Optimizing downstream migration of Atlantic salmon smolts at Mery site

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Optimizing downstream migration of Atlantic salmon smolts at Mery site

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Résumé

La dévalaison des smolts de saumon atlantique est entravée par diverses constructions utilisées principalement pour la production d'électricité ou à des fins de navigation dans les cours d'eau. Cette thèse contribue à l'optimisation de la dévalaison des smolts de saumon atlantique à un site de production d'énergie hydroélectrique à Mery, Belgique, en utilisant un modèle numérique du site et en réalisant différentes simulations. Le chapitre 1 propose une introduction à la thématique de dévalaison et donne un aperçu de la procédure de travail. Le chapitre 2 évoque l'état de l'art sur le comportement des smolts, des paramètres hydrodynamiques favorisant la migration et donne un aperçu des recherches effectuées sur la migration des smolts à ce site précis. Le chapitre 3 décrit le site ainsi que le modèle numérique utilisé pour cette thèse et accentue les problèmes rencontrés à Mery par rapport à la dévalaison des smolts. Le chapitre 4 présente les résultats des différentes étapes de simulation à partir d'une analyse de base sur l'influence de l'ouverture des incisions et l'exécution de différentes constructions hydrauliques comme des guides de flux ou des changements topographiques. Différentes combinaison de constructions avec différentes combinaison des incisions sont ensuite testées. Enfin, une comparaison des 3 combinaisons les plus performantes sous 3 scénarios de débit différents est donnée. Ce chapitre aborde également d'autres points à considérer pour l'optimisation d'un site de production hydroélectrique pour la dévalaison. Finalement le chapitre 5 conclut l'ensemble des observations faites, propose des solutions pour améliorer le comportement migratoire vers l'aval et mentionne des perspectives d'amélioration. La meilleure des méthodes en termes de paramètres hydrauliques favorisant la migration des smolts vers l'aval est un déplacement du chenal. La meilleure méthode globale pour le site de Mery est la construction d'un grillage a bars à l'entrée du canal d'admission de la turbine Kaplan combinée avec une incision profonde à côté qui fonctionne comme un bypass.

Summary

Downstream migration of Atlantic salmon smolts is obstructed by various constructions present in rivers used mainly for electricity production or shipping purposes. This thesis contributes on optimisation of Atlantic salmon smolt downstream migration at a hydropower facility at Mery, Belgium, using a numerical model of the site and performing different simulations. Chapter 1 provides an introduction into the thematic of downstream migration and gives an overview on the working procedure. Chapter 2 highlights state of the art knowledge about smolt behavior, the hydrodynamic parameters favoring migration and gives an overview of researches done on migration of smolts at this specific site. Chapter 3 describes the site and the numerical model used for this thesis and accentuates the problems encountered at Mery for downstream migration of smolts. Chapter 4 presents the results of different simulation steps from a basic analysis on the influence of incision openings and the execution of different hydraulic constructions as flow guides or topographic changes. To the simulation of different combinations of hydraulic constructions and incisions opening combos. And finally gives a comparison of the 3 best performing combinations under 3 different discharge scenarios. This chapter also discusses additional points to consider for the optimization of a hydropower production site. Ultimately chapter 5 gives a conclusion of all the observations made, proposes solutions to ameliorate downstream migration behavior on other sites and mentions prospects for improvements. The best performing method in terms of hydraulic parameters favoring downstream smolt migration is a channel displacement. While the best overall method for the Mery site is the construction of a bar rack at the entrance of the intake channel from the Kaplan turbine combined with a deep incision next to it working as a bypass.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1 General Introduction

Nowadays a major problem for upstream and downstream migration of aquatic animals are the heavily modified rivers, these consist of barriers and the modification of riverbeds. The barriers to free migration mainly consist of weirs and dams that were constructed for water storage, to increase water depth for navigation and also for hydro power production.

Some species need the possibility to travel from the sea upstream the rivers to reach adequate spawning territories to reproduce. The offspring then needs to head downstream to reach the sea in order to grow and years later they come back upstream when they are ready to reproduce themselves. The most famous of these species is likely the salmon. Certain other species have a similar life cycle, while others have opposite reproducing/development territories. They need to reproduce in salt water and mainly live in the rivers throughout their lifespan, the most known species of this kind is the eel. On top of these animals that travel from salt water to fresh water or vice-versa during their life cycle, there are a lot of species that travel to different types of river sections during their life. For all of these aquatic creatures it is crucial that they can pass-by the enormous amount of barriers that are built by the human being. The intervention of humans in these natural habitats resulted in the extinction of several species such as the Atlantic salmon in most of the European rivers.

During the last few decades a lot of effort was done in research and on-field to improve the upstream migration of fishes and aquatic insects. This resulted in the fact that nowadays there exist efficient fish passes and research material that allows us to have a good understanding of upstream migration behavior and the corresponding needs of different types of aquatic animals. This leads us to the point that we can rebuild the modifications built inside the rivers to ensure a flawless upstream migration. But contrary to these efforts only little research and effort was made to improve downstream migration. As for downstream migration fish can jump down the weir or pass through the turbines, the focus was more on how to let them reach areas upstream of barriers. But to reduce the overall influence of human made obstacles today the efforts to improve downstream migration gets more focus too. Due to the structure and position of fish passes for upstream migration they are not suitable for downstream migration. During the last years research focused on fish behavior for downstream migration, on fish-friendly routes through barriers and also on fish-friendly turbines for electricity production.

This thesis focuses on the optimization of downstream migration of Atlantic smolts at an existing site for hydro power production, basic behavior tests have been carried out in cooperation of different partners to understand the choice of route that fish take. These researches combined with general researches on downstream migration behavior of Atlantic salmon smolts are the base of this analysis of optimisation. Furthermore, different researches on the various component of the site have been considered to evaluate the effectiveness of the site.

