Test for evaluating the injuries suffered by downstream-migrating eels in their transiting through the new spherical discharge ring VLH turbogenerator unit installed on the Moselle River in Frouard (54).

-

Tests of October 2010 on yellow and silver eels.

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Synthesis

Eels are an amphihaline migrating species classified as vulnerable and inscribed on the Red List at a national level. Considering the alarming decline in their population at the three continental phases of their biological cycle, the European Community has set a framework for the protection and the sustainable exploitation of the European eel stock through its September 2007 regulation (EC) n°1100/2007. This regulation especially provides for each member state to implement, as fast as possible, adapted measures to decrease the eel mortality resulting from factors unrelated to fishery, such as hydroelectric turbines. The installation of so-called "fish-friendly" turbines, to replace existing turbines or on new developments, is one possible solutions.
MJ2 Technologies has embarked on this path, and has been developing and marketing the very low head turbine, VLH, designed to comply with the main "fish-friendliness" criteria relative to the passing of fish through turbines. To evaluate the actual efficiency of the compliance with these theoretical criteria, the VLH has been submitted to 2 series of in-situ tests. The first tests have been carried out on the first VLH commissioned at the Troussy site, on the Tarn river closely upstream of Millau (ECOGEA, 2007, 2008a, and 2008b). For an operation at full opening and full power, general mortality rates of 7.7% for adult silver eels (from 356 to 1045 mm; average size 846 mm) and 3.1% for Atlantic salmon smolts have thus been observed. These results already ranked the VLH as less penalizing than conventional Kaplan turbines. However, significant prospects of improvement of the "fish-friendliness" of the VLH had been brought to light during these first tests (mortalities mainly located at the level of an area where the fish were "pinched" between the blade ends and the discharge ring). Following these conclusions, MJ2 Technologies has decided to modify the hydraulic contour of its new VLHs (spherical contour at the discharge ring level) to attempt further decreasing the mortality caused to downstream-migrating fish. This new VLH has been installed in Frouard and submitted to this second series of tests, the main results of which are discussed in the present report.

The "lock" plant (centrale "de l'écluse") is implanted on the Moselle river, in Frouard, close to Nancy, and comprises the new VLH 4500 turbine provided with a spherical discharge ring. This turbine has 8 blades and develops a 400-kW maximum electric power, limited by the energy sales agreement. It discharges 22 m^3/s, with a 2.4-m net head.

The preferential downstream migration period of eels in France generally lasts from October to January, the migration essentially occurring by night, during environmental windows most often corresponding to flow increases ("water rushes"), along with a temperature drop and a turbidity increase. We have thus chosen to carry out the tests with a turbine operation very close to that occurring in high discharge conditions, that is, almost at full opening (95% of the nominal opening) and at full power (limited to 400 kW by the energy sales agreement), with a 38-cpm rotation speed.

The 244 eels used for this test originate from a professional fishery on the German side of the Rhine. Their size ranges between 610 and 1002 mm (average: 761 mm) and their weight varies from 557 to 1963 g (average: 843 g). They have been divided into 2 size groups ("Large individuals" of total length > 775 mm and "Small individuals" of total length ≤ 775 mm), to form 8 test batches of 25 individuals each (4 injection points x 2 size groups). They have been housed for the entire test period in large circular tanks permanently supplied with water from the Moselle by submersible pumps.

The system used for the test has enabled to inject eels at 4 points of the machine, as close as possible to the guide blades, and then to recover them in the tail race by filtering of the entire turbine discharge, by means of a net (6 m x 3.5 m opening; 14 m long; 3 degressive 27-mm, 15-mm, and 10-mm meshes) emerging into a semi-submerged fish box supported by a floating pontoon.

During the tests, the recapture rates have varied from 88% to 100% (93% average), for the "large individual" group and from 72% to 100% (84% average), for the "small individual" group. For this last size group, in 3 out of the 4 injected batches, 2 live eels have been seen escaping from the net, at the level of a pocket formed by the largest mesh, as the net was being lifted by the crane. Thus, given that the recapture rates had not been total for all batches, a batch of 25 dead eels has been injected next to the hub. All the dead eels having been recaptured, we have been able to make the assumption that the individuals that have not been recaptured are live individuals, capable of actively searching for a hole in the net to escape from it.

No direct mortality has been observed on the total 200 injected eels (8 batches of 25 individuals each). Among the 177 eels recaptured in the net after their passing through the VLH, a close examination of their external aspect (no autopsy) has revealed, in 4 individuals, the presence of external injuries, which were not lethal in the short term (no mortality after from 24 to 48 hours of observation in the storage tanks).

The tests show that the rate of immediately lethal injuries is extremely low, and even zero, and that the rate of injuries not lethal in the short term (from 24h to 48h) is close to 2%. Conversely to the tests carried out in Troussy, no effect of the injection point on the injury rates can be observed. Similarly, conversely to what can be observed on other types of turbines, no effect of the size of individuals on the injury rate can be observed.

During the different tests carried out in Frouard, individuals of other species than the injected eels have been captured in the net: 195 European perches (size from 66 to 185 mm), 8 ruffes (size from 112 mm to 120 mm), 1 roach (76 mm), 1 common bream (70 mm), and 3 non-indigenous crayfish (*Orconectes limosus*). No direct mortality by severing has been observed in these other species (however, the ratio of individuals having really crossed the VLH in operation to those having crossed the VLH while stopped or having been trapped in the tail race by the installation of the recovery device is not known).

As a conclusion, the rate of immediately lethal injuries of adult eels (from 60 cm to 1 m) transiting through the new spherical discharge ring VLH installed in Frouard, running at full opening and full power, is extremely low, and even zero, and the rate of injuries not lethal in the short term (from 24 to 48 h) is low, since it approaches 2%.

Regarding the short-term mortality, these results rank the new-generation VLH with a spherical discharge ring, running at full power and full opening, as a turbine with a very light impact on the downstream migration of silver eels (from 60 cm to 1 m).

However, the tests carried out in Frouard do not enable to assess the deferred mortaliy, which is always possible for eels transiting through a turbine, or the possible mortality generated by a VLH running at reduced opening and power.

It would eventually be useful to complete these trials with tests on other smaller fish species, in particular on Atlantic salmon smolts, which are also particularly affected by the injuries caused by hydroelectric turbines during their downstream migration.

1. Introduction

The European Water Framework Directive (directive 2000/60/CE), operative on December 22, 2000, sets a framework for Community action in the field of water policy. Among the defined priority objectives, the restoring of the ecological continuity, which can be defined as the free circulation of biological species and the proper conduct of the natural transportation of sediments, especially requires limiting as much as possible damages linked to the downstream migration of fish at the level of hydroelectric power plants.

