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DOWNSTREAM FISH MIGRATION ALONG THE LOW MEUSE RIVER

Action A1

Definitions and Nomenclature

Deliverable – Definitions and nomenclature

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I. Introduction

Given the linear nature of freshwater habitats, dams and weirs act as anthropogenic barriers that fragment the river. These barriers have frequently been implicated in the decline of anadromous fish population because of their effect on upstream and downstream migration (Noonan, 2012). Different devices or operations have been installed or conducted to restore connectivity and aid with both upstream and downstream fish migration (Clay, 1995). Fish downstream migration is a major concern due to the presence of hydropower plants. Passages through turbine are source of immediate and/or delayed mortality for migrating species, such as salmon and eel. Downstream devices have been deployed to divert fishes from passing via the turbine (Larinier, 2001). These devices are dedicated to small hydropower plants and solution for large plants are not efficient, considering fish protection efficiency and economic factors.

The Life4Fish project deals with the ecological continuity and more specifically with the downstream migration of Atlantic salmon smolt (*Salmo salar*) and the European eel (*Anguilla anguilla*). The three major objectives of the project are:

- to increase the survival rate of downstream migrating silver eels and salmon smolts to 80% and 90% respectively along the Lower Meuse River;
- to enhance operational management possibilities of hydropower plants with integration of fish migration intensity forecast;
- to maximize the renewable energy produced, designed as “green energy”.

In this project, the approaches deployed to restore the ecological continuity aim to reduce or compensate the impact of the obstacles, especially the HydroPower Plant (HPP). Efforts to restore the ecological continuity may consist of building structures (fishways, behavioral barriers), managing the turbines’ operation of the HPP or intervening directly with the animals, by trap and transport solution. These solutions may have variable performance (Bunt et al. 2016; Noonan et al 2012; Roscoe and Hinch 2010). To evaluate the effectiveness of these actions and devices, the scientists have to share a set of definition of specific terms, designation or concepts (T. Silva et al., 2017, Drouineau et al., 2018)

First, we will address the context of the LIFE4FISH project, definitions of specifics terms, study sites, targeted species and the different working scales. Secondly, we will define the objectives of the project and how we will evaluate the effectiveness of the solutions at each working scales.

II. Life4Fish project context

The aim of the project is to facilitate the fish downstream migration in the Belgian Lower Meuse. Ambitious species restoration programs are in progress, targeting Altlantic salmon and European eel. The focus will be put on these two species. The project includes a characterization of population stock and downstream migration routes along the study site. The project proposal includes installation, implementation and monitoring of innovative solutions designed to increase the migratory success of the targeted species. Specific and innovative technologies, such as fish guidance devices and fishways, and new hydropower control strategies will be applied and tested accounting for the downstream migrating process.

II.1 Definitions and terms.

With regard to estimate efficiency of fish passage solution, there are inconsistencies in definitions and methods used. We decided then to define several terms used in this project.

- Ecological continuity: free circulation of biological species and natural river sediment transport.
- Migratory Success: ratio between the number of individuals (migrating) of a species leaving the considered area (Lower Meuse river, HPP site, …) without damage, N_out, and the number of individuals entering and produced in the study area, N_in.
- Fish passage solution (FPS): Any device, structure or mechanism which is designed or operated to facilitate the safe movement of fish in an upstream and/or downstream direction past one or several impediments
- Overall FPS efficiency: The percentage of available fish attempting to pass an impediment(s) that find, enter and successfully negotiate, the FPS. Encompasses attraction, entrance and passage efficiencies.
- FPS passage efficiency: The percentage of fish entering the FPS that successfully negotiate and exit the FPS.
- Available fish: The number of tagged fish approaching the impediment. The approach distance will be site specific and fish are assumed to be motivated to pass.
- FPS passage Time: Time from first entrance of fish into FPS to exit (last detection in the FPS).
- Number of attempts: The number of attempts is the number of entries in the attraction area with or without passing the element considered (FPS, obstacle, dam, …)

II.2 Study area

The Meuse River is a European river stretching over 950 km with a catchment area of 36000 km². The Meuse River source is located in France in the department of the Haute Marne (Grand Est region) and flows through the Ardennes before reaching the Belgium. The River enters Wallonia (Belgium) at the city of Heer and then flows into the province of Namur. In the province of Liège, two main tributaries join the Meuse River: the Mehaigne on the left bank and the Ourthe on the right bank. In Wallonia, the Meuse River course extends over 128 km and provides water for several commercial and industrial activities: commercial shipping, nuclear production (Tihange nuclear power plant, called NPP hereafter) and hydropower (8 hydropower plants called HPP hereafter: Hun, Tailfer, Grand-Malades, Andenne, Ampsin, Ivoz-Ramet, Monsin and Lixhe).

Figure 1 : Meuse River catchment

The study area covers the Meuse River between Namur and the Belgium-Dutch border, from upstream Grands-Malades HPP to downstream Lixhe HPP. The river is highly channeled over this section with six majors obstacles to migration (HPP): Grands-Malade (dam, lock and power house), Andenne (dam, lock and power house), Ampsin (dam, 2 locks and power house), Ivoz-Ramet (dam, 2 locks and power house), Monsin (dam and power house) and Lixhe (dam and power house). The study area includes 2 tributaries of the Meuse River, the

Ourthe and the Mehaigne rivers and 3 leaving routes, the Meuse river downstream Lixhe HPP, the Albert Canal and the intake of cooling water system of the Tihange NPP.