2 Working procedure

To accomplish this task a certain working procedure has been established. The procedure used in this research focuses on gathering information on the migration behavior of Atlantic salmon smolt, then to define hydrodynamic parameters from those researches. Thereafter the problems from the site are defined and next some basic changes to the site are simulated. These solutions are then combined to get better hydrodynamic parameters for smolt migration. The following list gives a small overview about the different steps:

- Research
- Define Parameters
- Identifying on site problems
- Basic solutions simulation
- Combining
- Fine scale analysis of final solutions

2.1 Research

In order to fulfill the task of optimizing the downstream migration of smolts at Mery site, a good basic research is key to gain enough knowledge about the different parts of the weir, their functionalities and most important the correspondence of fish on obstacles in their migration behavior. As fish don't choose the route they use to pass by coincidence, the hydrodynamic parameters that favor their migration have to be known. Then a good knowledge of the different parts of the site to optimize is needed and the possibility of fish to pass them. The Mery site is composed of 2 Kaplan turbines, a bypass, a weir with 4 incisions, an Archimedes screw and a fish pass.

Complementing the researches that helped to choose the crucial site parts for downstream migration, a lot of the collected researches for specific parts focused on how to improve the effectiveness of each part. This can help at the last step to optimize specific parts of the site and to give further advice.

2.2 Define parameters

As basic research for this specific project 2 papers exist with on site fish-counting of salmon smolts analysing their downstream migration behavior. Other research provides information on how salmon smolts choose the most convenient migration route. There are a lot of different hydrodynamic parameters to consider evoked in numerous research papers and the most important are chosen to be investigated during this researches simulations:

- Main flow
- Flow velocity
- Water depth

2.3 Identifying on site problems

As fish guidance parameters are understood, the next part is to define which parts of the structure are safe for fish migration. To define safe routes the mortality and damage of possible routes have to be analyzed if data of this kind is available.

Next step is to identify the problematic parts of the structure, this site only has one potential mortal passing route which is the Kaplan turbine. The main flow direction and velocities favor the passage through this route which is the biggest problem encountered. The safe routes for passage is the Archimedes screw, the fish pass and the weir. As the weir does not cause mortal damages to fish but it can only harm the fish in cases where there is not enough water depth. With the research that was done on site for low and medium discharge the fish tend to use the Kaplan turbine only for high discharge the main flow leads the fish more towards the weir. This means that actions have to be made to lead the fish away from the intake channel of the Kaplan turbines towards the Archimedes screw or the weir.

The most crucial factors evoked in different researches to give appropriate routes are fish mortality/damage during passing specific installations, water velocity, change of velocity, discharge, light and noise. With this information different possible solutions could be worked out. Since for this specific site the most used ways could be identified with the help of the 2 papers we could reduce possible mitigation routes to these 4:

- Kaplan turbines
- Bypass
- Weir
- Archimedes screw

With this information, different possibilities of changing the site configuration can be imagined and tested.

2.4 Basic solution simulation

First simulations are all performed with the same discharge in order to simulate different configurations at a smaller time frame and to identify the effectiveness of each configuration. During this stage the only focused parameter is the discharge and its distribution because the main flow is the most crucial parameter that guides fish in their migration behavior, as explained in following section. In this study this leads to the testing of the influence on the flow distribution due to the opening of the individual incisions, the construction of flow control structures and changes in riverbed topography.

2.5 Combining solutions

Next the most efficient solutions can be combined, in a way to enhance their performance to guide the flow towards the wanted direction. Therefore the best performing methods of flow guide construction and the best performing change on the riverbed are combined with different incision openings.

2.6 Fine scale analysis of final solutions

From the best performing configurations 3 are tested with different discharge events to ensure that they perform well under different hydrologic situations and to check if the rest of the defined parameters that favor fish migration behavior are respected too. To choose the best final solution a checklist can be made comparing the different solutions to see their strong points and weaknesses in direct comparison.

Chapter 2

State of the art

1 Understanding smolt behavior

1.1 Atlantic Salmon

Atlantic salmon, with the latin name Salmo salar (Genus species) is classified in the family of Salmonidae. They belong to the anadromous species because they can survive in fresh and salt water, unlike their pacific brothers they are an iteroparous species which means that they migrate back to the ocean after reproduction and they can repeat this behavior several times during their lifespan. The total lifespan is about 3 to 7 years, the oldest documented fish was 13 years old. They can grow up to 1,5 [m] with a weight of 47,6 [kg] which is the biggest specimen ever documented, average size is 70 - 76 [cm] and average weight is 2,7 - 5,4 [kg]. They are the only salmon species native in the Atlantic Ocean divided in 3 main groups with North-American, European and Baltic origin. A form of Atlantic salmon that is landlocked, which means that they never migrate to the ocean, exists too. Population varies greatly from several individuals to thousands depending on the river system, with a global trend in declining population regardless of the efforts to maintain the populations. For reproduction they migrate upstream to their native river, which makes the possibility for free migration down and upstream so important. If this behavior is blocked due to dams, this results in the extinction of the species in some areas. Female Atlantic salmon can lay up to 7000 eggs depending on their size. (https://www.marine.ie/site-area/areas-activity/fisheries-ecosystems/salmon-life-cycle?language=en)

1.2 Atlantic Salmon life cycle

The life cycle begins as an egg, depending on water temperature the development time changes. As alevins, freshly hatched salmon, they can not withstand high water velocities, when they have absorbed their yolk sac they are developed into fry which can withstand and maintain their position in faster flowing water. During autumn they develop into Parr's where they begin to eat water insects while maintaining their position. At an age between 1-3 year(s) their coloration will fade and they begin to migrate downstream, at this stage they are called smolts. Smolts have an average length of 10 - 25 [cm] when they begin to migrate. After one year at sea they are completely grown adult salmon and begin to return for reproduction depending on their size and weight. After reproduction they are called Kelts, they are now vulnerable to diseases and predators. Only specimen that are fit and strong enough, migrate back to the ocean, and begin their cycle again. The whole procedure is summed up on the figure B.1.

