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EEL AND SALMON DOWNSTREAM MIGRATION BEHAVIORS ALONG THE MEUSE RIVER

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ABSTRACT

This paper presents an integrative approach to define the migration status of Salmo Salar and Anguilla Anguilla in various scales (work scale, site scale, global scale) according to the results of on-site studies led on the low Belgian Meuse river. According to the stocks repartition, fishes are introduced in the model along each reach. The losses along the reaches are than evaluated according to the loss percentages observed during the on-site fish tracking. On each site, composed by several structures (dam, sluice, hydropower plant, and/or industrial water intake), the fish repartition is realized according to the repartition observed in the tracking studies. A correction of these values is also proposed based on the literature to take into account variations of the river discharge. The fish survival related to the turbines is than applied to the part of the stock passing through the plant. This enable to define the part of the stock passing the site safely to the next reach. This approach provides results in terms of fish survival in each structure, on each site, and globally downstream the whole studied area. It also enables to analyze the sensitivity of the global system response function of the expected effectiveness of local solutions for downstream migration such as turbine replacement, predictive models, behavioral barriers and downstream fish passes.

Keywords: Fish passage, hydraulic modelling, hydropower plant, fish attraction

1 INTRODUCTION

Downstream migration of threatened species such as Salmo Salar and Anguilla Anguilla are key for hydropower plant (HPP) manager as well as for river manager. In Belgium, these species are of main importance and dedicated programs (Saumon 2000 and Eel Management Plan for Belgium) have been initiated respectively since 1987 and 2007. Parallel, a European program (Life4Fish) has been recently initiated enabling to develop several solutions to facilitate the downstream passage of salmon smolts and silver eels along 6 hydropower plants of the Meuse River in Belgium.

In order to define the initial status of downstream migration of these two species, on-site studies have been performed. An acoustic fish tracking enabled to define the fish passages along the varied structures (sluices, dams, hydropower plants, fish ways, industrial water intakes) and the indirect mortality along the reaches in between these structures (Sonny et al 2018a, Roy et al 2017). An injection/recapture approach has also been planned on 3 sites to characterize the fish survival according to a direct passage through the varied turbine technology present along the studied area (Sonny et al 2018b). According to the results of these on-site studies and the stocks repartitions defined in the protection plans of the two species, this paper presents an integrative approach to define the migration status of both species in various scale (work scale, site scale, global scale).

2 STUDY AREA AND ANALYSIS SCALE

The study area extends to the entire Belgian lower Meuse from Namur to the border with the Netherlands downstream of Lixhe. The water intakes of the Tihange nuclear power plant and the Albert Canal are the exhaust limits of the study area. The confluence with the Mehaigne and the Ourthe are the entry limits of the study area. In particular, the 6 dams equipped with HPP present in this area are investigated.

This paper is based on the nomenclature developed in the framework of the Life4Fish program (De Oliveira et al 2018). In order to model the whole study area (Figure 1) to allow calculation of the various outputs (N_{out}), the stocks repartition (N_{in}) and the influence of both sites and reaches need to be defined.

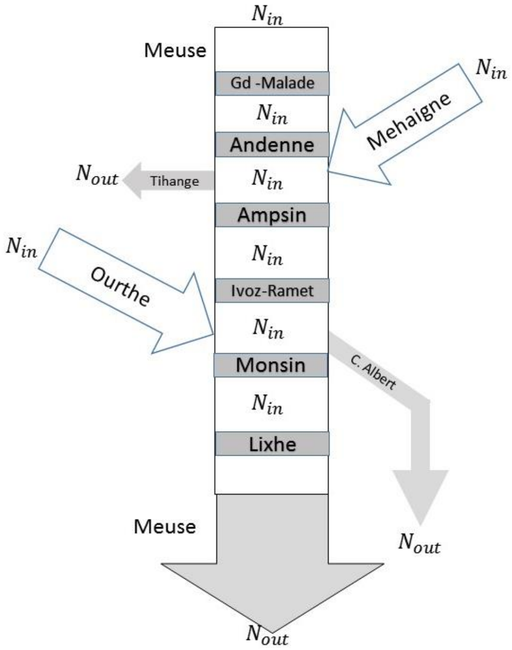

Figure 1. Schematic view of the study area (De Oliveira et al 2018)