The issue of downstream migration essentially concerns so-called “highly migratory” fish species for which part of the biological cycle necessarily implies a long upstream migration where they are likely to cumulate the impacts encountered all along their migration path (crossing of many developments). Some of the most especially vulnerable among said species are juvenile Atlantic salmons (*Salmo Salar* L.) and sea trouts (*Salmo Trutta* L.) which perform a downstream migration from the upstream parts of rivers, as well as adult seaward-migrating European eels (*Anguilla anguilla* L.) (called “silver eels”), which are likely to suffer significant injuries due to their size as they pass through turbines.

Eels are an amphihaline migrating species classified as vulnerable and inscribed on the Red List at a national level (KEITH *et al*., 1992). The state of European populations is considered as alarming by the specialist of the “Working Group on Eels”[1] (WGE, 2007) since the species is beyond biological security limits. Considering the alarming decline of its abundance at the three continental phases of its biological cycle, the I.C.E.S. (Internal Council for the Exploration of the Sea) advocates an emergency recovery plan especially decreasing anthropogenic mortalities of downstream-migrating silver eels down to the lowest possible level. Regulation (EC) n°1100/2007 of the European Community Council of September 18, 2007 sets a framework for the protection and the sustainable exploitation of the European eel stock: it provides the development by the Member States of an eel management plan with the long-term objective of decreasing the anthropogenic mortality to permit the escapement to the sea of at least 40% of the silver eel biomass, corresponding to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock. To achieve this objective, each Member State must especially implement appropriate measures for decreasing the mortality of eels caused by factors outside the fishery such as hydroelectric turbines, as quickly as possible.

Currently, the research and development efforts to solve the problems posed by the downstream migration at the level of hydroelectric developments bear on 3 main types of solutions (COURRET and LARINIER, 2007):

- Constructions of so-called "fish-friendly" water intakes with an associated downstream migration device letting the individuals transit downstream of the development without injuries,
- Partial or full stopping of the turbine operation during the preferential downstream migration period of the targeted species,
- Installation of specific so-called "fish-friendly" turbines, to replace the existing turbines or on new developments (generally still unharnessed low-head sills).

MJ2 Technologies has embarked on this path and, for a few years now, has been developing and marketing the VLH (very low head turbine). From the origin, the main “fish-friendly”

[1] Working group gathering members of the EIFAC (European Inland Fisheries Advisory Commission) and of the ICES (International Council for the Exploration of the Sea)

criteria relative to the passing of fish through turbines have been taken into account among the basic data used to design the VLH. Such criteria comprise:

- A large runner diameter (4.5 m) creating large spaces between guide blades and between blades, easing the passing of fish,
- A small runner rotation speed (on the order of 40 cpm),
- Water velocity inside the runner < 2 m/s,
- Very small pressure variations.

To assess the real efficiency of the compliance with these theoretical criteria, the VLH has been submitted to in situ tests on smolts and silver eels on the Troussy site, located on the Tarn river closely upstream of Millau (ECOGEA, 2007, 2008a, and 2008b). For an operation at full opening and full power, general mortality rates of 7.7% for large adult silver eels (from 356 to 1045 mm; average size 846 mm) and 3.1% for Atlantic salmon smolts have thus been observed. With such results, the VLH already appears as less penalizing than conventional Kaplan turbines towards the downstream migration of silver eels and salmonid smolts.

However, significant prospects of improvement of the “fish-friendliness” of the VLH had been brought to light, since the origin of the observed mortalities had been pinpointed (fish “pinching” areas between the blade ends and the discharge ring). Following these conclusions, MJ2 Technologies has decided to modify the hydraulic contour of its new VLHs (spherical contour at the discharge ring level) to attempt further decreasing the mortality generated by the crossing of a VLH by downstream-migrating fish.

2. Objectives of the study

Such a new "spherical dischage ring" VLH has been installed on the Frouard site (54) on the Moselle river, in February 2010. It must undergo tests with downstream-migrating fish (salmonids and eels, to begin with) to verify whether the structure modifications performed on the machine enable to substantially improve the mortality rate of downstream-migrating fish crossing the VLH.

The present report details the results of the tests carried out in October 2010 on yellow and silver eels transiting through the VLH in their downstream migration.

3. Partners of the study

3.1. Financial partners

The tests carried out in Frouard have been financially supported by:

- MJ2 Technologies,
- The ADEME, Department of Renewable Energies,
- France Hydro Electricité,
- The Société Hydro Electrique de Frouard.

3.2. Scientific and technical partners

The organization chart for the protocol design and the conduct of the tests is shown in Table 1 hereinafter.

		Organization	Nationality
Project design	J. Fonkenell	MJ2 Technologies	France
Project management	T. Lagarrigue	E.CO.G.E.A. research office	France
Scientific Committee Director	M. Larinier	Pôle Ecohydraulique ONEMA / CEMAGREF / IMFT	France
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Scientific Committee	S. Mougenez	ONEMA - DIR Nord-Est	France
Scientific Committee	D. Monnier	ONEMA - DIR Nord-Est	France
Scientific Committee	A. Gillet	Direction des Aménagements Paysagers	Belgium
Scientific Committee	P. Orban	Direction des Cours d'eau non navigables	Belgium
Scientific Committee	D. Sonny	Profish	Belgium
Scientific Committee	D. Ingendahl	Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur - und Verbraucherschutz des Landes Nordrhein-Westfalen	Germany

Table 1. Organization chart for the "eel tests" carried out on the Frouard VLH

4. Site of the study

4.1. The Frouard development on the Moselle River

The Frouard power plant, implanted on the Moselle River close to Nancy, is surrounded, upstream, by the Aingerey power plant and, downstream, by the Pompey power plant. The Moselle Module in Frouard is approximately 65 m^3/s (63.2 m^3/s at the Hydro data bank station in Toul, that is, approximately 10 km upstream of the Frouard power plant, over the 1960 – 2010 period).

The total power plant turbine discharge is approximately 72 m^3/s, under a 2.6-m gross head. The total electric power is 1500 kW. It has a run-of-the-river operation. During the tests, the inflows have been influenced by flow rate irregularities essentially due to the operation of upstream locks.

The Frouard power plant is actually formed of 3 small independent power plants. The "mill" power plant ("centrale du moulin") comprises 2 propeller turbines of 10 m^3/s each, with a 200-kW unit power. The "Island" power plant ("centrale de l'Ile") comprises a 30-m^3/s single regulation Kaplan turbine, for a 700-kW power. Finally, the "lock" power plant ("centrale de l'écluse") comprises the new VLH 4500 used for the tests.