1.3 Migration behavior

This study focuses only on smolts. To understand their migrating behavior it is important to know how they migrate, to do so a few things have to be explained:

- Rheotaxis
- Swimming speed
- Day/nighttime movement
- Exploring behavior
- Migration triggers
- Thrust force
- Mortality

The aforementioned parameters help to understand the migration behavior which consists of fine scale relations between the turbulent hydraulic environment, the sensory function of fish, their bio-mechanic and behavior of individual fish and fish schools. All those play a role to guide the smolts towards the right migration path (Silva et al., 2017).

1.3.1 Rheotaxis

Rheotaxis describes the direction in which a fish is looking while swimming. There are 2 kinds of rheotaxis, positive and negative. Negative rheotaxis describes the state in which a fish swims with the flow thus has his head directed downstream, while in positive rheotaxis the fish has his head directed upstream and therefore is swimming actively against the flow. Fish that group in schools often swim with the same rheotaxis (Haro et al., 1998).

When fish realise intensification of hydraulic conditions they swim in positive rheotaxis and swim actively against the flow to increase their ability to react quick, which is often the case when they approach turbines, a bypass or other hydraulic structures that increase the water velocity and turbulence (Jebria et al, 2021).

In positive rheotaxis fish also maintain their position better but when the flow acceleration passes by their ability to maintain position they change into negative rheotaxis. While passing over a weir fish were observed to maintain positive rheotaxis (Haro et al., 1998).

1.3.2 Swimming speed

Swimming speed of smolts can be classed in 3 different states as sustained, prolounged and burst swimming speed. Swimming speed can be approximated by:

- Sustained: $2,6 * BL(bodylength)/s$ which results in $0,38[m/s]$ for smolts
- Prolounged: $2,5 - 4,5 * BL/s$ which results in $0,5[m/s]$ for smolts
- Burst: $5,0 * BL/s$ which results in $1[m/s]$ for smolts

When following the main current smolts usually swim below or with sustained swimming speed, when swimming away from the main current they usually swim with a prolounged or higher speed even exceeding burst swimming speed. While swimming in positive rheotaxis in front of a bypass smolts were observed to exceed their burst swimming speed (Silva et al., 2020). In general smolts swim faster to get away from high or average velocity and turbulence.

Renardy et al. (2020) observed a median swimming speed of $0,38[m/s]$, a minimal median swimming speed of $0,16[m/s]$ and a maximal median swimming speed of $0,52[m/s]$ for smolts. Another observation was that there was no change in swimming speed observed after passing a migration pass, but this statement was contrary to observations made by Havn et al. (2017), for fish passing an Archimedes screw.

Another factor influencing swimming speed is 3 dimensional velocity direction, vertical flow has a high effect on swimming speed as with upwards water velocity, same TKE and a direction away from the flow lower speed was observed compared to a predominant downwards water velocity. Transverse velocities higher then $> 0,5[m/s] + sustainswimmingspeed$ force fish to use their burst swimming speed in order to avoid unpredictable flow and velocities (Silva et al, 2020).

The maximal water velocity to which fish could escape using burst swimming speeds was observed at $2m/s$, while they tend to use the burst swimming speed already for velocities of $1[m/s]$ (Havn et al, 2019). Migration speed increases in general with water discharge increase (Havn et al, 2017).

When fish swim with positive rheotaxis with the main flow this is called drift, hydrodynamic parameters that favor drift are a velocity $> 0,2[m/s]$, an acceleration of $3 * 10^{-4} m/s^2]$ and a TKE of $> 8 * 10^{-5}[m^2/s^2]$ (Jebria et al., 2021).

1.3.3 Day/nighttime movement

It is not very clear if there is a correlation of downstream migration and day or night time. Karpinnen et al. (2021), stated that when smolts migration is delayed due to obstacles they tend to migrate at dusk or during the night for different water flows. Renardy et al. (2020) observed a preference for migration before dusk, but most research observed a preference for nighttime migration (Haro et al, 1998; Renardy et al., 2021; Kärgenberg et al., 2020; Karppinen et al., 2021).

Tétard et al. (2021), observed that for high flow conditions $> 30[m^3/s]$ fish migrated most during night $43,4\%$ and dusk $37,9\%$, while for low flow conditions most fish migrated at night $74,6\%$.

While there exist a general favor for nighttime migration, when the migration period comes to an end the daytime migration willingness increases (McCormick et al., 1998).

1.3.4 Exploring behavior

When approaching a barrier fish can express different behavior, in total there exist 2 main types of explorer which are characterized by the approach, exploration of the different migration routes and the time required.

The first category consist of fish that show an exploratory behavior, these are called explorers. This category can be divided into another 2 types, there are proactive explorers which explore the different migration possibilities and then choose their final pass with a short decision time. The second type is called reactive explorers, these also explore different migration routes but with a significantly higher decision time to choose the optimal migration pass.

The second category consists of non-explorers, fish showing this research behavior only approach a single migration route. Again there exist 2 types of non-explorers, proactive non-explorers need a short decision time while reactive non-explorers need more time to decide if the approached route is safe for migration (Renardy et al. 2022, 1; Renardy et al. 2022, 2).

Renardy et al. (2020), observed a median research time of $0,58[h]$ for the radio tagged smolts at the Mery site.

Jebria et al. (2021), observed some hydrodynamic parameters that define the exploring behavior. For flow velocities of $0.12[m/s] - 0,3[m/s]$ proactive explorers needed an average time of $5 - 13[min]$ in their study. He also observed that fish exploring the reservoir of Putès were most of the time in a burst state which will be explained below.

1.3.5 Migration triggers

As main migration trigger the water temperature is defined in most researches (Haraldstad et al., 2018; McCormick et al, 2015). The trigger is set when water temperature in the swimming layer reaches ocean temperature (Havn et al., 2017) more activity was observed when the temperature exceeded $10[°C]$ (Karppinen et al., 2021).