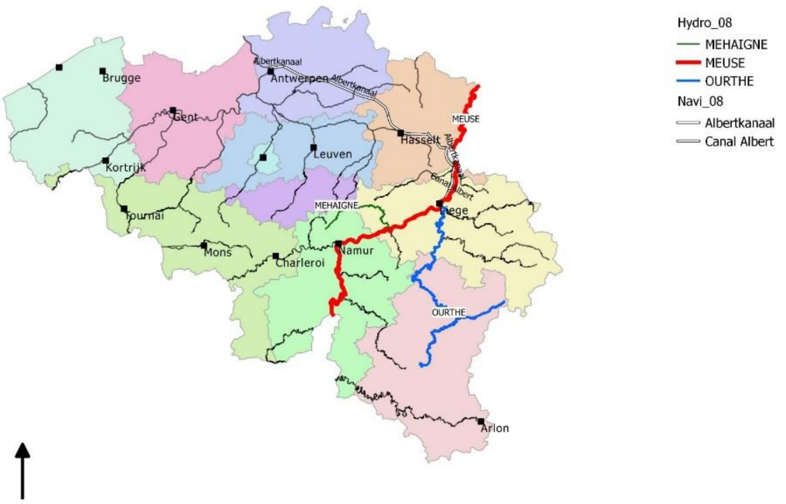

Figure 2 : River Meuse in Belgium

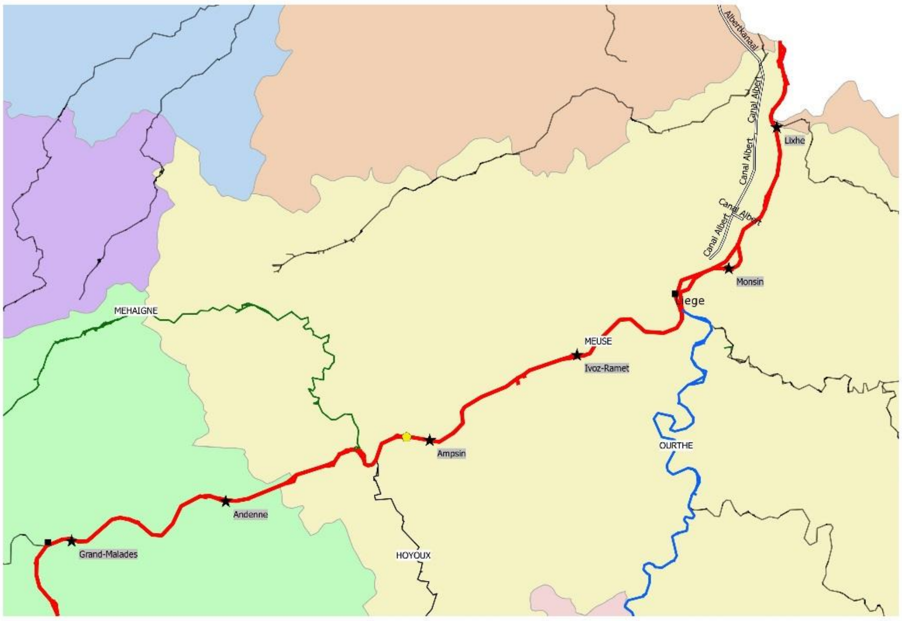

Figure 3 : Locations of the hydropower plants on the Meuse River (Nuclear power plant of Tihange is symbolized in yellow)

Table 1 : Characteristics of the lower Meuse River and its main tributaries.

	Average Discharge	Maximal annual average discharge	Minimum annual average discharge	Power plants
Meuse (Amay)	208,6 m3/s (1996-2016)	309 m3/s	126 m3/s	6 HPP 1 NPP
Mehaigne (Moha)	2,6 m3/s (1974-2000)	4,1 m3/s	1,2 m3/s	
Ourthe (Sauheid + Chaudfontaine)	55,5 m3/s (1992-2016)	78,9 m3/s	30 m3/s	
Canal Albert (Haccourt)	36,3 m³/s (1997-2017)	41,1 m³/s	32,4 m³/s	

II.3 Targeted Species

The Meuse River was previously home to several diadromous migratory fish species including, sturgeon (*Acipenser sturio*), shad (*Alosa Fallax* and *Alosa alosa*), sea lamprey (*Petromyzon marinus)*, Atlantic salmon (*Salmo salar*) and houting (*Coregonus oxyrinchus)* which disappeared from the river basin sometimes between the end of the 1800s and the middle of the 20th century (Philippart and Vrancken, 1983). The two targeted species in this project are the European eel (*Anguilla anguilla*) at silver stage and the Atlantic salmon (*Salmo salar*) at the smolt stage.

II.3.1 Atlantic salmon (*Salmo salar*)

Atlantic salmon is a fish that undergoes growth in the saltwater of the North Atlantic but breeds in the freshwaters of European rivers from November to January. Their eggs are laid in the very oxygen-rich freshwaters they hatch between February and April. Between March and May, after spending between one and two years in freshwater, the smolts start to migrate outwards to the sea off the coast of Greenland and the Faroe Islands, where they reach their adult size within one to four years. They then embark on the return migratory journey back to their native rivers where they reproduce. The Atlantic salmon is capable of completing the migration and spawning pattern two or three times in its life. The project is seeking protection for the species as it migrates downstream to the ocean, i.e. during the smolt phase. The salmon kelts will beneficiate of the developed actions in the project.

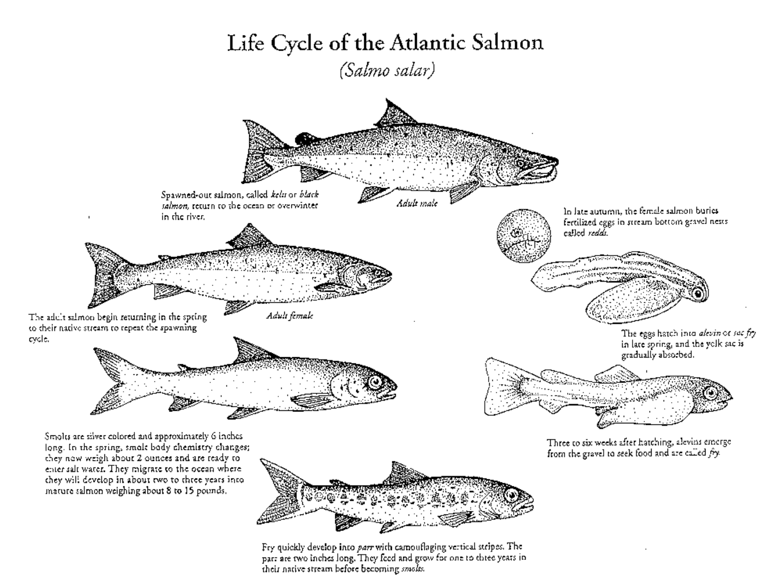

Figure 4: Life cycle of the Atlantic salmon (U.S. fish & wildlife service)

In the early 19th century, Atlantic salmon was abundant in the Meuse river basin (Belgium part). A combination of several factors, including the construction of hydraulic infrastructures such as dams effectively blocking migratory routes, led to salmon disappearing from the Meuse after the 1930s. In the 1990s, adult specimens were found but the species remains under severe threat and is in danger of extinction at regional level. The species is included on the IUCN red list of threatened species (1996). It is covered by numerous reintroduction programs in Europe and a specific program in Belgium known as “Meuse Saumon 2000” aiming to restore the Atlantic salmon’s complete life cycle through restocking, monitoring migratory movements, and studying hydraulic works in the Meuse river basin.

Atlantic salmon populations in the Meuse river basin are now dependent on restocking actions conducted by the Fisheries department within the framework of the Meuse Saumon 2000 restoration work. Historically, Atlantic salmon was found in the Meuse river basin in an area stretching as far as France. The current distribution area varies from year to year according to restocking operations. The Ourthe river basin is currently the priority focus of these replenishing efforts. The Samson, Lesse and Semois are targeted on a variable basis, depending on the abundance of young salmon available for transfer. Finally, the Houille river basin, a French tributary of the Meuse near Givet, has recently seen fish transfers (2009 or 2010) by the relevant French authorities (Source: Philippart, personal statement). In Netherlands, a new restocking operation was made on the River Geul in 2016, with promising results. The International Commission for the Meuse's masterplan for migratory fish (2000) proposes an assessment of the potential for young smolt production in the Meuse river basin, on the basis of the surface area of sills assessed in tributaries to the Meuse.

Smolt production potential in the Walloon Meuse basin is estimated at 393,000 individuals. This population is divided as follows: a good third in the Meuse River upstream of confluence with the Ourthe, and two thirds coming from the Ourthe river basin. The adult return rate is estimated at 3% of the smolt population, so the pristine adult salmon population in Wallonia could be around 12,000 individuals. Between 2011 and 2014, nearly 250,000 smolt equivalents were introduced in the Belgian Meuse river basin (Source: Rollin – personal statement). Given the geographical distribution of restocking actions in the various tributaries, the number of salmon smolts potentially transiting via the study area is 59,631 individuals/year. These values are deliberately conservative because they do not take into account elements that tend to lower the figures, such as the non-migrant portion of the stock, natural mortality before arrival in the project area, and mortality related to other structures upstream of the project area.

To disentangle the influence of these parameters, we can compare the values calculated using these stocking figures with those obtained by extrapolating measurements from Sonny (2009) for the Ampsin-Neuville dam. Extrapolating from the captures taken at the Tihange intake structure, this demonstrates that out of the 10,589 smolt equivalents from restocking operations heading downstream, only 1,400 young salmons are observed at the Ampsin-Neuville dam. This would mean a mortality rate of 87% before fish arrive at the site. If we apply this rate to all the sites, the total number of smolts transiting via the project zone would be 7,884 individuals/year.