This machine with a spherical discharge ring has been running since February 2010. It comprises 8 blades and develops a 400-kW maximum electric power, limited by the energy sales agreement. It discharges 22 m^3/s, with a net head of 2.4 m.

Image 1. The lock power plant VLH in Frouard as the turbine chamber is being emptied

Image 2. Outlet of the Frouard VLH in operation

5. Description of the employed system

The system used for this study is very similar to that used for the Troussy tests (ECOGEA, 2007, 2008a, 2008b). It is formed of two main parts: a device for “injecting” the eels into the turbine and a device for recovering the individuals at the turbine outlet.

5.1. Eel injection device

An injection device has been designed to force the eels to transit through the turbine. Indeed, it would have been hardly conceivable to release the eels upstream of the turbine and wait for them to swim down the machine by themselves since the risk was then taken i) to lose part of the individuals which could have swam up the headrace channel to join the Moselle (no upstream thin grids and relatively low flow velocities in the headrace channel) and ii) to damage the eel recovery device (fast clogging of the net and of the fish box in this season).

Even though it is of smaller size, the principle of the eel injection device used in Frouard takes its inspiration from different tests, and especially those performed in Quebec on the Saint-Laurent River (DESROCHERS, 1995; THERRIEN, 1999). It is formed of a water tank containing from 5 to 10 eels, connected to a PVC tube (∅ 200 mm) enabling injection of the eels directly at the level of the turbine guide blades. For an injection at a specific point of the turbine, a specific metal part has been designed to stabilize the injection tube at the point where the injection is to be performed. This metal part has been installed by two divers swimming in the turbine chamber, with the turbine stopped.

Image 3. Water tank connected to the PVC tube enabling to inject eels directly at the turbine guide vane level

Image 4. View of the injection tube connected to the metal part installed on the VLH distributor , the turbine chamber being empty

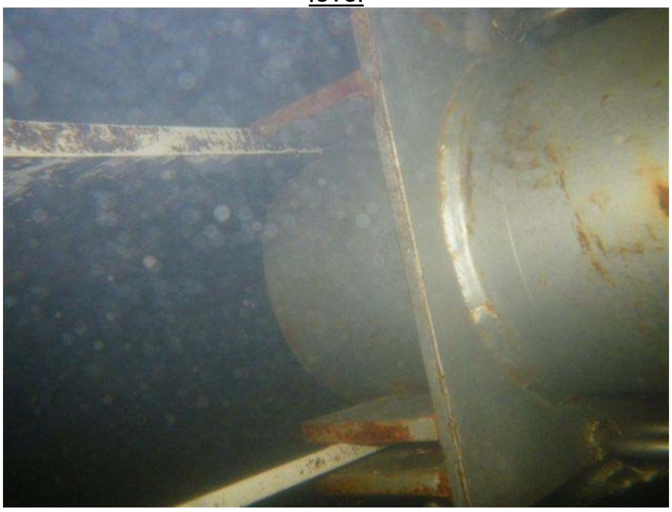


Image 5. Underwater view of the installed metal part, astride the metal spokes of the distributor

Image 6. Water tank containing the eels about to be injected

For the injection, the tank plug is removed, thus enabling to discharge the water and part of the eels, the remaining eels being manually forced to enter “head first” into the PVC tube.

5.2. Eel recovery installation

The eel recovery installation is formed of a 6 x 3.5-meter metal frame, placed at the turbine outlet, set in reserved grooves on the side walls and supported by a concrete floor. To limit as much as possible the risk of individuals escaping at the turbine outlet, the divers have verified that there remained no space between the frame and the concrete parts (floor and grooves in the side walls) once the frame had been installed.

Images 7 and 8. Frame supporting the net installed with the crane

Image 9. Divers inspecting the junctions between the concrete parts and the frame

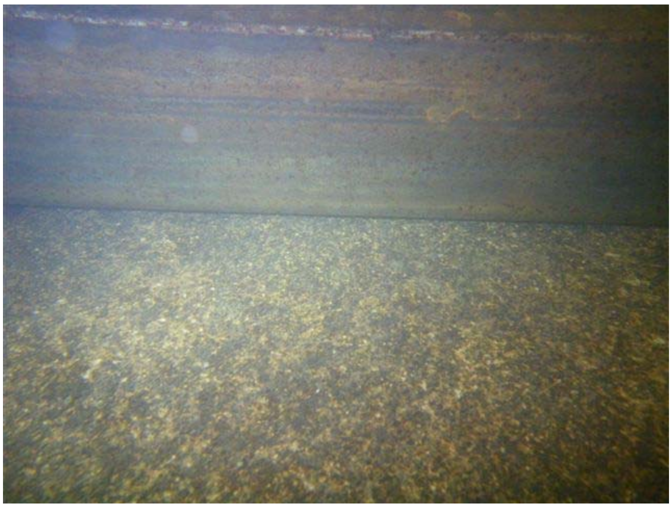


Image 10. Underwater view of the fine junction between the frame and the concrete floor

This frame supports a knotless polyamide net which is very flexible and non-abrasive for the fish (see appended plans). It is formed of 3 decreasing meshes (27, 15, and 10 mm) and is approximately 14 meters long.

Image 11. View of the pocket formed where the mesh is the largest before entering the "sock" formed by the 2 finer meshes

Image 12. Detail of the 2 stiffeners in the final portion of the net held by the crane

The net is provided with stiffeners to maintain the pocket open until it emerges into a fish box (dimensions 1.5 x 1 x 1 meter – see appended plans) enabling to house and recover the fish. The fish box is attached to a floating pontoon and is maintained immersed by 2/3. The entrance is provided with a non-return system to avoid for the fish to leave the fish box once they are inside. It is dressed with a 10-mm mesh knotless polyamide net. The travels between the bank and the pontoon are performed by means of a rigid boat.

Image 13. Complete recovery installation in place, VLH running

Image 14. Recovery with a landing net of the eels present in the fish box supported by the floating pontoon

Once they have been recovered with a landing net from the fish box, the fish are conveyed to the housing premises in plastic bins (distance of approximately 80 m to be traveled).

The recovery installation is installed by means of a crane (40-ton lifting capacity). The pontoon supporting the fish box is put into the water first. Then comes the frame, after which the net is connected to the fish box.

Image 15. Crane installed at the weir level

Image 16. Installation of the frame by means of the crane

6. Biological material

6.1. Origin of the eels

The 244 eels used for the tests have been captured by electric fishing (which is why both yellow and silver eels are present). They have been bought to a professional German fisherman (Götz Kuhn) from Karlsruhe, who works on the German side of the Rhine. The transportation to Frouard has been taken care of by the Association Saumon Rhin, which owns a trailer with a tank and its oxygenation system adapted to this type of transportation. To avoid overloading the tank during the transportation, 2 travels have been performed, on September 29 and October 10, 2010.