1.3.6 Thrust force

Jebria et al. (2021), defines thrust force as how fish respond to what they encounter in order to be ready to escape. 3 different states of behavior were described based on thrust force, passive, endurance and burst. Passive means that fish swim with the flow. Endurance means that fish swim not with the flow but lower then their maximal sustained speed. Burst state is reached when fish swim faster then their sustain swimming speed. Thus they can be longer in a burst speed as they can swim with burst speed because they are considered in a burst state while swimming with prolounged speed. For low conditions his observations showed that fish tend to swim in positive rheotaxis with varied direction, for intermediate conditions smolts are swimming with a negative rheotaxis, while for higher conditions fish tend to drift with negative rheotaxis but lower thrust. For very low hydraulic conditions 61[%] and for low conditions 58[%] of smolts are observed in burst state. While for medium conditions 57[%] swam at endurance swimming speeds and for high hydraulic conditions 69[%] were swimming in an endurance state. This behavior expresses that they increase their ability to escape from danger.

1.3.7 Mortality

Most fish die due to two different reasons, due to predation or due to turbines. Higher mortality is observed due to predation in general, as in low flow condition zones fish are subjected under high predation pression from other fish like pikes or from birds like cormorant (Fjelstad et al., 2018). Renardy et al. (2021), observed mortality due to predation as up to $1/3$ $36,8[\%]$ of the released fish during their research. Thus water zones with low flow conditions need to be avoided.

Karppinen et al. (2021), observed mortality rates as $0-50\%$ in fore-bay's, $4-64[\%]$ during the passage and $2-30[\%]$ after the passage due to exhaustion and damages increasing their susceptibility for predation.

For Kaplan turbines, Kärgenberg et al. (2020), observed a mortality of 38[%], generally the mortality for Kaplan turbines is estimated at $0-30[\%]$, depending on the size of the blades and the turning speed.

2 Hydrodynamic parameters favoring migration

Understanding fish behavior is key to optimize the site. To ensure that the salmon smolts find the safest route for downstream migration hydrodynamic parameters have to be established to guide them towards the corresponding part of the site. The behavior of fish is described in numerous research, although the parametric description of downstream fish migration behavior coupled to hydrodynamics is still in research and not a lot of conclusions have been established and validated.

As of now the overall literature divides downstream (and upstream) migration behavior in 2 categories, large scale an fine scale behavior. Large scale behavior is dictated by the main flow, which corresponds to the main discharge. Karppinen et al. (2021), observed that the fish tend to migrate in the upper water layer following the main flow. Renardy et al. (2020), stated that this behavior is to reduce energy costs while travelling.

Silva et al. (2020), observed that fish follow the main flow to some extent. In this specific article it was observed that they followed the main flow regarding which bank site they were released, as 2 main flows were present at that river. It showed that fine scale behavior is defined through kinematics of the water where water velocity, acceleration, angular difference, spatial/temporal variation which are detected by the mechanosensory system of fish. These parameters play a role on the fish's rheotaxis or swimming speed and can cause fatigue or disorientation. For regions with high TKE fish were detected in a burst swimming state. As explained above TKE and 3 dimensional velocities affect the swimming speed directly.

Silva et al. (2017), showed that the shape of the weir can reduce flow acceleration.

Jebria et al. (2021), stated that migrating smolts tend avoid areas with high acceleration and on the other hand are attracted by regions of low turbulence, low velocity and low acceleration. But the velocity itself cannot be too small as this can cause disorientation, thus for a good orientation a minimum of $0,2[m/s]$ is needed.

In a research done by Szabo-Meszaros et al. (2019), smolts following the main flow tend to swim to the intake of the turbines if the discharge is high and to dam when more gates are opened, which underlines the observation that fish tend to follow the main flow. Again there were 2 main flows in the river and again the fish tended to follow the main flow which was on the same side as on which they were released. Another statement was that fish avoid regions of recirculation and with low velocity.

Xinya et al. (2018), observed that salmon mainly swam in a water depth of $50[\%]$ of the total water column but also that this did not interfere much with their final chosen migration route.

Haro et al. (1998), investigated the effect of water acceleration and concluded that smolts avoid passing over sharp crested weirs. Another observation made is that it is favorable to reduce the velocity gradient in front of bypass and by creating a larger transition zone positive effects are observed for maintaining schools and increasing the overall acceptance of a bypass.

Enders et al. (2012), investigated migration behavior for Chinook salmons which is a close relative of Atlantic salmon. They also detect velocity changes through their mechanosensory lateral line and can detect changes of $0,4-1[cm/s]$. They avoid acceleration zones because a decrease leads due to migration delay and an increase can cause physical injury. The study also defined the maximal velocity gradient for Salmo salar at $1[m/s/m]$.

Renardy et al. (2021), defined the minimal velocity that favors migration with $0,15[m/s]$, although to avoid disorientation it is better if the velocity is $0,2[m/s]$.

Kärgenberg et al. (2020), was the only research paper that described that Atlantic salmon smolts don't follow the main flow. This is due to trash rack installed with a bar spacing of $25[mm]$. Bigger smolts tend to use the fish-way as downstream migration routes when lower discharge conditions prevail (Havn et al., 2021, states the same), while smaller individuals still tend to use the turbine.

The summary of the parameters defining migration behavior of Atlantic salmon smolts are represented in the following tables.