3 STOCKS REPARTITION

The distribution of salmonid smolt stocks is carried out based on the Saumon 2000 program's reintroduction data. According to data transmitted by the SPW fishery service (X. Rollin – personal communication 2017), 48,288 wild smolt equivalents were reintroduced into the Ourthe-Amblève basin and 11.861 wild smolt equivalents were reintroduced to the tributaries of the Meuse upstream of Namur (mainly on the Lesse and the Samson). Making the hypothesis of equivalent impacts from reintroduction places to entry in our system, this study therefore considers:

- $N_{in\ upstream}$ = 20%
- $N_{in\ Ourthe}$ = 80%

The Eel Management Plan for Belgium (Vlietinck et al. 2007) gives assessment of the distribution by river basin of eels on the non-channeled streams of the watershed of the Belgian Meuse and an estimation of stocks on the channeled courses (Meuse, Sambre and Albert Canal). Based on the assumptions that the annual silvering rate is similar across the entire watershed (spatial repartition of yellow eels and silver eels are equivalent) and that the Meuse biomass is distributed homogeneously in proportion to the lengths of the reaches (conservative assumption because the stock is more important downstream (near the sea) than upstream), this study therefore consider:

- $N_{in\ upstream}$ = 37%
- $N_{in\ reach\ 1}$ = 9%
- $N_{in\ reach\ 2}$ = 11%
- $N_{in\ reach\ 3}$ = 9%
- $N_{in\ reach\ 4}$ = 11%
- $N_{in\ reach\ 5}$ = 8%
- $N_{in\ Mehaigne}$ = 2%
- $N_{in\ Ourthe}$ = 7%
- $N_{in\ downstream}$ = 1%
- $N_{in\ Albert\ Canal}$ = 5%

4 SITE INFLUENCE

4.1 Ways of passage

A downstream migration surveys of both species along the 6 sites of the study area have been performed during the 2017-2018 migration period. For salmon smolts, this survey (Roy et al 2018) gives the sites last detection schemes. These last detection profiles have than been former studied regarding the works opening and the capacity of detection of the probes at the passage time. This enable to clarify some of the undefined last detections and some of the inconsistent patterns observed. For the remaining undefined passages, there have been divided in between the opened works at the passage time. According to these assumptions the ways of passage on each site are shown in Table 1.

Table 1. Salmon smolts presence observed on each site and ways of passage considered.

Site	Grands-Malades	Andenne	Ampsin-Neuville	Ivoz-Ramet	Monsin	Lixhe
Upstream presence	55	38	15	14	7	12
Dam	17,5	0,5	0,33	0	0	6
Hydropower Plant	26	28,5	9,33	9,5	0	1
Sluice	1,5	3	2,33	2,5	-	-
Non crossing	10	6	3	2	7	5

For salmonid smolts, crossing rates vary greatly from one site to another. The same applies to the distribution between the crossing areas. However, we can distinguish three site classes:

- The sites of Grands-Malades, Andenne, Ampsin-Neuville and Ivoz-Ramet have a similar operation with a large number of crossings by the plant and some passages isolated by the other works. For these sites, the crossing rates are above 80%. The plant allows the passage of the site to the downstream.
- The site of Lixhe shows a different operation with a lower rate of crossings of the plant for the benefit of the dam. This element is linked to the presence of a permanent water leaf of minimum 10cm on the site of Lixhe. This training of fish to the dam decreases on these sites the direct impact of the plant but also increases the rate of non-crossing (probably due to the too weak water slides generated). The crossing rate falls under 60%. The plant no longer provides a preferential route, and downstream migration is therefore partially interrupted at the site level.
- Finally, on the site of Monsin, only 1 individual ventured into the water intake of the plant before going back to the Albert Canal. The remaining individuals stuck in front of the dam in closed position most of the time. The crossing rate for this site is zero creating a major obstacle to the descent of the species. However, low water discharge and low number of fishes observed on that site during the survey may influence these results.

