likelihood of spawning is reduced when conditions deviate from these criteria. A schematic presentation of a typical substrate addition and preferred hydraulic conditions are given in Figure 4.

In the present study, we recorded the position of individual Atlantic salmon nests in the gravel added upstream from the Strubru weir in river Nidelva. The nests were aggregated towards the weir as 27 (73%) of the nests were recorded within the first 6 m upstream of the weir and 10 nests were found from 7 to 19 m further upstream. This distribution of nests most likely reflects preference for the increased water velocity towards the weir (Figures 5 and 6). The nests were found at water depths ranging from 60 to 150 cm. The total area had a low gradient and the nests were in general found at low water velocity (<10 cm/s), not expected to be used by salmon for spawning. This result can most likely be explained by high competition for very limited spawning areas in this river. In general,

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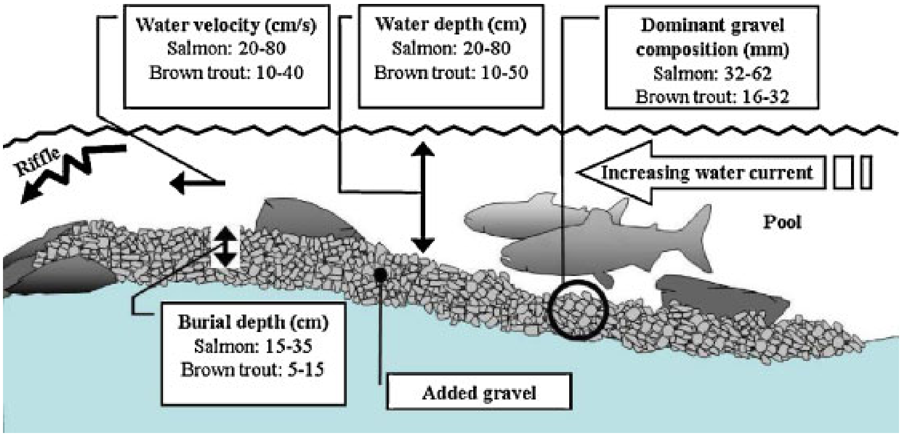

Figure 4. Schematic representation of a gravel addition to establish a new spawning area at an outlet of a pool. Typical characteristics of spawning areas are shown in boxes. These values can be used as guidelines when locating potential areas for addition of spawning gravel. Characteristics for brown trout is given for trout with length <30 cm. This figure is available in colour online at www.interscience.wiley.com/journal/rra

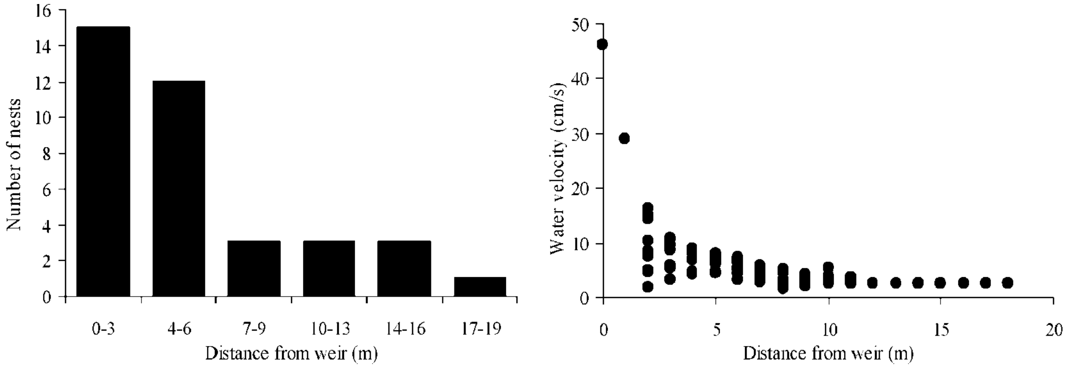

Figure 5. Number of nests (left) and measured water velocity relative to upstream distance from the Strubru weir in river Nidelva