Source	Discharge [m^3/s]
Renardy et al. (2022, 1)	main flow (highest discharge)
Renardy et al. (2020)	main flow (highest discharge)
Fjelstad et al. (2018)	main flow (highest discharge)
Larinier et al. (2002)	main flow (highest discharge)
Silva et al. (2020)	main flow (highest discharge)
Szabo-Meszaros et al. (2019)	main flow (highest discharge)
TLUG (2011)	proportional to flow distribution
LUBW (2007)	main flow (highest discharge)
Renardy et al. (2021)	main flow (highest discharge)
Karppinen et al. (2021)	main flow (highest discharge)
Kärgenberg et al. (2020)	not with main flow
Havn et al. (2017)	main flow (highest discharge)
Haraldstad et al. (2018)	main flow (highest discharge)
Conclusion	**main flow (highest discharge)**

Table 2.1: Large scale migration parameters

Table 2.1 summarizes the large scale behavior defined in numerous research articles and construction guides. It shows that the research standard for large scale migration behavior is that the main flow is the most crucial factor. The German construction guide from the TLUG (2011), stated that it can be assumed that the distribution of fish is equivalent to the discharge distribution. In the research of Kärgenberg et al. (2020), where the fish did not follow the main discharge towards the turbine, a bar rack prevented the fish to follow the main flow.

Source	Velocity [m/s]			Water depth [m]	
	min	max	max infront rack	min	max
Renardy et al. (2022, 1)	0,2	0,5		0,2	2,5
Fjelstad et al. (2018)			0,5		
Larinier et al. (2002)			0,5		
Schweizerische Eidgenossenschaft			0,5		
Jebria et al. (2021)	0,2				
Szabo-Meszaros et al. (2019)		1			
Xinyaet al. (2018)				50 percent of column	
Haro et al. (1998)		1			
Enders et al. (2012)		1			
Renardy et al. (2021)	0,2				
Machiels et al. (2019)	0,5	1	0,5		
Range favoring migration	**0,2**	**1**	**0,5**	**0,2**	**2,5**

Table 2.2: Fine scale migration parameters analysed in this research

Fine scale behavior parameters are represented in table 2.2. A general observation is that a lot less researches defined specific values regarding these parameters. For the velocity favoring migration the range can be defined through the different researches as there is a correlation between the results of the individual papers. The water depth on the other hand is a parameter that is not described in a lot of researches, the values from the research of Renardy et al. (2022, 1), are the only quantitative values where water depth for Atlantic salmon is described. Although it has to be mentioned that the maximal water depth is not significantly higher on the site compared to the maximal depth where fish were detected from Renardy et al. (2022, 1), therefore the maximal value is not significant. Another point is that Karpinnen et al. (2021), stated that they swim in the upper layer most of the time. Therefore the minimal value is considered in this research but not the maximal water depth.

Source	Acceleration [m/s^2]		TKE [m^2/s^2]			Bypass to Turbine Discharge [%]		
	min	max	min	max	average	min	max	average
Fjelstad et al. (2018)		1						
Larinier et al. (2002)						5	10	7,5
Silva et al. (2020)				0,03		2	10	6
Jebria et al. (2021)	0	0,007	0		0,0028			7,1
Tétard et al. (2021)								7,1
Haraldstad et al. (2018)						6,7		
Average	**0**	**0,5035**	**0**	**0,03**		**4,57**	**10**	**6,93**

Table 2.3: Fine scale migration parameters for additional investigations

Table 2.3 sums up additional parameters that define fine scale downstream migration behavior. These acceleration and turbulent kinetic energy parameters are not investigated in this research as there is not enough correlation between the different values and they need to be investigated further before considering them. The bypass to turbine ratio is not investigated because the bypass is not included into the model.

3 Mery site migration researches

As fundamental data for the current state of smolt migration at Mery site, 2 papers documented the migration behavior of salmon smolts.

3.1 Renardy et al. (2019)

The first document, Renardy et al. (2019), aimed to analyse the effectiveness of the bypass and to quantify if the Archimedes screw can be considered as an attractive alternative for migration compared to the Kaplan turbines. The downstream migration of individual smolts was tracked using radio and RFID (Radio Frequency Identification) telemetry. This paper focused on the behavior influence of water temperature, discharge, research time, time of passing and fish body length. The smolts were released in 4 groups with a total of 17 individuals (Group 1 - 2, Group 2 - 4, Group 3 - 5, Group 4 - 4), the migration behavior compared to discharge is shown in table 2.4. The percentual distribution regarding the first approached route and the final chosen migration route is shown on table 2.5:

			Used migration route							
	Discharge	Total nbr of fishes	Weir		Archimedes screw		Bypass		Kaplan	
Release goup	[m^3/s]	[/]	[/]	[%]	[/]	[%]	[/]	[%]	[/]	[%]
1	35-40	2	2	100	0	0	0	0	0	0
2	20-25	4	1	25	1	25	1	25	1	25
3	15-20	5	0	0	1	20	4	80	0	0
4	15-20	4	0	0	0	0	2	50	2	40

Table 2.4: Migration route used per release group and discharge

	Smolt migration behavior	
	First Arrival	Used route
Migration route	[%]	[%]
Bypass	35,3	41,2
Kaplan		17,6
Weir	29,4	17,6
Archimedes	23,5	11,8
Incision	0	0
Not defined	11,8	11,8

Table 2.5: First approached route and final used route distribution from Renardy et al. (2019) research at Mery site

It shows that the fish tend to arrive in the intake channel of the Kaplan turbines/bypass and the most favored migration route is the bypass. None of the smolts passed through or first approached the new incision gate, although 2 of the fishes that used the Archimedes screw as final route were located at the new incision gate just before.

From the smolts that approached first the bypass all except one chose the bypass as final migration route the other one passed through the Kaplan turbine. Another observation made is that the smolts which approached first the bypass, were those with the fastest passing behavior with only one fish that had a research time over an hour regardless of the period of the day. This may be because the main flow is directed to this area or because of the placement of the Kaplan turbines/bypass on the lowest part of the site.

The Archimedes screw was used only from $11,8[\%]$ from the smolts which is less then half of the fishes which first approached this route. The bad acceptance of this route may come due to different factors like the bad placement of the turbine and also due to a lot of noise.

The weir was used as much as the Kaplan turbine but it was used only for high discharges (>20 $[m^3/s]$), as the main flow for high discharge scenarios passes over the weir. The passage time varied greatly 2 of the 3 fish that used this route passed in 4 and 11 minutes but they did not approach any other route, the third fish that passed above the weir needed more then 20 hours of research time and it first approached the Archimedes screw.