The behaviour difference of the smolts upstream of the plants must be looked for in the approach conditions specific to each of the sites. At this stage of the study, we can only compare the conditions in the horizontal and vertical planes at the level of the water intake. In the horizontal plane, we note the presence of plunge beams (1 m below the surface) at the entrance of the inlet channel at the sites of Ivoz-Ramet and Monsin. 2D behavioural follow-up along the Ivoz-Ramet plunge beam showed that it was acting as a crossing delay to the plant but that all the fish crossed it after a period of research. It therefore does not seem at this stage to be able to explain the non-crossing of the Monsin plant. The position of the inlet channel of the plant at the upstream of the dam can also play a role. The distance between the entrance of the inlet and the dam is 30 m on the site of Ampsin-Neuville, 20 m on the site of Ivoz-Ramet and 110 m at Monsin. Monitoring of salmonid smolts has shown that, under observed monitoring conditions (low discharge), the fish first shows up at the dam. The entry into the inlet channel of the plant would therefore require a movement of the fish more or less important upstream. On the site of Monsin, this phenomenon seems to play an important role because only 1 fish has been detected within the water intake of the plant. This phenomenon is not present on other sites where fish are observed several times upstream of the plant. The depth of the water intake can finally play a significant role. Indeed, salmonid smolts are surface fishes usually moving within the upper 2 meters of the water column. The passage within the water intake of the plant therefore requires diving more or less deeply. At the sites of Monsin and

Ivoz-Ramet, the Kaplan turbine technology with vertical axis makes the water intake close to the upstream surface level. The depth of water intake is low, and the fish should practically not dive to pass within the plant. This behavior is confirmed in Ivoz-Ramet where there is very little research movement directly upstream of the turbines. For other sites, horizontal-axis turbine technologies make the water intake close to the downstream surface level. The depth of water intake is then even more important as the fall is important (4,85 m to Grands-Malades, 3,45 m to Andenne, 4,65m to Ampsin-Neuville and 5,65m to Lixhe). On these sites, the creation of a surface water flow at the dam can locally alter surface courantology in comparison to the main background courantology. This phenomenon allows to attract and maintain more smolts from the Lixhe and the Grands-Malades dams. However, it is therefore appropriate to provide these fish with an effective way of crossing in order to avoid attracting them to a no-escape route that would increase the rate of non-crossing.

For silver eels, the survey (Sonny et al 2018b) gives the sites last detection schemes. Regarding the works opening and the capacity of detection of the probes at the passage time enables to clarify some of the undefined last detections and some of the inconsistent patterns observed. For the remaining undefined passages, there have been divided in between the opened works at the passage time. According to these assumptions the ways of passage on each site are given in Table 2.

Table 2. Silver eels presence observed on each site and ways of passage considered.

Site	Grands-Malades	Andenne	Ampsin-Neuville	Ivoz-Ramet	Monsin	Lixhe
Upstream presence	45	47	54	94	89	83
Dam	24,5	38	42,5	59,33	58	81,5
Hydropower Plant	19,5	7	11,5	32,83	31	1,5
Sluice	1	2	0	1,83	-	-
Non crossing	0	0	0	0	0	0

For silver eels, the distribution between the crossing zones is fairly constant from one site to another. On the site of Grands-Malades, however, there is a greater presence at the plant compared to the other sites. Here we feel the influence of a drop zone close to the site during the survey. It is observed that 15% of the crossings take place before the first peak of migration, at lower discharges than the installed discharge (closed dam). On the other sites, less than 5% of the crossings are observed over the same period. At the Lixhe site, there is a very low rate of crossing by the plant. This can come from the operation with a permanent water slide of about 20 centimeters on the dam. Especially when the Meuse discharge is lower than the installed discharge of the plant. This can also be the result of site-specific hydrodynamic conditions. On this site we observe an important vortex upstream of the turbines.

4.2 Turbine influence

The impact rate of the HPP is deducted from field studies (Sonny et al. 2018a). For the sites of Grands-Malades and Andenne, the rates measured in these studies are considered directly. For the sites of Ampsin-Neuville and Lixhe which have configurations close to the other two sites with safer turbine characteristics, it is considered conservatively the most important impact measured on each species on the two tested sites. Finally, in the absence of results on the sites of Monsin and Ivoz-Ramet characterizing the impact of the large vertical Kaplan turbines, the rates of impact on each of the two species are arbitrarily determined. According to the larger size of the machines and the lower rotational speeds, the turbines can reasonably be expected to have smaller impacts than for the other groups. The proposed values therefore appear to be largely conservatives. These values will be adapted when in situ tests have been conducted (planned in December 2019 and January 2020).