II.3.2 European eel (*Anguilla anguilla*)

European eels begin their life cycle as transparent larvae, known as leptocephali, in February or March in the northeast Atlantic. The larvae are passively transported by the Gulf Stream to the coasts of Europe (from Norway to Morocco). The duration of the oceanic drift is not perfectly known but estimates vary from 7 months to more than 2 years (Bonhommeau et al

2010). The larvae then metamorphose into “glass eels” when they arrive on the continental shelf. As they approach the European coast, they enter estuaries, progressively become pigmented yellow eels (Tesch 2003) and colonize the freshwaters of the Meuse. As the European eel continues to grow, it becomes a “yellow eel” -6-8 cm length, cylindrical shape and transparent to slightly pigmented) and settles in the connecting rivers and estuaries (Keith et al., 1992). The continental growth phase lasts between 3 to 30 years, depending on the region and the sex (Vollestad, 1992). Under the influence of environmental factors, the yellow eels metamorphose again into silver eels that are ready to migrate. Silver eel are characterized by dark pigmentation dorsally and silver ventrally, a clear contrasting black lateral line and enlarged eyes (Tesch 2003). When environmental factors generate stronger water discharge and low light conditions (Trancart et al 2017), the migration is triggered and the silver eels move back downstream to return to the Atlantic spawning grounds. There is still much mystery surrounding their life cycle, especially the factors affecting colonization and the start of the migratory period. The project is seeking protection for the species as it migrates downstream to the ocean, i.e. the silver eel stage

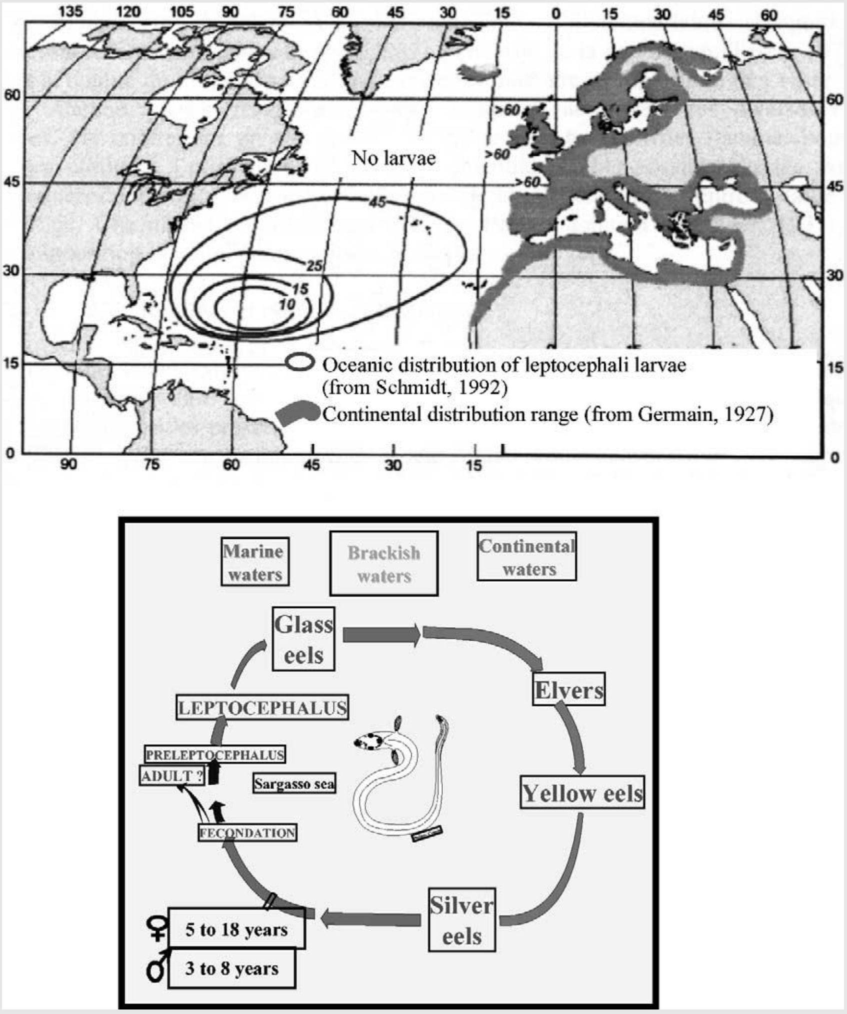

Figure 5: Distribution and biological cycle of the European Eel (from Feunteun 2001)

Since the 1980s, we have observed a reduction in the species distribution area as well as a clear reduction in the population and the decline of the natural recruitment of glass eels due to the formation of obstacles (dams) to the juveniles' upstream journey and the influence of other factors reducing the abundance of local populations. The eel was listed by the International Union for the Conservation of Nature as "in critical danger of extinction" worldwide in 2009. In 2007, the European eel was listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora. It now benefits from a management plan applicable in all European Union countries. These plans endeavor to reduce all anthropogenic causes of mortality so that, in the long term, an escapement level of 40% of the biomass of silver eels compared to the "pristine" population (i.e. free from any impact from human activities), is achieved in line with the regulation on the recovery of European eel stocks, EU no. 1100/2007.

Since the 1980s, the eel population has seen a marked decline. A recent study conducted by the University of Namur (De Canet et al., 2014) reassessed the stocks of yellow and silver eels in the Belgian Meuse river basin in 2013 and in 1980 using the “Eel Density Analysis” model. Totals of 21,374 yellow eels and 1,069 silver eels were estimated for 2013 in the Belgian stretch of the Meuse basin (including its main tributaries). This represents around 17% of the pristine population number. The probability of presence and abundance of eels was linearly linked to the distance of the site from the sea and the cumulated height of the dams. This indicates greater abundance of the species in the middle and lower Meuse. On the basis of this data and despite the modeling work done and which is to be encouraged in the future, there are still numerous uncertainties surrounding the estimated rates of the escapement of silver eels towards the sea. (Source: Vlietinck and Rollin 2015).

The impact of operations to restock glass eels (134 kg or around 470,000 glass eels in all between 2011 and 2015 according to the WGEEL report) is only just being felt with silvering among males and it has not therefore influenced stock distribution in the river basin so far. Silvering among females is not expected to occur before 2021.

As stock distribution is not known, to define where the 1,069 silver eels started their outward migration journey, we have worked with an assumption that stocks are distributed proportionally to the surface areas of the tributary river basins. On the basis of this assumption, the total number of silver eels transiting via the project zone is 945 individuals/year. This value is somewhat conservative because it does not take into account factors likely to reduce the number, such as the decline in the number of eels expected between 2013 and 2016, the actual distribution of eels which are more abundant in the lower river basins, the non-migrant portion of the stock (evaluated at 58% of the stock during a study conducted on the upstream portion of the Meuse (Verbiest et al. 2012)), natural mortality before arrival in the project zone and mortality related to other structures upstream of the project zone. However, to date the available data is insufficient if we are to establish the impact of these factors on the silver eel populations in Belgium Meuse.

II.3.3 Legal aspects

At the international level, in 1996, the Benelux fix a goal of fish stock restoration by prioritizing the removal of barriers from the Strategic Priority Map and taking the necessary steps to:

- 90% of first priority obstacles are removed by December 31st, 2015 and the rest of these obstacles by December 31st, 2021,

- 50% of the second priority obstacles will be lifted by 31 December 2015 and the remainder of these obstacles in two increments of 25% each, the first by 31 December 2021 and the second by 31 December 2027;

A Meuse international Commission was set up in 2002 to ensure sustainable management of the Meuse and coordinate the obligations set out in the European Water framework Directive between, France, Luxembourg, Belgium and Netherlands. It also ensures salmonid migration via the “Meuse” action plan (1998-2003).