The new incision gate therefore was not used at all which showed that the influence for fish passage may be contested although as stated above that it can help to guide the smolts to a certain direction.

3.2 Renardy et al. (2022, 1)

The second paper relative to the site at Mery, Renardy et al. (2022, 1,) focused on understanding the downstream migration behavior of Atlantic salmon smolts. It described different behavioral tactics as described before at the section of smolt behavior and used hydrodynamic modeling in order to determine hydraulic parameters to guide fishes in their choice of a downstream migration route. For this research 6 groups of 6 smolts were released, they were located with an implanted radio transmitter. The migration route choice is shown in table 2.6 below:

	Smolt migration behavior	
	First Arrival	Used route
Migration route	[%]	[%]
Bypass	87	18
Kaplan		36
Weir		41
Archimedes	13	5
Incision	0	0

Table 2.6: First approached route and final used route distribution from Utashi et al. research at Mery site

It shows that most smolts followed the main flow and arrived first at the lower part of the weir or in the intake channel leading to the Kaplan turbine and the bypass. Only 13[%] first arrived near the Archimedes screw.

As final migration route most smolts tend to use the weir with 41[%]. Second most used route was the Kaplan turbine with 36[%] followed by the bypass with only 18[%] of use. The Archimedes screw was used by only 5[%] of the smolts as migration route.

What can be highlighted here is that only half of the smolts that first attempted the screw also passed over it which again shows that the fish might be suspicious about this route. Another point is that in this study the attraction to pass through the turbine instead of the bypass is double as high, which leads to the conclusion that the bypass has to be optimized because it's not working properly in terms of attraction.

This paper also showed that only 16[%] of the smolts passed directly and $84,4$[%] were hesitant in the choice of an optimal migration route. 28[%] of the hesitant fish approached all 4 routes and $68,8$[%] of the hesitant fishes approached the same route several times, the hesitant behavior was higher with low discharge.

Chapter 3

Site & Model description

1 Site Description

The site to optimize is situated in Mery, Belgium. It is used as a hydro-power production facility, in the river Ourthe (figures 3.1 & 3.2). The river Ourthe has 2 sources which are located in the east of Belgium in the province of Luxembourg at Libramont-Chevigny and Ourthe-Deiffelt-Beho, the two sources confluence at the border of the municipalities of La-Roche-En-Ardenne and Houffalize which is located in the reservoir of Nisramont. The total length of the river Ourthe is $181,2[km]$ and has a catchment area of $3624[km^2]$, it has 3 affluents called Aisne, Amblève and Vesdre. The Ourthe river discharges into the river Meuse at Liège. The Meuse has a total length of $874[km]$ and a catchment area of $33.000[km^2]$. Its source is located in France and it discharges into the north sea in the Netherlands at the Rhine-Meuse-Delta also called Hollands Diep south of Rotterdam.

Figure 3.1: Mery Site upstream panorama

Figure 3.2: Mery Site upstream view

The river Ourthe was part of a project to connect the Meuse basin with the Moselle basin in the early XIX^{th} century. For the purpose of this project a total of 205 locks, a tunnel of $2[km]$ and a shipping canal were build. During this process the riverbed that still exists today was created. This project came to an end with the invention of railroads. More than 40 years ago (approximately around 1980) the site was transformed for energy production purposes, it first consisted of a steel manufacturer named Merytherm S.A., afterwards the weir was equipped with 2 micro turbines to produce green hydro-power energy which were in place for more than 20 years. Nowadays the site is equipped with a slot fish-pass and an Archimedes screw too. Due to the heavy inundations of July 2021 the Kaplan turbines and Archimedes screw were damaged and out of service until April 2022 for the Archimedes screw and October 2022 for the Kaplan turbines.

The site consists of different parts listed below, their locations are represented in figure 3.3:

- Slot fish-pass (figure C.1)
- Archimedes Screw (figure C.2)
- Weir (figure C.3)
- 4 Incisions (figure C.3)
- Bypass (figure C.4)
- 2 Kaplan turbines (figure C.4)

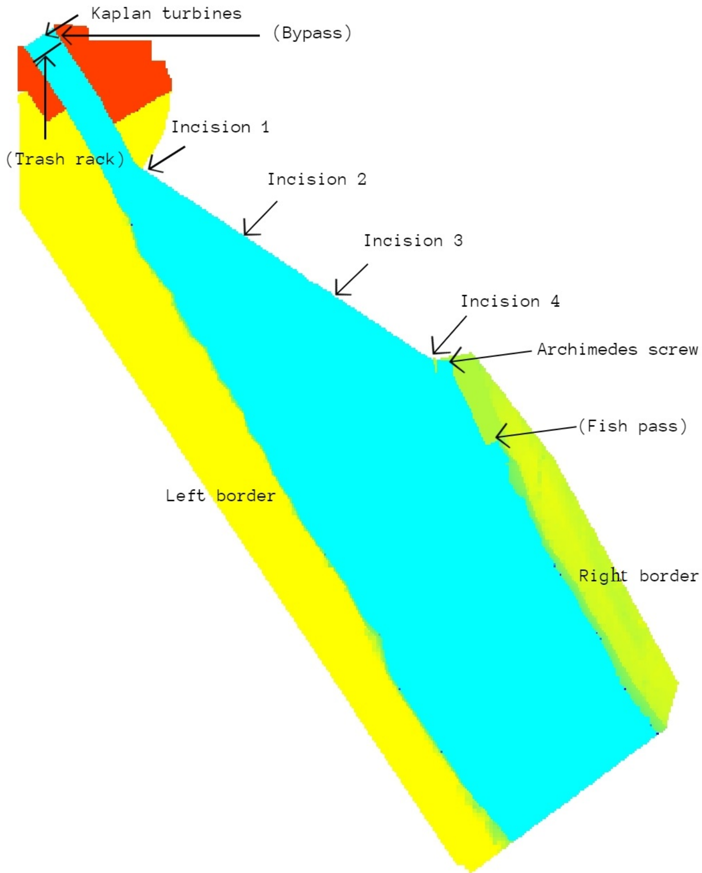


Figure 3.3: Mery Site downstream panorama

2 Numerical modeling

2.1 Flow solver

The hydrodynamic 2D simulations are performed with the Wolf2D flow solver software developed by the University of Liège. The software uses the shallow water equations to solve the hydrodynamic model. The shallow water equations are derived from depth-integrating the Navier-Stokes equations. The equations are solved based on a discretization with a finite volume approach to ensure that the mass and momentum equations are conserved.