Table 3. Turbines impact ratios considered in the site scale model.

Plant		Grands-Malades	Andenne	Ampsin-Neuville	Ivoz-Ramet	Monsin	Lixhe
Salmon smolts	Direct impact	**2,0%**	**6,7%**	6,7%	10%	10%	6,7%
	Moreover impact after 72h	**0,5%**	**0,6%**	0,6%	0%	0%	0,6%
Silver eels	Direct impact	**2,0%**	**0,7%**	2,0%	0%	0%	2,0%

	Moreover impact after 72h	**19,1%**	**10,6%**	19,1%	20%	20%	19,1%

4.3 Other ways influence

In a first approximation, the passages through the dam or the sluice are considered non-impacting for the downstream. In fact, studies have shown that significant impact rates can be observed mainly in terms of flow conditions within the structure and energy dissipation downstream from it (Larinier and Travade 1999). The determination of the specific impacts of each work requires a specific study of each of these which is outside the scope of the Life4Fish program.

4.4 Considered sites influence

According to the assumptions developed here before, the influence of each site is divided between turbines influence and non-crossing. In the global view, we consider thus the influence rates depicted in Table 4.

Table 4. Sites impact ratios considered in the global scale model.

Site		Grands-Malades	Andenne	Ampsin-Neuville	Ivoz-Ramet	Monsin	Lixhe
Salmon smolts	Non crossing	18%	16%	20%	14%	100%	42%
	Turbines	1%	5%	5%	7%	0%	1%
Silver eels	Non crossing	0%	0%	0%	0%	0%	0%
	Turbines	9%	2%	4%	7%	7%	0,4%

5 REACHES INFLUENCE

5.1 Reaches impact

An individual is considered to have crossed the reach if he is present both upstream and downstream. If the last detection of an individual is established at one of the water intakes (Tihange for reach 2 or Albert Canal for the reach 4), it will be categorized as non-crossing "water intake". In the case of individuals who have crossed the upstream site but are not present at the downstream site or a water intake, the number of individuals concerned will be compared to the expected impact rate of the upstream turbine crossing. These individuals will not be taken into account in the calculations of the crossing and impact rates at the reach scale as already considered at the site scale. Finally, fish present upstream and not falling into any of the above categories will be characterized from interrupted descent. The causes of migration interruption for these individuals within the reach can be:

- A decrease in swimming capacity after crossing the upstream site.
- A degraded state of health status and stress.
- Predation within the reach.
- A physiological stop of migration within the reach.

The Table 5 shows the number of fish present upstream, downstream the reach and at the water intake as well as the number of fishes expected to be impacted by the passage within the upstream turbines.

Table 5. Fishes presence observed along each reach.

Reach		CHG-CHA	CHA-CHN	CHN-CHR	CHR-CHM	CHM-CHL
Salmon smolts	Upstream	61	48	30	30	18
	Impacted by upstream site	0,65	2,08	0,68	0,95	0
	Water intake	-	7	-	11	-
	Downstream	38	15	14	4	12
Silver eels	Upstream	57	61	104	107	101
	Impacted by upstream site	4,11	0,79	2,43	6,57	6,2
	Water intake	-	5	-	8	-

	Downstream	47	53	94	89	83

5.2 Considered reaches influence

According to the assumptions developed here before, the influence of each site is divided between water intakes influence and non-crossing. In the global view, we consider thus the influence rates of Table 6.

Table 6. Reaches impact considered in the global scale model.