In 2007, the European Union fix as goal in the regulation on the recovery of European eel stocks, EU no. 1100/2007, an escapement level of 40% of the biomass of silver eels compared to the “pristine” population (i.e. free from any impact from human activities). This goal must be achieved in coordination with the Council Directive 92/43 / EEC of 21 May 1992 concerning the conservation of natural habitats and wild fauna and flora (2) and Directive 2000/60 / EC of the European Parliament and of the Council of 23 October 2000 creating a framework for a community water policy (3). In particular, the management plans for eel should be amended in Directive 2000/60 / EC.

At the national level, national management plan for the preservation of European Eel follows the European Council’s regulation defining the measure to be implanted to replenish European Eel stock. It sets out measures to reduce direct mortality related to fishing and other human activities, to address obstacles to migration upstream and downstream, to improve biological quality of water bodies, to reintroduce glass eels, and communication and dissemination activities.

The watercourses selected for the implementation of the management plan for the Meuse watershed are navigable waterways and non-navigable first-class watercourses. Unlike smolts salmonids, silver eels can find in the Albert Canal a favorable environment for their lives and the continuation of their migration towards the sea via the estuarine Scheldt.

The management plan for Belgium fix pristine escapement to an annual production of 40 tonnes, using the method proposed by Dekker, namely to consider a production of 10 kg / ha / year of silver eels on an area of 4,000 ha of habitat favorable to the species in the Walloon part of the Meuse basin. Compared to such a reference production, an exhaust rate of 40% corresponds to a biomass of 16 tonnes. The actual escapement is fixed at 10,2 tonnes as an average value between evaluation based on extrapolation of values for the Meuse in the Flanders region and in the upstream part of the Netherlands course. The efforts to achieve the goal of the management plan are dispatched on several actions with a contribution to the goal of 45% fix for the actions in order to mitigate the mortality along the downstream migration (specifically along the pump stations and the hydropower plants). This represent an increase of the annual escapement of 2,6 tonnes, representing an increase of the actual escapement of 25%.

At a regional level, the Walloon region has implemented two strategic management plans to tackle biodiversity loss in the Meuse, to improve the Walloon aquatic environment and to protect its fish resources. *The Wallonia fish resource management plan* introduced in 2013, within the framework of application of Water Framework Directive in Belgium (2000/60/EC), the goals of which are to preserve and restore aquatic environment and their biodiversity. The master plan for migratory fish in the Meuse river basin, drafted in 2011, the aim of which is to coordinate the initiatives taken to re-establish the ecological continuum of the various action within the framework.

The program Meuse Salmon 2000 is the outcome of cooperation between teams at the University of Namur and Liège and the Walloon regional fisheries department. It was as part of this program that the sites of Monsin (in 2000), Ivoz-Ramet (in 2001) and Lixhe (in 1998) were fitted with new fishways enabling upstream migration.

At a local level, there are conditions linked to the fish protection in the licenses of four of the six Hydropower plants which set the maximal mortality rates separately on each plan for 2 species:

Table 2 : Maximal mortality rates linked to the fish protection in the licenses of four HPP

	Smolt salmon	Silver eel
Grands-Malade	1.75%	3.65%
Ivoz-Ramet	1.75%	3.7%
Monsin	2%	3.65%
Lixhe	2%	

III. Definition of the Project objectives: Migration success and renewable energy

The two main objectives of the project are to improve the Migration success of the salmon smolts and the silver eels and to maximize the renewable hydroelectric energy produced by the HPP in the study zone.

III.1 Migration success

The migratory success (S) is the ratio between the number of individuals (migrating) of a species leaving the study area without damage, N_{out}, and the number of individuals entering and produced in the study area, N_{in}.

$$S = \frac{N_{out}}{N_{in}}$$

In the study area the different entering and leaving ways are localized on the Figure 6. Three entering ways will be considered:

- Upstream the first HPP (Grand Malade HPP), on the Meuse River;
- In the sections of the Meuse river in the study area;
- 2 tributaries of the Meuse River, Ourthe and Mehaigne Rivers.

Three leaving ways will be considered:

- Downstream Lixhe HPP on the Meuse river;
- The Albert canal;
- The intake of the Nuclear Power plant of Tihange.

The canal Albert is out of the project area, stakeholders being not allowed to implement any measure there. The focus on the canal is already foreseen by the authorities that manage the canal (INBO, SPW). Several studies of the downstream migration ways and the survival rates along the canal are ongoing. These authorities will be represented in the different project committees in order to exchange information about the fish behavior.

The fish stock of the two species will be evaluated differently. Smolt production potential in the Walloon Meuse basin is estimated at 393,000 individuals and is divided as follows: 1/3 upstream the confluence with the Ourthe and 2/3 coming from the Ourthe river basin. The main part of the smolt production comes from the restocking operations. For the current project, Ourthe Basin is the priority focus and will be the main production of smolt. For the next step, the Samson, Lesse and Semois will be targeted as new potential production area of smolts.

Since 1980’s, the eel population is declining. A recent study conducted by the University of Namur (De Canet et al., 2015) reassessed the stock of yellow and silver eels in eth Belgian Meuse river basin in 2013 and in 1980 using the “Eel density Analysis” model (EDA) (Briand et al, 2015). EDA is a modeling tool which allows the prediction of yellow eel densities and silver eel escapement from electrofishing survey networks. Totals of 21,374 yellow eels and 1,069 silver eels were estimated in 2013 in the Belgian stretch of the Meuse basin (including its main tributaries). A new estimation of the eel population with EDA will be conducted during the project.

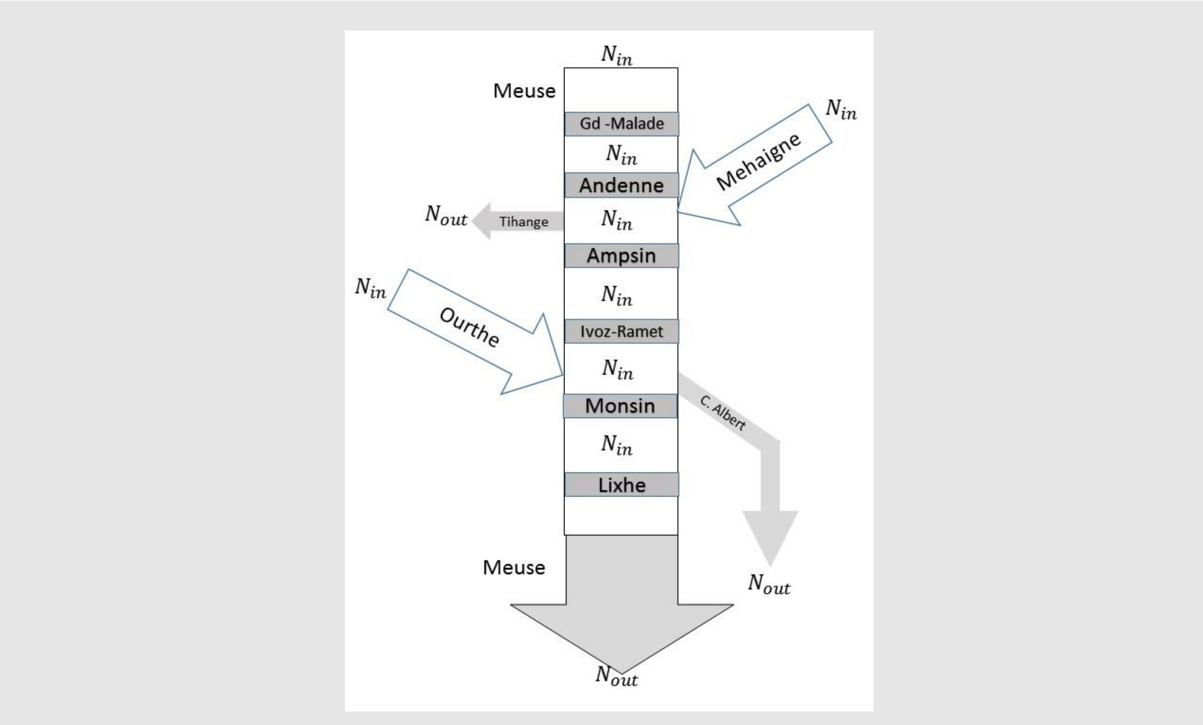

Figure 6: Schematic view of the study area and localization of the different sites considered in the project.