The Mery site is modeled with a Cartesian grid (rectangular mesh), each cell has an edge size of $0,5[m]$. This has the benefit of a lower computation time and a gain in accuracy compared to unstructured grids. There is a total of 52831 cells, the model is represented over a total length of $230,9[m]$. The topography of the site which is the main input for the model, is defined with LIDAR data from an airborne survey lead by SPW combined with manual bathymetric data collection done with GPS measurements with a GPS Trimble R10 and a Leica total station. The output of the collected data has a horizontal accuracy of $0,5[m]$ and a vertical accuracy of $< 0,15[m]$ (Renardy et al., 2022, 1).

Boundary conditions are the discharge of the river entering the model for the inflow condition, the discharge passing through the Archimedes screw and the Kaplan turbine as fixed discharges exiting the model for the outflow conditions, they are represented in table 4.4. The discharge passing over the weir and the incisions are calculated in function of the water depth. The bypass, fish-pass and the trash-rack are not included into the model.

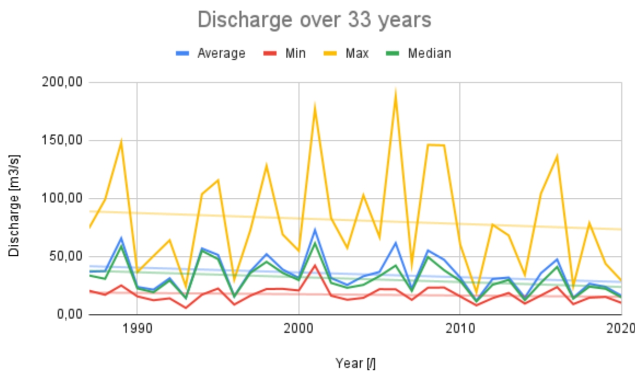
In order to favor fish migration and to reduce the discharge leading towards the Kaplan turbines the simulations are done with only one active Kaplan turbine. This is favoring migration behavior while still allowing to produce energy. As the migration period of Atlantic salmon smolts is only happening during a small period throughout the year, this measure is a first reasonable measure to consider.

2.2 Discharge

The discharge for the simulations is defined on behalf of the measurements from the Sauheid station. For this station the measurements from the last 33 years are collected. The smolt migration period typically takes place between mid march to mid of June (figure C.5 & figure C.6) depending on the water temperature as this is the main parameter that triggers migration behavior. As the trigger parameters in the Ourthe river are not known over the last decades and can vary greatly depending on the region, the analyzed period is taken from the 1^{st} of April to the 31^{th} of May in order to be sure not to take irrelevant discharge data. During the month of march there might be higher discharges but water temperature might still be lower especially combined with higher discharge as this often results from snow melt. During the month of June the discharges may often be lower. As the ambient temperatures generally are elevated, the water temperature often passed beyond the migration triggering temperature at this month.

From the simulations done in the research paper by Renardy et al. (2022, 1), it is known that for a high discharge $>40[m^3/s]$ the main flow passes almost completely above the weir. For such high discharges the fish tend to migrate fast above the weir because they are guided by the main flow, which is a favorable migration route. Thus the smaller discharges are investigated further in this research as they tend to lead the fish towards the intake channel of the Kaplan turbine.

Figures 3.4 & 3.5 below show the discharge over the last 33 years from April to May, the logarithmic representation helps to have a better view on the discharge values:



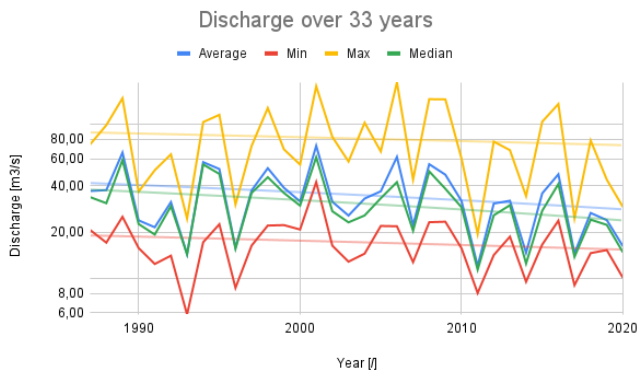


Figure 3.4: Discharge Sauheid over 33 years - April to May

Figure 3.5: Discharge Sauheid over 33 years - April to May - logarithmic

A first observation is that the total discharge declined over the whole period. This favors the decision to focus more on the lower discharges for the study.

As the main discharge flows in an unfavorable direction at low discharge, the minimal values are inspected for the analysis of the different solutions. The discharge for the analysis and comparison of the first modeled solutions is set at $18,4[m^3/s]$. For the analysis of the final solutions the simulations are performed with 2 additional discharges of $10,7[m^3/s]$ and $26,5[m^3/s]$ to ensure that the solutions perform well under extremely low and median conditions.

The model is run with a constant discharge as it represents specific values observed over the past 33 years, the turbines are implemented with constant values as outlet boundary conditions and the precise discharges for outlet boundary conditions at turbines are known from real observations relative to a certain inlet condition.

2.3 Limitations & Improvements

To improve the quality of the research some improvements could be done to the simulation.