Reach		CHG-CHA	CHA-CHN	CHN-CHR	CHR-CHM	CHM-CHL
Salmon smolts	Water intake	-	15%	-	38%	-
	Non crossing	37%	52%	52%	48%	33%
Silver eels	Water intake	-	8%	-	8%	-
	Non crossing	11%	4%	7%	3%	12%

6 DOWNSTREAM MIGRATION CAPACITY ALONG THE STUDY AREA

6.1 Modelling method

According to the stocks repartition fishes are introduced in the model along each reach. The losses along the reaches are than evaluated according the loss percentages observed during the on-site fish tracking. On each site, composed by several structures (dam, sluice, hydropower plant, and/or industrial water intake), the fishes repartition is realized according to the repartition observed in the tracking studies. The fish survival related to the turbines is than applied to the part of the stock passing through the plant. This enable to define the part of the stock passing the site safely to the next reach. This approach provides results in terms of fish survival in each structure, on each site, and globally downstream the whole studied area. It also enables to analyze the sensitivity of the global system response function of the expected effectiveness of local solutions for downstream migration such as turbine replacement, predictive models, behavioral barriers and downstream fish passes.

6.2 Salmon smolts

Based on the distribution of stocks and the successive influence of the different elements, the percentage of the stock ending its migration within each element is defined (Figure 2). Thus 1% of the stock would end up impacted by the turbines. 17% of the stock would end up upstream of the sites (non-crossing). 1% of the stock would end up in the water intake of Tihange. 31% of the stock would end up in the Albert Canal. 50% of the stock would end up within the reaches. Finally, 0% of the stock would arrive downstream of Lixhe.

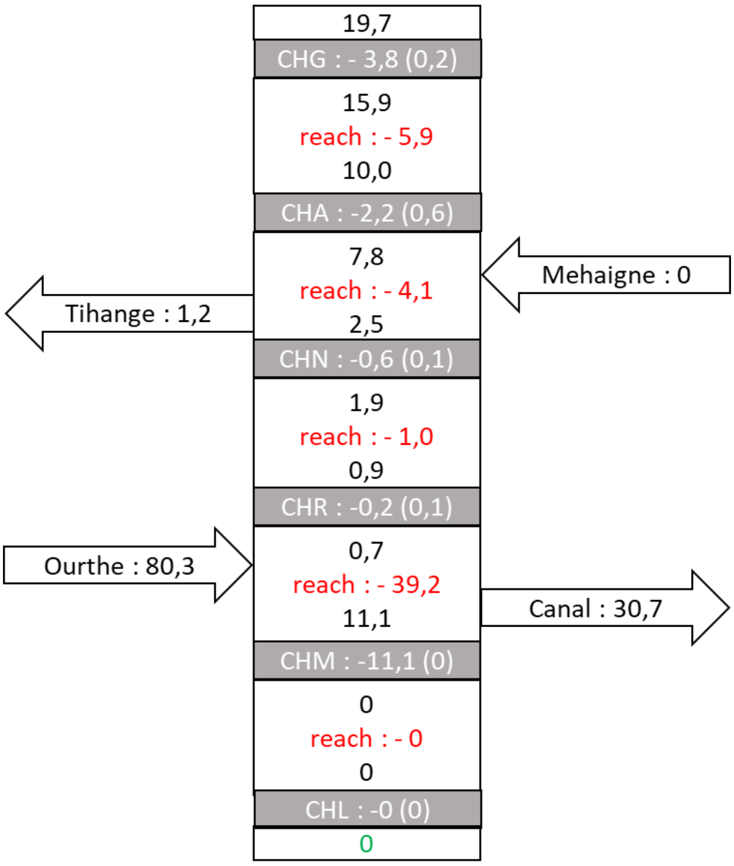

Figure 2. Repartition of salmon smolts passages within the study area.

If it is considered that for smolt only the downstream of Lixhe is a potential route of migration, 0% of the stock of the Belgian lower Meuse would have an assured escapement. The major impacts are the disappearances upstream of the site of Monsin (reach, water intake of the Albert Canal and non-crossing site of Monsin). These elements are all related to the management and distribution of flows within this particularly complex node. The extremely low flow conditions during the survey period necessitated equally special management conditions, the impact of which is felt on the results presented.

6.3 Silver eels

Based on the distribution of stocks and the successive influence of the different elements, the percentage of the stock ending its migration within each element is defined (Figure 3). Thus 13% of the stock would end up impacted by the turbines. 4% of the stock would end up in the water intake of Tihange. 10% of the stock would end up in the Albert Canal. 20% of the stock would end up within the reaches. Finally, 53% of the stock would arrive downstream of Lixhe.