The passage of HPP is key parameter of the downstream migratory success. A passage of an obstacle is considered as a success if the fish pass the obstacle in a reasonable time and without damage and is able to continue its migration. The damage observations will be based on the guideline for injury classification for fish passage survival studies using the Hi-Z tag developed by Nomandeau inc. (Normandeau Inc., 2012). The damage to fish passing through a turbine are almost exclusively evaluated by in-situ experiments. We will consider that a fish cannot continue its migration if:

- Bruises are size dependent. Major if 10% or more of fish body per size ;
- Hemorrhaged eyes : Major if 50% or more;
- Deformed pupil(s) are a major injury ;
- Scale loss: major if 20% or more of fish per side.
- An X-ray examination will be made to reveal injuries especially damages on swim bladder and spinal column.

Associated with the damage ratio, the physiological and the stress status will be analyzed, as far as possible, in different areas of the study area, i.e. around to the HPP site and in the section between the HPP.

III.2 Physiological stress and health status

Physiological stress status and health status will be assessed at the two pilot sites of Monsin and Grands-Malades both for eels and smolts.

Assessing health status:

The term "health" is often interpreted as "absence of disease" especially in aquaculture. In our work this term is widened beyond the absence of disease to also cover pathology defined as detrimental arrangements of molecules, cells, tissues and their dysfunction (Broom 2007). We defined health as the ability of an animal to perform normal physiological functions and to maintain homeostasis and to withstand infectious and non-infectious stressors.

- Pathological code: Based on the ONEMA, actually AFB, guidelines (Girard and Elie, 2007) this code describes the type, severity and location of injuries and the type and abundance of external parasitism in European eel (Annex 2).
- Apart from the above heath indicators, Herpes virus detection in eel will be determined using a non-invasive diagnostic by RT-qPCR on blood and mucus from some individuals (Van Beurden et *al.*, 2015) passed through from the hydro turbines compared to control fish.
- Since a good health status is sustained by an effective immune status, immune markers will be analysed using a non-invasive diagnostic by RT-qPCR on blood and mucus from both eels and smolts. The following immune markers will be analysed:
  - Plasma alternative complement pathway activity,
  - Plasma lysozyme activity,
  - Plasma peroxidase activity,
  - Plasma total immunoglobulins:
  - Immune expression of key genes related to various immune functions: Interleukin-1 Il-1, Interleukin-6 Il-6, Interleukin-10 Il-10, Tumour necrosis factor-α TNF-eC3 complement.

Assessing physiological status:

Since, long-term stress response is considered as causative trigger of various diseases, stress biomarkers should be investigated as far as negative agents on health status are concerned. We will not focus on the acute stress response, but the long-term response will be enabled by the following biomarkes:

- For both species: Plasma cortisol, GH and thyroid hormones (T4 and T3),
- For smolts: liver heat shock proteins HSP70 and HSP90, peroxidase and brain serotonin activity

Long-term stress response may also affect the migration rate by affecting swimming performances. So, it is highly relevant to analyse the swimming capacity of treated fish by hydroturbine compared to controls by analysing various swimming variables, namely:

- Critical swimming speed (Ucrit): special category of prolonged swimming introduced by Brett (1964). Fish are enclosed in a swim tunnel respirometer and are forced to swim against a particular water velocity for a set time interval. Water velocity is then increased by a set increment until the individual fails to swim during an entire time interval. Critical swim speed (Ucrit) is calculated using the following equation: $Ucrit = Um + (tm / \Delta t)\Delta U$ with Um = highest velocity at which fish swam for the full time interval, ΔU = incremental speed step, tm = time fish swam at fatigue velocity (last velocity step), Δt = prescribed time step for the incremental speed step (Katopodis and Gervais, 2016).
- Optimum Cruising Swimming Speed: it is a continuous steady swimming performance measured when fish are exposed to a certain velocity without alteration or swimming failure at the end of the test (Gui et *al.*, 2014)
- Burst swimming speed: Sprint ability or burst swimming can be measured by bringing flow speed ton an estimated maximum such as twice the maximum flow speed used for the Ucrit (see above) and motivate fish to swim with a mechanical (e.g. touch) or electrical (e.g. a small charge applied to the grid at the back of the swim tunnel) *stimulus*.
- Ventilation rate and tail beat frequency: These parameters can be measured by sampling over periods of several seconds the opercula pumping rate and number of tail beats.

III.2.1 Migrating period

Migrating period are not similar for the two species. First approach, we will used the catches data on the Ourthe River (Philippart 2010) to define a migration period of Mid-March to Mid-June. The migration period of silver eels takes place on august to February, based on the data collected on the intake of the Nuclear power plant of Tihange (Sonny, 2006, 2009). The project focuses only on the smolt stage for the salmon and on the silver eel stage. The Duriff's silvering index will be used to select the silver eels and to determine the different silver stages. This index is based on two metrics, the ocular index (Pankhurst, 1982) and the pectoral index (Duriff, 2003). Based on this index, only the stages 3, 4 and 5 will be considered as potentially migrating fishes.

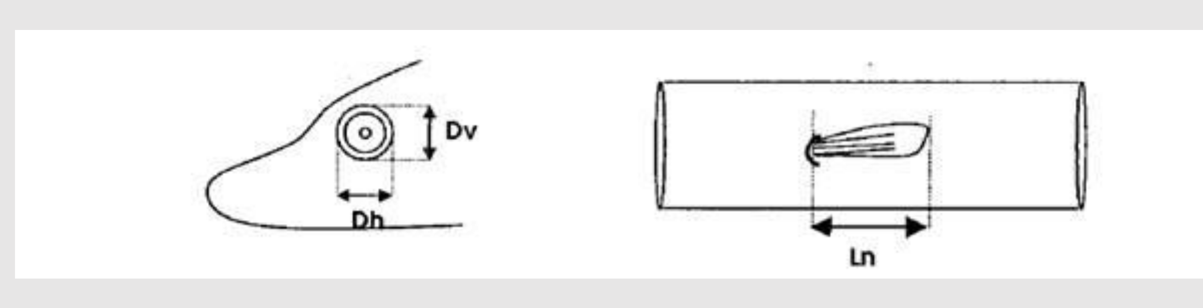

Figure 7 : Silvering index : ocular and pectoral indices (from Durif, 2003). Dh: horizontal diameter of the eye. Dv: Vertical diameter of the eye. Ln: Pectoral fin length

About the smolt downstream migration model, a temporal window of the migration based on the river temperature and average swimming capacity will be defined. A temperature-related smolt window indicates that delays in migration will decrease smolt survival and these negative consequences will be greater in warmer condition (Mc Cormick et al. 1998). According to the results of Mc Cormick et al., we will apply a parameter of 400 degree.days as the maximum threshold of the window. From the results of the telemetry study conducted by Profish in 2017 (Roy et al., 2017), the fish migration velocity has been calculated in the upstream part of the study area (between Grand-Malade and Ivoz-Ramet) and the maximal velocity (subtracting the river water velocity) is between 0.1 and 0.2 m/s.