6.2. Eel storage

The eels have been stored in 6 circular tanks (600-liter capacity), continuously supplied with Moselle water by 2 submerged circulation pumps. The tanks have been installed in the Frouard power plant, close to the VLH.

Image 17. View of 5 of the 6 circular eel storage tanks and of their water supply

Image 18. View of the 6 covered storage tanks and of the weir discharges (2 per tank)

	Moselle water – In-tank measurements
O_2	9.90 mg/l
	98% sat.
Temperature at 10:00 am	13.9°C (57.02°F)

Table 2. Main physico-chemical characteristics of the Moselle water.

The physico-chemical characteristics of the Moselle water measured in the tanks on the 2010/10/07 at 10:00 am show that the water is well oxygenated but still relatively “warm” for the season.

6.3. Morphometric measurements carried out on the eels

After all individuals have been anaesthetized with cloves, their health condition has been visually assessed and noted for each individual, with a schematic representation of the location of possible malformations or wounds (necrosis, abscess…). Then, they were all measured (to within one mm) and an individual weighting has been performed for a single sample of 55 individuals (to within 1 g).

The silvering level of the individuals has not been accurately assessed (no ocular index or pectoral fin length measurement, for example) but a mere qualitative observation of the eye size and of the general livery have enabled to roughly estimate that from 20 to 25% of the eels used for the tests had reached the silver stage.

6.3.1. Size and weight structure

	Size (mm)	Weight (g)
median	761	843
average	760.5	886
min	610	557
max	1002	1963
nbr. of individuals	244	55

Table 3. Characteristic sizes and weights of the eels used for the tests.

The 244 eels used for the Frouard tests have a size ranging between 610 mm and 1002 mm (median: 761 mm (29.96 in)). Their minimum 610-mm size indicates that they probably all are females (on the Loire, silver males have a size below 47 cm).

The weight of the 55 weighted eels ranges between 557 g and 1963 g (median: 843 g (29.74 oz)).

7. Implemented experimental protocol

The tests were performed from October 4 to October 8, 2010, after preliminary trials on farmed rainbow trouts to test the equipment in June 2010.

7.1. Origin of the implemented protocol

The protocol developed for this study, very similar to that used for the Troussy tests, is widely inspired from the experimental protocol developed in the late 80's based on the return on experiences carried out on a few rivers in France (DARTIGUELONGUE and LARINIER, 1987; LARINIER and DARTIGUELONGUE, 1989) and abroad (MONTREAL ENGINEERING COMPANY, 1981 and 1982; KYNARD *et al.*, 1982; GLOSS and WALH, 1983; BELL and KYNARD, 1985; MONTEN, 1985). It comprises introducing the fish close to the end of the runner and recovering them immediately by filtering all the turbine output flow with a net.

7.2. Tested injection points

Since the level of the runner at which eels in "natural" seaward migration are likely to engage was not known beforehand, we have attempted to be as accurate as possible by performing injections at 4 points (3 points had been tested in Troussy: close to the hub, at mid-blade and at the runner periphery).

After division into 4 equal ring-shaped surfaces, the 4 injection points are located at the barycenter of these 4 ring-shaped surfaces (*see appended plans*).

7.3. Composition of the different batches used for the tests

To appraise a possible "size effect" on the mortality rates generated by the VLH, we have separated the eels in 2 size groups. To avoid having to anaesthetize each eel twice (a first time to obtain the median size of the 244 individuals and a second time to separate them in 2 groups), the size group limit has been determined on measurement of a sample of 40 individuals and applied to the remaining individuals, that is:

- "Large individuals": eels of total length > 775 mm (108 individuals),
- "Small individuals": eels of total length ≤ 775 mm (136 individuals),

	Size (mm)		Weight (g)	
Size group	"Small"	"Large"	"Small"	"Large"
median	726	800	687	959
average	719	812	726	1065
min	610	778	557	785
max	775	1002	1090	1963
nbr. of individuals	136	108	29	26

Table 4. Characteristic sizes and weights of the 2 eel size groups used

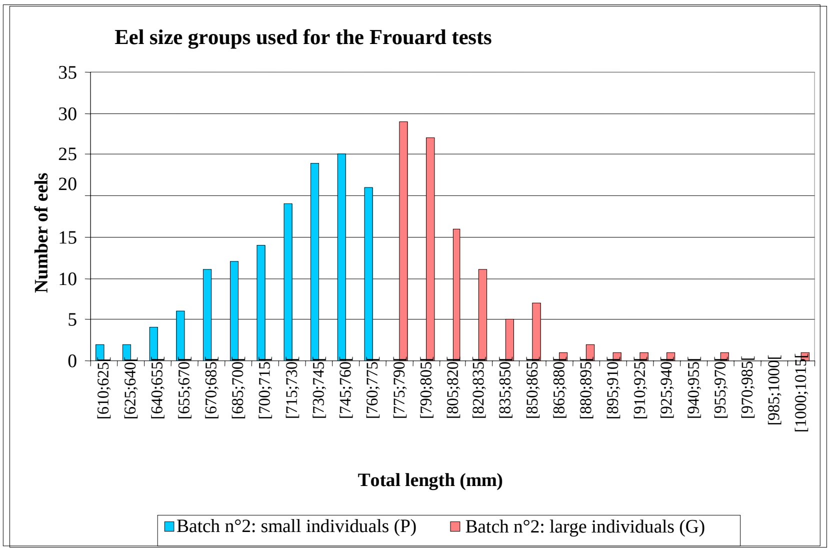


Fig. 1. Distribution in size groups of the eels used for the Frouard tests

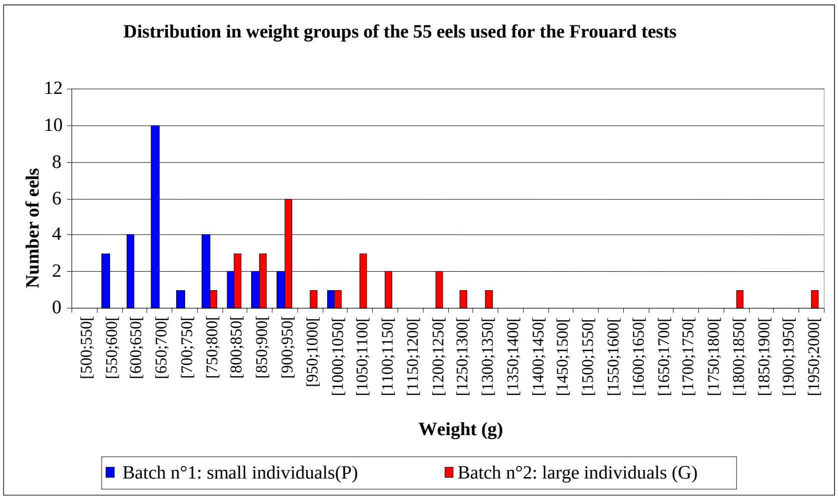


Fig. 2. Distribution in weight groups of the eels used for the Frouard tests

Thus, 9 batches have been formed:

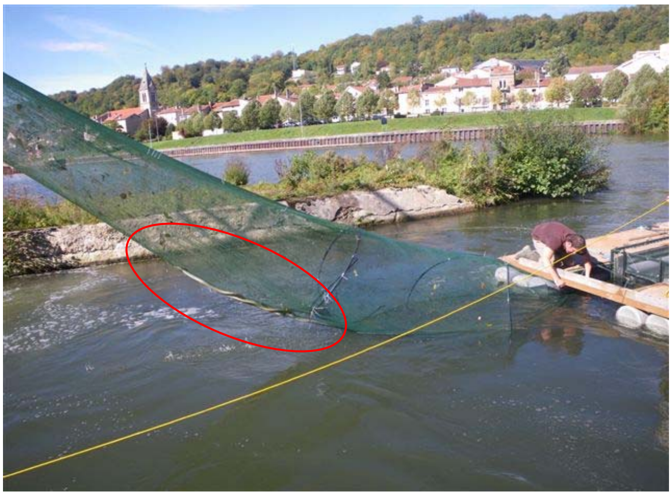
- "Large individuals" (Lt > 775 mm): 4 batches of 25 individuals for injections at 4 points of the machine,
- "Small individuals" (Lt ≤ 775 mm): 4 batches of 25 individuals for injections at 4 points of the machine,
- Dead eels (mixture of the two size groups): 1 batch of 25 dead eels to assess the recapture rate for dead individuals.

7.4. Typical eel release process

The recapture system (frame with net connected to the fish box on the floating pontoon) is installed, after having started the VLH at low power (from 100 kW to 150 kW) to create a current avoiding for the net to catch at the bottom of the tail race. When the recapture system is installed, the batch of eels to be released is carefully recovered from one of the storage tanks. The eels are brought to a container filled with water on the right-bank side wall and poured into the container connected to the injection tube. Once the turbine speed is steady (full opening and full power), the tank plug is removed and the eels are "injected" via the PVC tube directly at the level of the turbine guide blades.

Image 19. "Hand" injection of the last eels in the tank

Within half an hour after the injection, most eels end up in the recovery net and/or in the fish box after having transited through the turbine. While maintaining the turbine at full power to avoid for individuals to escape by swimming up the net, the frame is lifted by the crane, which enables to concentrate the individuals in the low portion of the net. After closing of the fish box, the net is separated to be emptied into the floating fish box where the eels are fished by means of a landing net.



Images 20 and 21. Lifting the net with the crane enables to concentrate the eels in the low portion of the net

Image 22. The eels gathered in the low portion of the net are emptied into the fish box

Image 23. Recovery with a landing net of the eels present in the fish box supported by the floating pontoon

All the captured species (eels and others) are taken back to the storage tanks. The species other than eels are only identified, counted, and measured for the most part. The eels are counted, and then attentively observed one by one to spot possible injuries (bruises, scratches, severing, injured vertebral column…) before returning to their storage tank to have their behaviour observed for a period ranging from 24 to 48 hours (assessment of a possible short-term deferred mortality).

7.5. Adjustments performed to improve recapture rates

The recapture rates for the first two tested batches were poor, since they were 32% only (8/25) for the “small” eel size group and 68% (17/25) only for the “large” eel size group. Thus, although no mortality had been observed on the recaptured individuals of the two batches, we have decided to start again after adjusting the protocol by:

- Dedicating a long time to thoroughly inspecting the net to mend as many remaining holes as possible along its entire length before resuming the tests,
- Letting the VLH run at full power for at least 25 minutes after the injection (this time being much shorter for the first 2 batches).

These two adjustments have enabled to significantly improve the recapture rates for the 2 eel size groups.

8. Testing conditions

As seen, the Moselle water temperature during the tests, ranging between 12.5°C and 14.2°C according to the day and the time of the measurement, was relatively warm for the season. This is partly due to the low hydrology during the test period.

8.1. Turbine operating rate during the tests

Although it can be observed from July to spring, and even sometimes all year round in case of adverse hydroclimatic conditions, the preferential downstream migration period of eels in France generally lasts from October to January (GOSSET *et al.,* 2002; DURIF, 2003). It occurs in essentially nocturnal stages, during environmental windows most often corresponding to flow increases ("water rushes"), along with a temperature drop and an increase in the turbidity (GOSSET *et al.*, 2002; SUBRA *et al.*, 2003; TRAVADE *et al*., 2010).

During this high-flow period of the year, river flow rates are generally greater than the maximum discharge of low-head power plants equipped with VLHs. We have thus chosen to carry out the tests **with a turbine operation very close to that occurring in high flow rate conditions, that is, almost at full opening (95% of the nominal opening) and at full power (limited to 400 kW by the energy sales agreement), with a 38-rpm rotation speed.**

9. Results

9.1. Recapture rate

Recapture rates have varied between 88% and 100% (average 93%) for the "large individual" size group. None of these large individuals has been observed trying to escape from the net.

However, for the "small individual" size group, recapture rates have varied between 72% and 100% (average 84%). In 3 out of the 4 batches injected for this size group, 2 live eels per batch have been observed escaping from the net as it was lifted by the crane. They would each time escape from the same area, that is, a pocket formed by the largest mesh, just before entering the "sock" formed by the 2 finer meshes.