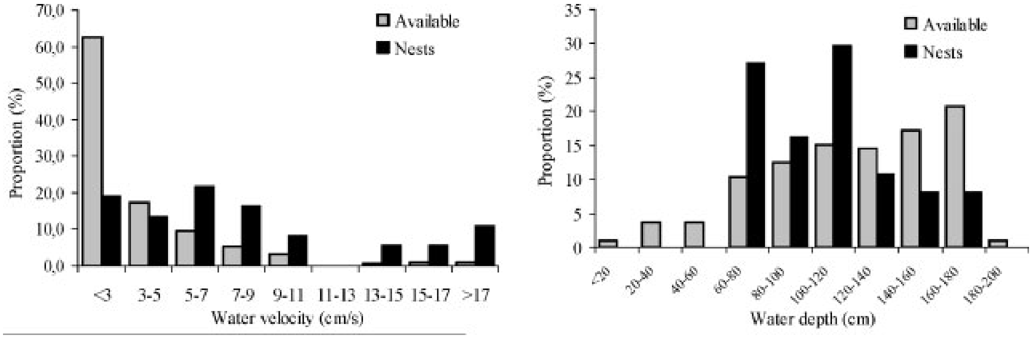

Figure 6. Observed distribution of water velocity and water depth found for nests of Atlantic salmon relative to available water velocity (left) and water depth (right) at the area with added gravel at the Strubru weir in river Nidelva

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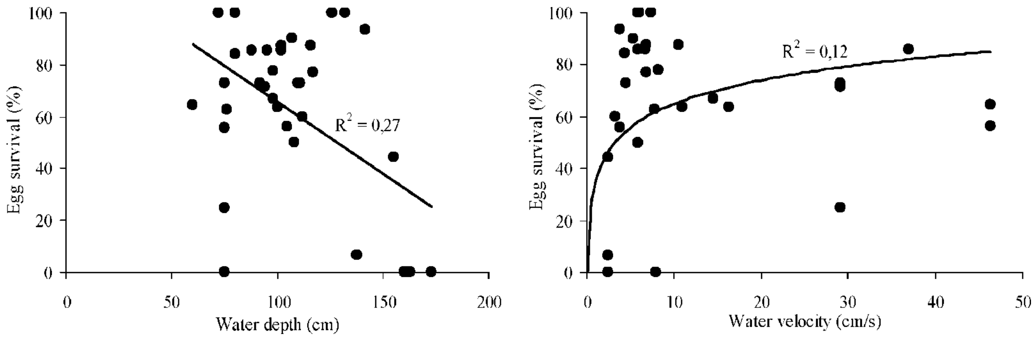

Figure 7. Egg survival found in nests of Atlantic salmon relative to water depth and water velocity at the area with added gravel at the Strubru weir in river Nidelva

selection for water velocity and water depth is likely to allow a higher degree of variation than selection for substrate composition as spawning in substrate with too much fines is detrimental to egg survival (Witzel and MacCrimmon, 1983; Chapman, 1988).

In the added gravel in river Nidelva, low egg survival were found in several of the nests spawned in areas with low water velocity ($<4\,\mathrm{cm\,s^{-1}}$) and at deep water ($>150\,\mathrm{cm}$), but no significant relationships were found (Figure 7). Normal survival found in a number of nests at this locality suggests that gravel additions can be successful even if the only available areas are suboptimal with respect to water flow and water depth. However, negative effects of suboptimal conditions may first be expressed after the egg stage currently studied. Studies which include survival to the fry stage are therefore needed to fully evaluate spawning success in added gravel where conditions are considered suboptimal.

In conclusion, the extensive spawning recorded at all seven localities shows that addition of gravel can be an important tool for habitat restoration leading to an increase in available spawning locations for salmonids in regulated rivers. Downstream displacement of gravel during floods and sedimentation which may lead to harmful conditions for egg survival are major drawbacks. Monitoring of spawning success relative to displacement of gravel or sedimentation is therefore essential to evaluate the method. Based on this information, favoured areas with high spawning success can be expanded by supplementary addition of gravel. The results also suggest that the Atlantic salmon will use suboptimal areas for spawning when more optimal areas are very restricted or lacking. The findings of relative high egg survival at such areas suggest that gravel additions can be successful even if the only available areas are suboptimal with respect to water flow and water depth.

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