III.3 Renewable energy saved

We define the green hydroelectric production as the number of GWh produced by year by the 6 hydropower plants in the study area. The associated objective of the project is to minimize the loss of hydroelectric production, considered as green energy. For each devices or actions tested during the project, the migratory success of both species will be estimated as well as the loss of hydroelectric power production.

IV. Scales of study: river sections

The HPPs of the study area encompasses two kinds of river sections: the HPP site and the river reaches. A river reach is a river section between two HPPs. Migration success will be estimated for every HPP and reach while the renewable energy production will be estimated only for every HPP. Parameters used at these 2 scales are presented and detailed in this section.

IV.1 Reach scale

Reach is a river section between two HPPs. Actions and devices tested in this project do not concern directly this scale, but it encloses indirect effects. In the reach section, the estimation of the loss of fishes will be estimated between the number of individuals passing downstream the site n and the number of individuals reaching the upstream of the site n+1. The protocol and methodology used in this project will provide information to identify the causes of the loss of individuals, such as:

- Delayed mortality after the passage of the HPP site;
- Decreasing of the swimming capacity after the passage of the HPP site;
- Sanitary and stress status;
- Entrainment of fish in the intake of the Tihange NPP (provided from the telemetry study);

Natural predation, disorientation and loss of motivation after the passage of the HPP site and/or the river conditions in the forebay could not be identified from the studies conducted in this project.

Based on the telemetry study, downstream migration dynamic will only be studied according to the River environmental conditions and the power plants operational management.

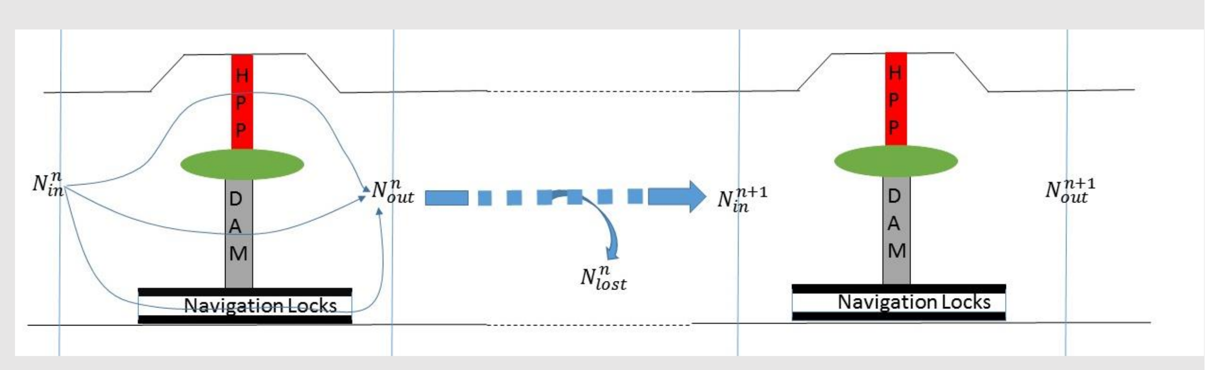

Figure 8 : reach scale

If the loss of individuals in the reach is important, the experimental protocols may have to be adapted, such as the telemetry monitoring, the catches, the analysis of the health and the stress status.

IV.2 Scale of the HPP site

Each HPP site is composed of three main elements, the power house (turbines), the dam and the navigation locks (Figure 9). Dam and navigation locks are considered as safe passage ways. Fishways and bypasses are considered as safe passage ways. The migration success will be estimated at every HPP:

$$S^{site} = \frac{N_{out}^{site}}{N_{in}^{site}}$$

With, N_{in}^{site}, the number of individuals entering in the attraction area of the site n, and N_{out}^{site}, the number of individuals passing the site without damage. According to the site characteristics, an attraction area will be delimited for every site.

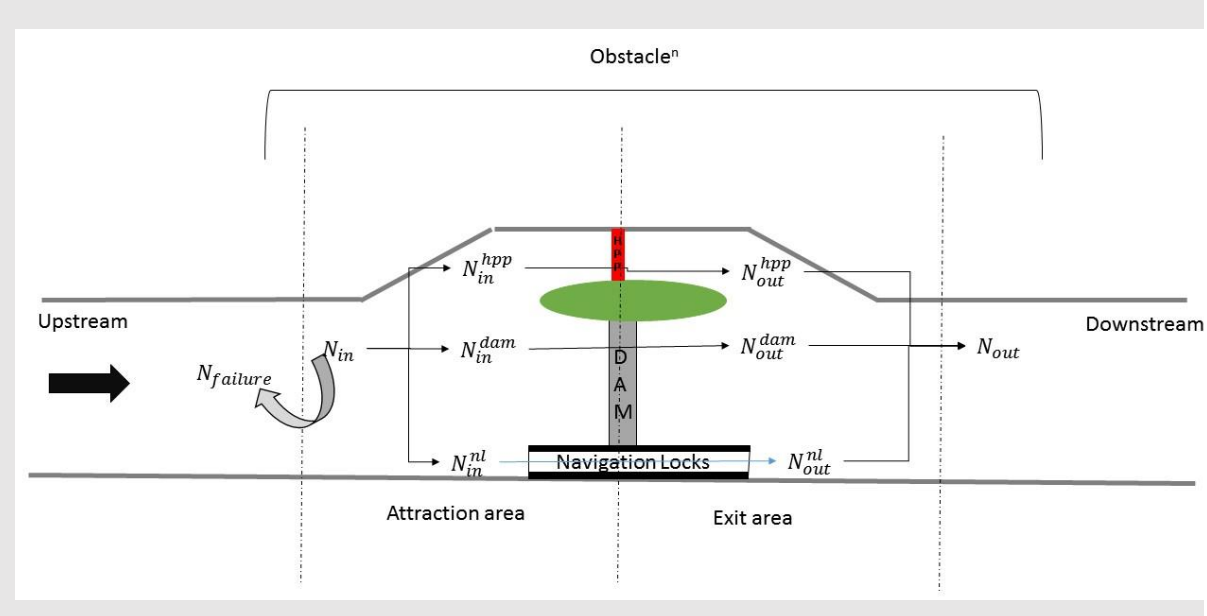

Figure 9 : Scale of HPP site

Associated to the migratory success, two other parameters will be estimated:

- Delay to pass the site;
- The number of attempts to pass the site.

Migration delay is the time between the first arrival of the fish in the attraction area and the obstacle passage, whatever the way of passage. The number of attempts is the number of entries in the attraction area with or without passing the obstacle. In a first approach and based on our experience, the minimal time to consider a new attempt is fixed at 1 hour between 2 successive detections. The time limit will be reevaluated during the project.

V. Devices and actions tested to improve the migratory success

The downstream passage technologies to exclude fish from turbines are dedicated bypass (based on hydraulic attraction), physical screens (bar racks, louvers, …) , fish guidance devices and behavioral guidance devices or barrier. Three solutions aiming to increase the turbine avoidance will be tested:

- Dedicated bypass close to the power plant site (associated to the existing rack), designed to guide the fish and to avoid the turbine;
- Guidance devices or behavioral barrier will be tested to guide the fish to the bypass or to a safe passage;

- Optimization of the turbine operational management to increase the discharge of spillways during the migrating period.