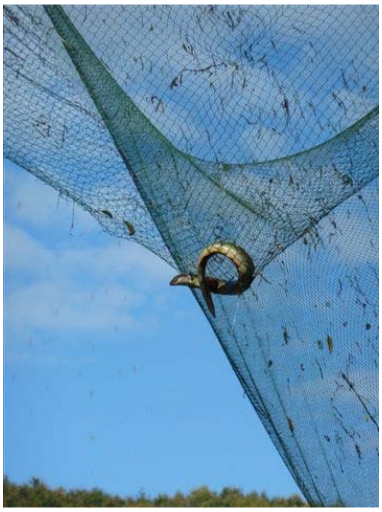


Image 24. Eel from the "small individual" size group escaping from the pocket formed in the upstream portion of the net

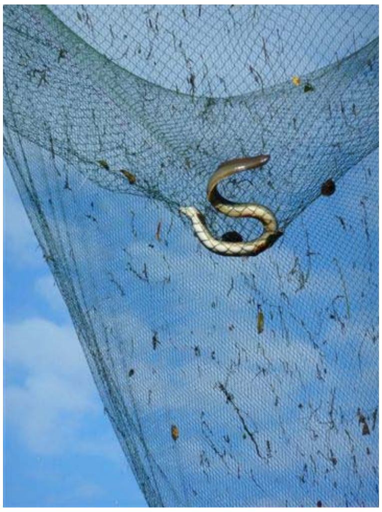


Image 25. Eel from the "small individual" size group blocked in the pocket formed in the upstream portion of the net before escaping from it

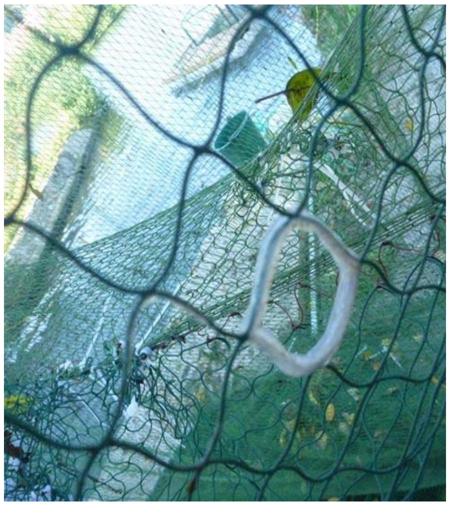


Photo 26. Mucus left by an eel from the "small individual" size group while crossing a large mesh in the pocket formed in the upstream portion of the net

Batch n°9 – Dead eels:

Given that the recapture rates have not been 100% for all batches, we have created a batch with 25 dead eels (mixture of the two size groups) and injected them at point P1 (close to the hub).

All dead eels have been recaptured (100% recapture rate), which enables us to assume that **the individuals from the test batches which have not been recaptured are live individuals**, capable of actively searching a hole in the net to escape from it, as observed on 3 out of the 4 injected batches of eels from the "small individual" size group during the lifting of the net.

Test n°	Injection point (distance between the hub and the injection point)	Size group	Nbr. of eels			Recapture rate
			injected	recaptured	not recaptured but seen escaping live from the net	
1	P1 – Inside (30 cm (11.81 in)).	"Large individuals" (Lt > 775 mm)	25	23	-	92%
2		"Small individuals" (Lt ≤ 775 mm)	25	18	2	72%
3	P2 (76 cm (29.92 in))	"Large individuals" (Lt > 775 mm)	25	22	-	88%
4		"Small individuals" (Lt ≤ 775 mm)	25	23	2	92%
5	P3 (113 cm (44.49 in))	"Large individuals" (Lt > 775 mm)	25	23	-	92%
6		"Small individuals" (Lt ≤ 775 mm)	25	25	-	100%
7	P4 – Outside (146 cm (57.48 in))	"Large individuals" (Lt > 775 mm)	25	25	-	100%
8		"Small individuals" (Lt ≤ 775 mm)	25	18	2	72%
9	P1 – Inside (30 cm (11.81 in))	Mixture of "large" and "small" dead individuals	25 dead	25 dead	-	100%

Table 5. Recapture rate per eel size group and per injection point

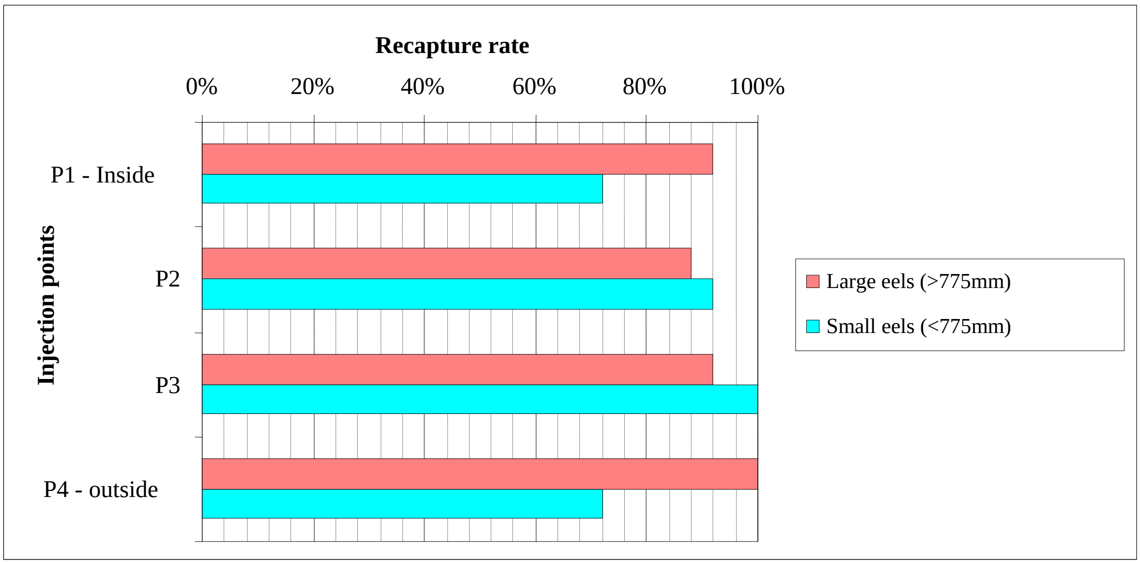


Figure 3. Recapture rate of the different injected eel batches

9.2. Evaluation of the damage to the eels

Test n°	Injection point (distance between the hub and the injection point)	Size group	Nbr. of eels				Images of the superficial injuries
			recaptured	intact	severed	live, with bruises	
1	P1 – Inside (30 cm (11.81 in))	"Large individuals" (Lt > 775 mm)	23	23	0	0	
2		"Small individuals" (Lt ≤ 775 mm)	18	18	0	0	
3	P2 (76 cm (29.92 in))	"Large individuals" (Lt > 775 mm)	22	21	0	1 (scratch with bleeding under the head)	
4		"Small individuals" (Lt ≤ 775 mm)	23	21	0	2 (1 scratch with bleeding and 1 gill cover bleeding)	
5	P3 (113 cm (44.49 in))	"Large individuals" (Lt > 775 mm)	23	23	0	0	
6		"Small individuals" (Lt ≤ 775 mm)	25	25	0	0	
7	P4 – Outside (146 cm (57.48 in))	"Large individuals" (Lt > 775 mm)	25	24	0	1 (one slight bruise on the body)	No image
8		"Small individuals" (Lt ≤ 775 mm)	18	18	0	0	

Table 6. Main test results.