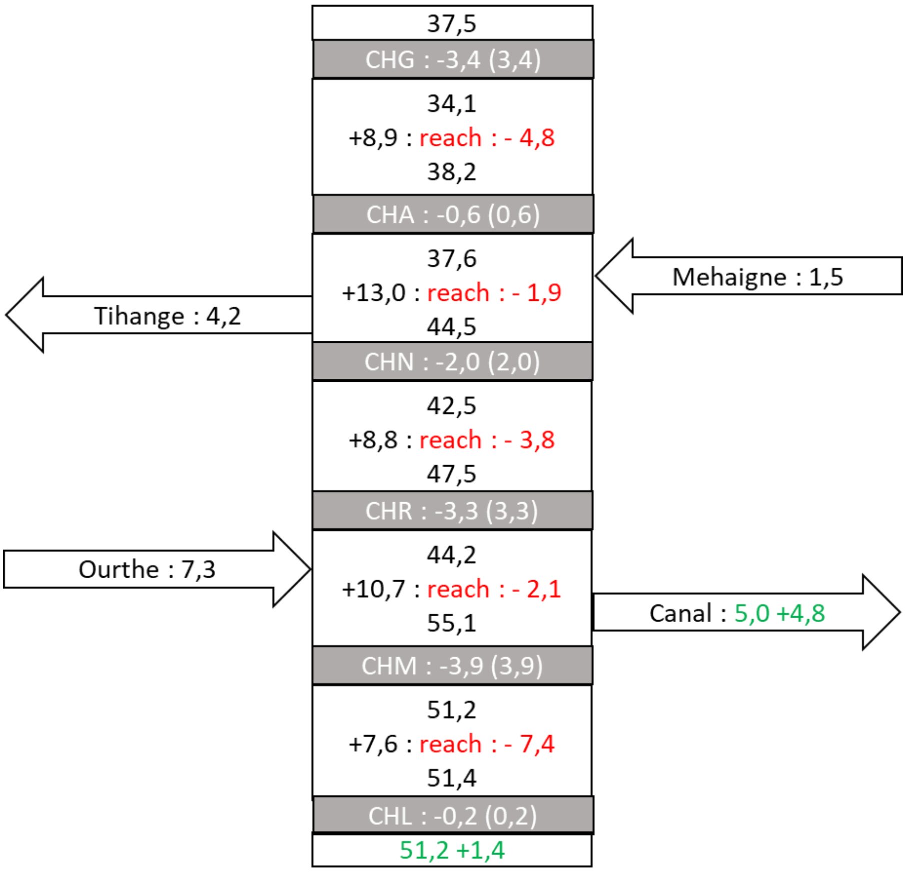

Figure 3. Repartition of silver eels passages within the study area.

If it is considered that for the eel, the downstream of Lixhe and the Albert Canal are potential routes of migration, 62% of the stock of the Belgian lower Meuse would have an assured escape to these routes of migration. The 20% of the stock remaining in the reaches may be partly made up of individuals still having the capacity to migrate during the next season. Only the overall impact of the plants and Tihange water intake allows to define a confirmed impact on the migration of 18% of the stock of silver eels.

7 CONCLUSION

In order to determine the biological status of downstream migration of Salmo Salar and Anguilla Anguilla along the low Belgian Meuse, a multi scale model has been developed. Based on field surveys (injection/recapture in plants, fish tracking along reaches and sites), impact ratios have been calculated both at site scale and reach scale. These ratios are then included in a global scale model taking into account the stocks repartition along the study area and from its main tributaries. The stocks are then corrected from upstream to downstream applying respectively the sites and reaches impact ratios.

This approach enables to highlight the threatened status of salmon smolts in the particularly dry conditions observed during the on-site survey. However, it also enables to mitigate the relatively low impact of the HPP turbines (1% of the global stock) compared to the ones related to the sites (17% of the global stock non crossing), the reaches (50% of the global stock non crossing) and the water intakes (32% of the global stock). The situation is largely better for silver eels as 63% of safe escapement is observed. The remaining impacts are distributed between the reaches (20% of the global stock), the HPP turbines (13% of the global stock) and the Tihange water intake (4% of the global stock).

The definition of these initial status enabled to redefine the goals of the Life4Fish program to decrease the common influence of sites and HPP turbines under a total value of 10% for both species.

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