The use of eco-sustainable turbines specially designed to mitigate their impacts on the two targeted species will be evaluated in parallel to this study.

V.1 Bypass and fish guidance devices: downstream fish passage

The Grands-Malades and Ivoz-Ramet sites have been selected as pilot sites. Great attention will be paid to the water supply and entrance of the bypass. A specific valve system will be put in place to adjust the supply flow and the size of the entrance to maximize the effectiveness of the solution. The pass must therefore be carefully sized to create an attraction flow that is sufficient to draw the species to the pass without causing excessive losses of hydro-electric power. We will create a non-turbulent flow with moderate acceleration, avoiding counter current or ascending current creation. In terms of flow rate, the literature indicates that the recommended minimum flow rate through the pass should be 2% to 8% of the maximum turbine flow rate, with the lower range more suited to large hydropower facilities regarding loss production of energy. Precise localization of the bypass is not yet defined, in the inlet canal of the HPP or close to the dam.

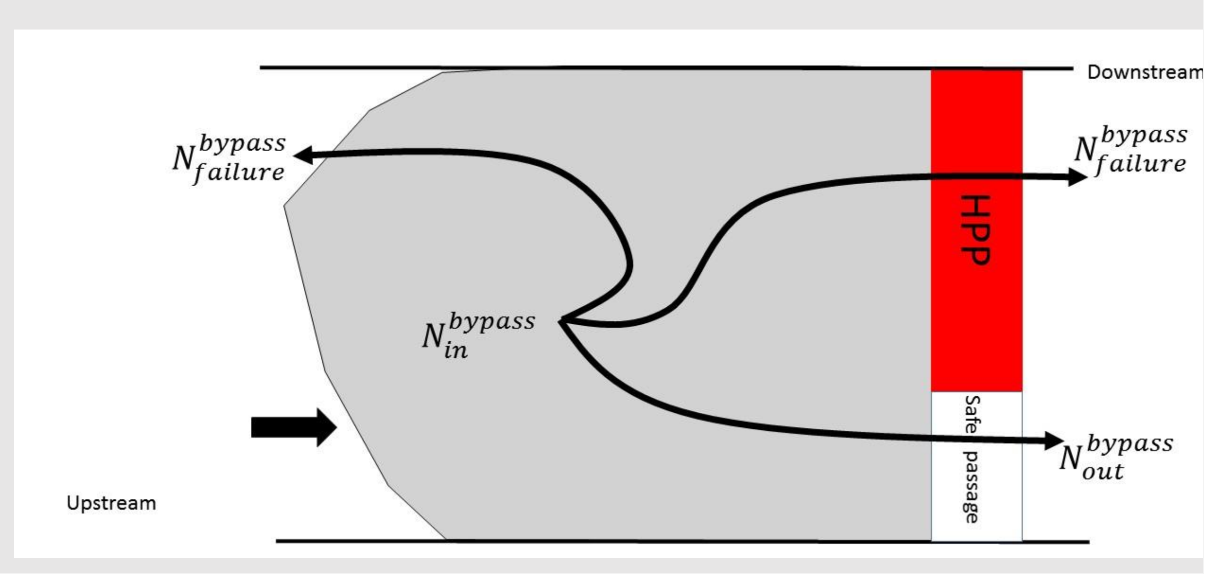

Figure 10 : Efficiency measurement of a surface bypass.

At least 4 fish guidance devices will be tested during the project. A guidance device is always associated to a bypass with the aim to guide the fish to a safe passage. The kind of devices will be defined during the first year of the project. The different failure cases will be identified (through the rack, through the barrier or non-passing fishes) to analyses the failure causes.

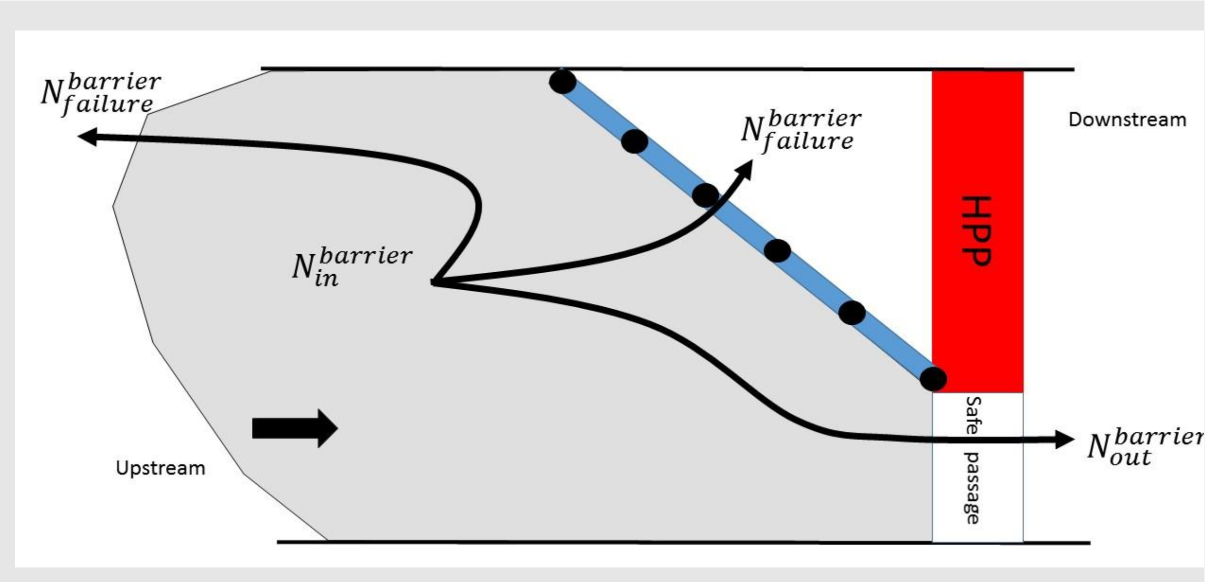

Figure 11 : Efficiency measurement of a surface behavioral barrier.

V.2 Remote controlled hydropower management

The purpose is to predict downstream migration peaks in order to reduce turbines 'entrainment rates. This solution consists of determining when the operation of turbines must be adjusted or stopped, based on the intensity of the downstream migration events or peaks.

A model for predicting downstream migration peaks will be developed based on historic data, knowledge and the telemetry studies conducted in the project. The aim is to create a model capable of being applied to different types of waterways. With such a model in hand, it will be possible to propose rules to manage plant turbines so as to optimize the survival rates for migrating individuals and turbine flow rates. To accomplish this, it will be necessary to first collaborate on choosing a target escapement rate based on the survival rate for smolts and eels for each plant and each type of turbine. This model will make it possible to run through a large number of scenarios, for instance, in terms of plant management methods or changes in turbine mortality rates.

V.3 Efficiency of the solutions

Efficiency of these solutions will be measured with the same parameters and at the same scale. An attraction area will be delimited according to the location of the guidance system. The attraction area of each element will be defined based on the local hydrodynamic conditions. All tagged fished entering at least once in the area will be counted as $N_{in}^{barrier}$. The efficiency is the ratio between the number of fishes entering in the attraction area and the number of fishes passing through the bypass.

$$S^{barrier} = \frac{N_{out}^{barrier}}{N_{in}^{barrier}}$$

The non-passing fishes will be quantified as a parameter of the non-migration and will be included as failure.

Associated to the measurement the migration success, 2 other parameters will be assessed:

- Migration delay due to the obstacle;
- Number of attempts to pass throw the obstacle.