No direct mortality has been observed (by severing of the individuals, like in Troussy, for example) on the total 200 injected eels (8 batches of 25 individuals each).

A close examination of their external aspect of the 177 eels recaptured in the net after their passing through the VLH (no autopsy), has revealed, in 4 individuals (2 for each size group), the presence of external injuries, which were not lethal in the short term (no mortality after from 24 to 48 hours of observation in the storage tanks). Further, it cannot be asserted that these injuries are only due to the transiting through the VLH, since the recovery conditions may also have caused them, especially as the eels have attempted to escape through the net meshes.

Thus, the performed tests show that **the rate of immediately lethal injuries is extremely low, and even zero**, and that **the rate of injuries not lethal in the short term (from 24h to 48h) is close to 2%.**

Conversely to the tests carried out in Troussy, no effect of the injection point on the injury rates can be observed. Similarly, conversely to what can be observed on other types of turbines, no effect of the size of individuals on the injury rate can be observed.

9.3. Other species captured during the tests

During the different tests carried out in Frouard, individuals of other species than the injected eels have been captured in the recovery device: 195 European perches (size from 66 to 185 mm), 8 ruffes (size from 112 mm to 120 mm), 1 roach (76 mm), 1 common bream (70 mm) and 3 non-indigenous crayfish (*Orconectes limosus*).

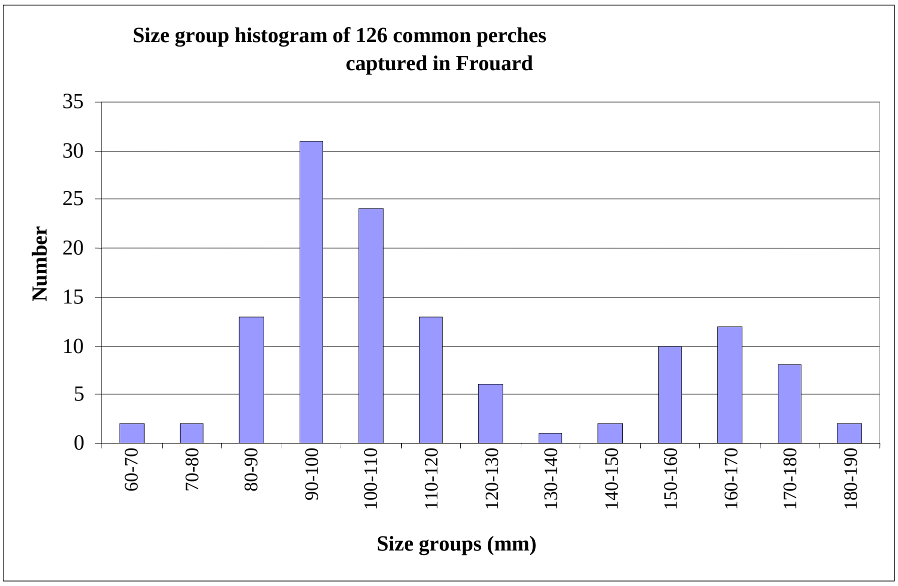


Figure 4. Size group histogram of European perches captured in the net in Frouard

No direct mortality by severing has been observed in these other species. However, the ratio of individuals having really crossed the VLH in operation to those having crossed the VLH while it was stopped or having been trapped in the tail race by the installation of the recovery device is not known.

10. Discussion

Modification of the hydraulic contour of the VLH

In the Troussy tests, the injection of eels at 3 points of the VLH had enabled to show that there was no mortality close to the hub, an intermediary mortality rate at mid-blade, and a maximum mortality rate at the runner periphery. This maximum mortality at the runner periphery, the nature and the cleanness of the observed injuries (eels and trout cut in two), the relatively low runner rotation speed and the very rounded profile of the leading edges of the blades had led us to believe that such injuries could not have been caused by a shock with the blades and that they were most probably **due to the presence of a severing point between the discharge ring and the blade tip** (cylindrical discharge ring of the VLH at the blade tips which left enough space for an eel, even large, to get stuck and be severed).

This has led to manufacturer **to modify the hydraulic contour at the blade tip** towards a spherical profile almost suppressing this space on the new VLHs such as that installed in Frouard.

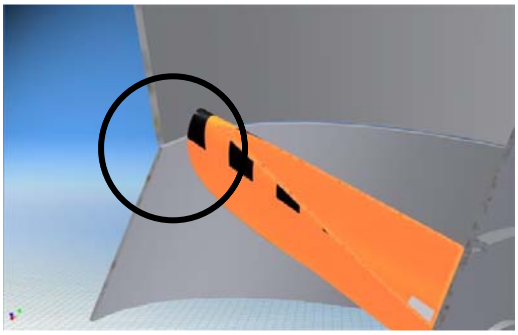


Figure 5. Discharge ring of the Troussy VLH and possible severing area at the blade tip

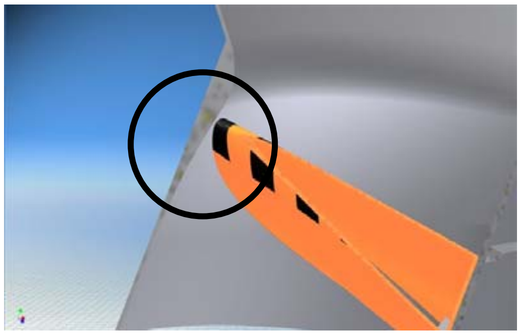


Figure 6. Spherical discharge ring at the blade tip of the new VLHs enabling to decrease the possible severing space

The Frouard tests have been devised to check whether these structure modifications resulted in a decrease in mortality, especially with an eel injection at 4 points of the machine for as accurate an evaluation of the mortality as possible.

Turbine running conditions during the tests

The tests have been carried out with a turbine at full opening and full power, that is, with the operating rate most frequently encountered in the migration period. The preferential downstream migration period of eels in France generally lasts from October to January (GOSSET *et al.,* 2002; DURIF, 2003), during environmental windows most often corresponding to flow increases ("water rushes"), along with a temperature drop and an increase in the turbidity (GOSSET *et al.*, 2002; SUBRA *et al.*, 2003; TRAVADE *et al*., 2010). Studies have shown that the mortality tends to significantly increase for a *very limited* turbine opening (GOMES and LARINIER, 2008), this increase being counterbalanced by a lower extracted flow. Thereby, turbines are generally only tested at full opening and the predictive formulas are given at full opening only.