The objective is to reduce the migration delay at every site to less than 24 hours. This delay will be compare to the maximum delays allowed for each species to ensure a complete migration to the sea.

The efficiency of the prediction model will be evaluated, from the results of the telemetry, as the ratio between the number of individuals passing the obstacle via a safe way (dam, navigation lock, bypass, fish way) and the number of individuals that enters at least once in the attraction area of the HPP site. This ratio will be defined as the turbine avoidance rate.

An attempt is the number of entries in the attraction area with or without passing the obstacle. The minimal time to consider a new attempt is fixed at 1 hour between 2 successive detections. The time limit will be reevaluated during the project.

VI. Conclusions

The success of the downstream migration of the two species and the maximization of the renewable energy produced on the Belgian Lower Meuse will be evaluated over a year. The aim of the project is to increase the escapement rate of the smolt and silver eels during the downstream migration (safe passage of the obstacle) and to improve the migratory success. However, this project will not improve migration conditions in the reach, but may highlight other issues.

The efficiency of turbine management will be evaluated on the one hand by the escapement rate of the fishes on the other hand by the production of renewable energy (Figure 11). The percentage of renewable energy saved will be calculated from a reference situation that will have to be defined, such as for the eel stopping the turbines every night during the migration period.

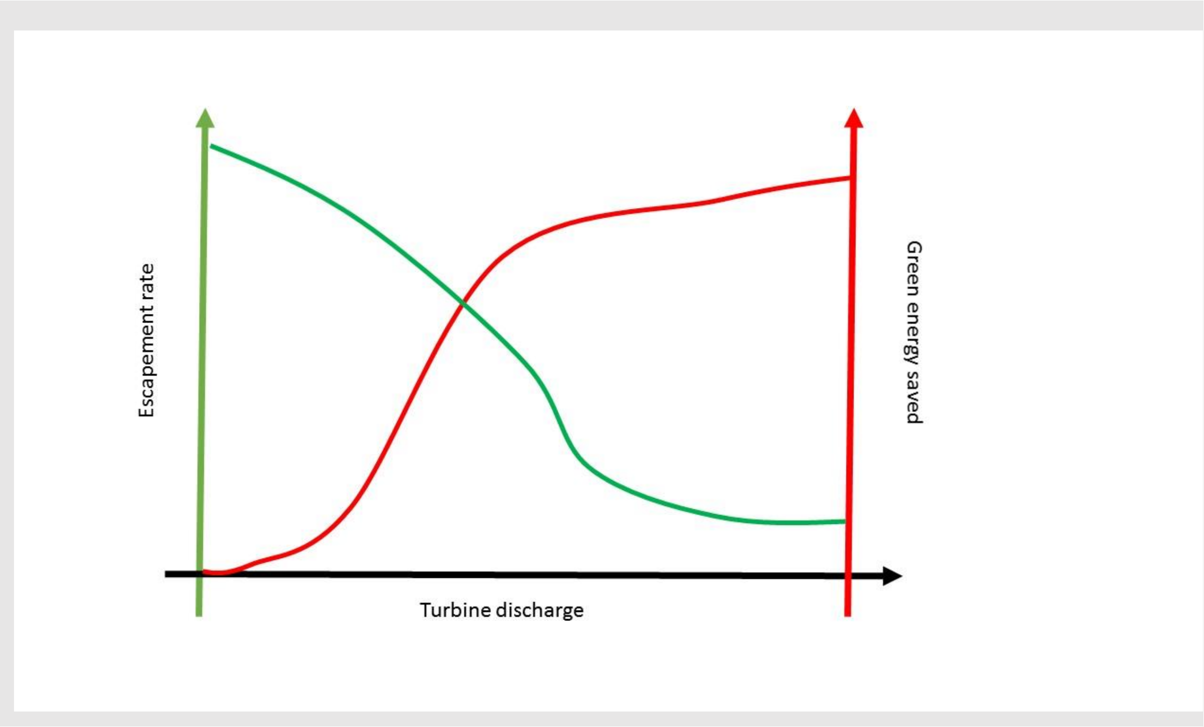

Figure 12 : Schematic representation of the evolution of the turbine escapement rate and the proportion of green energy saved as a function of the turbined flow at a hydroelectric structure.

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VIII. Annex 1 : Guidelines for major and minor injury classifications for fish passage survival studies using the HI-Z Tags.

- A fish with only Loss Of Equilibrium is classified as major if the fish dies within 1 hour. If it survives or dies beyond 1 hour it is classified as minor.
- A fish with no visible external or internal maladies is classified as a passage related major injury if the fish dies within 1 hour. If it dies beyond 1 hour it is classified as a non-passage related minor injury.
- Any minor injury that leads to death within 1 hour is classified as a major injury. If it lives or dies after 1 hour it remains a minor injury.
- Hemorrhaged eye: minor if less than 50%. Major if 50% or more
- Deformed pupil(s) are a: major injury.
- Bulged eye: major unless one eye is only slightly bulged. Minor if slight.
- Bruises are size-dependent. Major if 10% or more of fish body per side. Otherwise minor.
- Operculum tear at dorsal insertion is: major if it is 5 % of the fish or greater. Otherwise minor.
- Operculum folded under or torn off is a major injury
- Scale loss: major if 20% or more of fish per side. Otherwise minor
- Scraping (damage to epidermis): major if 10% or more per side of fish. Otherwise minor.
- Cuts and lacerations are generally classified as major injuries. Small flaps of skin or skinned up snouts are: minor.
- Internal hemorrhage or rupture of kidney, heart or other internal organs that results in death at 1 to 48 hours is a major injury.
- Multiple injuries: use the worst injury

IX. Annex 2: The pathological code in European eel (Girard and Elie, 2007)

Injuries types and localisation			
Morpho-anatomic injuries	Code	Localisation	Code
Colour alteration	AC	Abdomen	A
Deformation, deformity	AD	Anal opening	U
Erosion	ER	Back	H
Eye damages	LO	Body	C
- **Haemorrhage, bleeding**	HE	Caudal fin	Q
- **Exophthalmia**	EX	Caudal peduncle	K
- **Ulcer**	UL	Dorsal fin	N
- **Loss of the eye**	AO	Eye	Y
- **Parasitism**	PA	Gill	B
Gas bubble	BG	Gill slit	O
Gill damages	LB	Head	T
- **Necrosis, erosion**	NE	Jaw	M
- **Cyst**	KY	Lateral line	L
- **Congestion**	CH	Mouth	G
Haemorrhage, bleeding	HE	Pectoral fin	P
Lumps	AG	Side	F
Mucus hyper secretion	SM	Spine	V
Multiform pathological condition	ZO		
Necrosis	NE		
Organ loss	AO		
Red or prominent anus	US		
Thinness	AM		
Ulcer (haemorragic)	UH		

Injuries severity			
Abundance/Number/alteration degree	Quality index (QI)	Overlapping rate	Quality index (QI)
Absence: N=0	0	No overlapping: S^2=0%	0
Low abundance/alteration: N<3	1	Low overlapping: S^2<5%	1
Medium abundance/alteration: N=4-6	2	Medium overlapping: S^2=5-10%	2
High abundance/alteration: N=7-10	3	High overlapping: S^2=10-20%	3
Very high abundance/alteration: N≥10	4	Very high overlapping: S^2>20%	4
Parasitism			
External parasitism	Code	Abundance	Quality index (QI)
White point	PB	Absence	0
Mycosis	PM	Low abundance	1
Crustacean	PC	Medium abundance	2
Fish leech	PH	High abundance	3
Others	PX	Very high abundance	4