Recapture rate

The recapture rates in Frouard have not been as good as those obtained in Troussy where they were 100% for the 3 tests with the "large individual" size group (Lt > 850 mm) and ranged between 90.5 and 93.3% (average 91.9%) for “small individuals” (Lt ≤ 850 mm). This can be explained by two main factors. 1) the net used in Frouard is the same as in Troussy. It has thus aged and weakened. Further, although it has been inspected several times during the tests, there always remain unnoticed holes that some eels have obviously been able to find. 2) the configuration of the Frouard tail race is different from that in Troussy and less favorable to the recapture of eels. Indeed, the Frouard tail race is much deeper than that in Troussy, with lower speeds. Thus, the fish are not as readily guided into the net and from there to the fish box. Accordingly, unlike in Troussy, where almost all injected individuals had reached the fish box a few minutes only after the injection, in Frouard, the VLH had to run at full power for several tens of minutes, with a small part only of the eels reaching the fish box, a majority of them remaining the in net and a non-negligible proportion thereof remaining in a pocket formed in the upstream portion of the net (area with the largest mesh) before the entrance to the “sock” formed by the 2 finer meshes. In the case where new tests would be envisaged in Frouard (or elsewhere?), **a shorter net with a regular conical profile would have to be made, with the two smaller meshes only to limit escape risks as much as possible.**

Mortality rates and injury rates

The mortality rates for adult eels are most often greater due to their size (LARINIER and TRAVADE, 2002): being from 4 to 5 times greater than for salmon juveniles, they generally vary from **15 to 30% in the case of large-diameter Kaplan-type turbines used for low heads** and may rise up to 50 and 100% for low-diameter turbines equipping most small hydro power installations and/or high heads (DESROCHERS, 1985; MONTEN, 1985; LARINIER and DARTIGUELONGUE, 1989).

For very low heads like in Troussy or Frouard, a very small number of mortality tests on conventional Kaplan turbines comparable to the VLH are available (turbine most often of equivalent or greater size together with a much higher turbine discharge (LARINIER, *pers. comm.*). Thus, to compare the mortality rates obtained with the VLH to those which would have been obtained with a conventional Kaplan turbine for a same turbine discharge, we have attempted to size a “Kaplan turbine equivalent” of the VLH installed in Frouard. Considering the characteristics of the turbines provided by most manufacturers and the installations already performed on quite similar sites, the equivalent Kaplan turbine could have the following main characteristics, for a maximum 20-m^3/s discharge and a 2.5-m head height: runner diameter close to 2.4 m; runner rotation speed of approximately 115 cpm; runner comprising 4 blades.

With such a sizing, the mortality rate obtained on this equivalent conventional Kaplan turbine, estimated according to the last predictive formulas devised by GOMES and LARINIER (2008) would be from 30% à 37% for 70-cm eels and would rise up to from 45% to 53% for 90-cm eels.

On the first-generation VLH, the Troussy tests had shown that the mortality rates were already much lower than those of an equivalent Kaplan turbine since they had been assessed at 7.7% (ECOGEA, 2008a).

After the Troussy tests, the structure modifications of the VLH towards a spherical discharge ring equipping the second-generation VLH used in Frouard have **substantially improved the fish-friendliness, since the rate of immediately lethal injuries to the eels is extremely low, and even zero, and that their rate of injuries non lethal in the short term (from 24 h to 48 h) is on the order of 2%.**

Deferred mortality

The deferred mortality has not really been assessed during these tests. Indeed, among all the living individuals of the 8 test batches recovered in the net (that is, the 177 recaptured eels), no mortality after from 24 h to 48 hours of observation has been observed. The individuals all seemed in good health and apart from 4 eels, none of them had injuries (bruises, scratches, injured vertebral column…) or any sign of perturbation of any kind (normal swimming behavior and posture, good touch responsiveness when manipulated…).

Therefore, we have decided **not to evaluate the deferred mortality** given that it remains difficult to be correctly assessed with this species (keeping the eels under observation for several weeks implies significant epizootic risks, especially for silver-stage eels which amount for at least more than 20% of the individuals) and that, even if it decreases the biases resulting from a mortality after the delays, it does not suppress sub-lethal effects on behavior, migration, and breeding (HOLZNER, 2000 *in* GOMEZ and LARINIER, 2008).

Lack of effect of the size of individuals

Since the mortality in transiting through a turbine increases along with the fish size (Monten, 1985; Larinier and Dartiguelongue, 1989; GOMES and LARINIER, 2008), we have deliberately used large individuals (respective average and maximum sizes of 761 mm et 1002 mm), to be in the most constraining conditions for the tests. However, no effect of the size on the mortality rate has been demonstrated.

It would be desirable to **assess the possible mortality on species of smaller size** (smolts, for example) to verify the absence of severing areas accessible for small species but inaccessible to larger species like eels (minimum size of the eels used in Frouard: 610 mm (24.02 in)).

Lack of effect of the eel injection point

Despite an eel injection at 4 points of the VLH, no effect of the injection point has been demonstrated, either on the short-term mortality (which remains very low, or even null, whatever the injection point), or on injuries not lethal in the short term (3 of the 4 injured eels for injections at median points 2 and 3, that is, close to the mid-blade). The structure modifications of the VLH thus seem to have suppressed the severing area which existed between the blade end and the cylindrical discharge ring on first-generation VLHs such as the Troussy VLH.

11. Conclusions - Perspectives

The rate of immediately lethal injuries of adult eels (size ranging from 60 cm to 1 m) transiting through the new spherical discharge ring VLH installed in Frouard, running at full opening and full power, is extremely low, and even zero, and the rate of injuries not lethal in the short term (from 24 to 48 h) is low, given that it approaches 2%.

It should further be reminded that the eels transiting through the turbine are a portion only of the downstream migrating population. The other individuals can take several paths (dam, spillways, bar screen openings…) and the proportion between the two groups may considerably vary according to the degree of harnessing and the characteristics of the installation, the hydrology in downstream migration period, and the fish behavior.

Regarding the short-term mortality, these results rank **the new-generation VLH with a spherical discharge ring, running at full power and full opening, as a turbine with a very light impact on the downstream migration of silver eels (from 60 cm to 1 m).**

However, the tests carried out in Frouard enable to assess neither the deferred mortality, which is always possible in eels transiting through a turbine, nor the possible mortality generated by a VLH running at more reduced opening and power.

It would eventually be useful to complete these trials with tests on other smaller fish species, in particular on Atlantic salmon smolts**, which are also particularly affected by the injuries caused by hydroelectric turbines during their downstream migration.**

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APPENDIXES

Injection points tested in Frouard

Fish recovery installation

- Net support frame,
- Net,
- Floating fish box.