First improvements are related to the different parts of the model. The model could be complemented with the discharge going through the fish-pass and the bypass, also the trash rack in front of the Kaplan turbine could be included into the model. Another thing to enhance the output is to simulate the discharge going to the Kaplan turbine and the Archimedes screw in function of the water head available instead of fixing it at a specific discharge.

A second improvement would be to do the simulations by using a 3D software which would allow to create a more realistic model of the site. It could also produce better results as the velocity distribution over the water depth could be investigated and therefore the regions favorable for migration could be defined with more precision. Because fish react to up and downstream velocity differences their change in behavior could be analysed at different areas of the model.

Another positive effect of using a 3D-model is that it can also produce a better indication on turbulence.

3 Identifying on site problems

This section focuses on identifying the problematic parts of the Mery site. The discharge used for the simulation is set at $18,4[m^3/s]$.

3.1 Definition of fish friendly routes

First thing to analyse is to define which parts of the site provide a potential harm to the fishes during migration.

The only component which can cause a real harm is the Kaplan turbine. Due to the rotation of the blade, fish can be injured which results in direct mortality or severe damages. The overall mortality of Kaplan turbines is described in chapter 2 at section 1.3.7.

The other components such as the bypass, the Archimedes screw and the fish-pass are considered as fish-friendly. These can be used by the fish without the risk of damages, if they are dimensioned and executed the right way. The weir is also a fish friendly route if the drop height is not too high and if the water layer passing over is deep enough. The water depth necessary for migration is already described in table 2.2 and should be at least $20[cm]$. Even without that depth the fish will not die using the weir as migration route but only minor damages could occur.

3.2 Mery site analysis

Qualitative representations give a good overview about the distribution of the hydrodynamic parameters. For a quantitative analysis the values are extracted at different cross sections, in the intake channel of the turbine, along the weir and at 3 parts of the river as shown in figure 3.6. The reference points for the different cross sections are represented in table C.1.

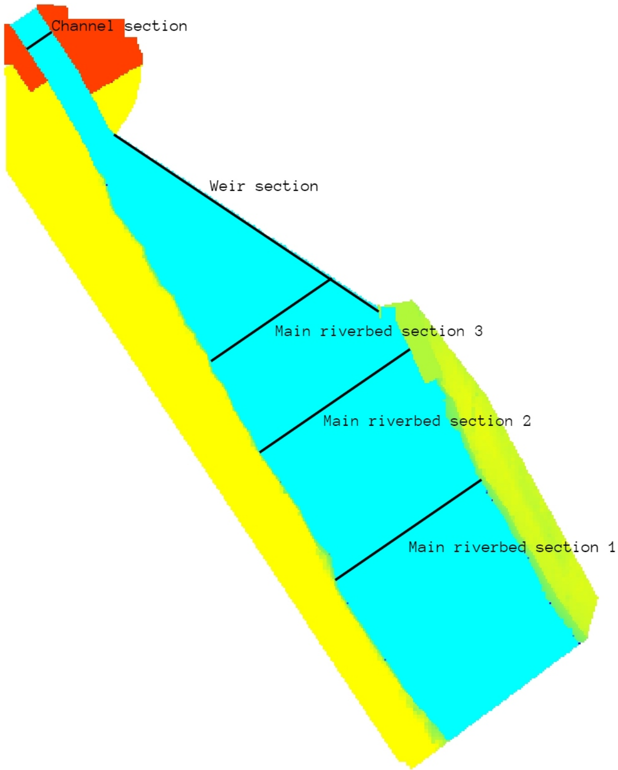


Figure 3.6: Mery Site - Sections

3.2.1 Discharge

The first parameter to observe is the discharge at the site.

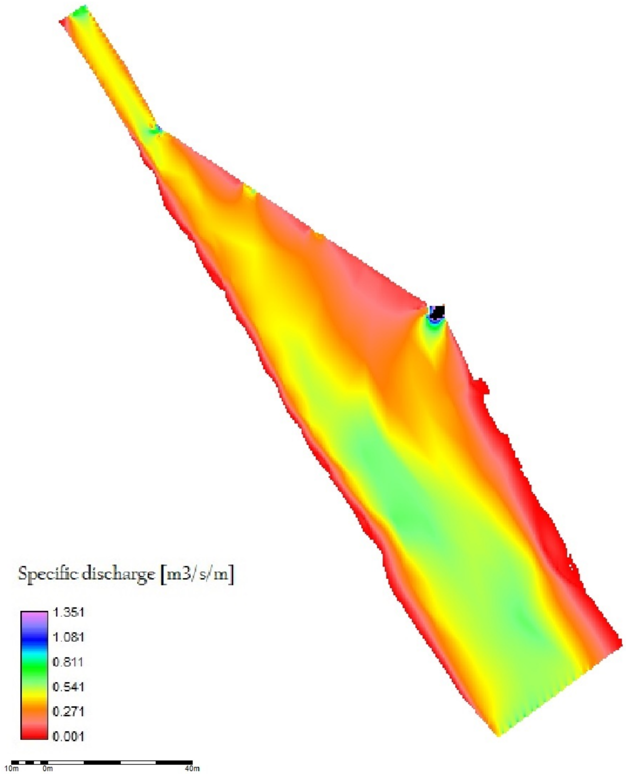


Figure 3.7: Mery Site - Discharge

Figure 3.7 represents the discharge over the whole site of Mery. The lowest discharge is represented in red while the highest discharge is represented in violet. When entering the simulated area the distribution is uniform and then is concentrated towards the left border. It can be seen at first sight from the figure that the main discharge is going towards the Kaplan turbines as the areas with average absolute values form a continuous pattern, represented in green and yellow. Highest values are only observed next to the outlets from the simulation area at the Kaplan turbine, the Archimedes screw and the incision gates. Figure C.7 represents the vectors of the discharge, the vectors in the green and yellow range are directed towards the Kaplan turbine which underlines the previous statement of the main flow going towards the Kaplan turbine.

The cross-section representations at cross-section 1 shown in figure 3.8 and 3 in figure 3.9 also show a higher discharge for the left border.

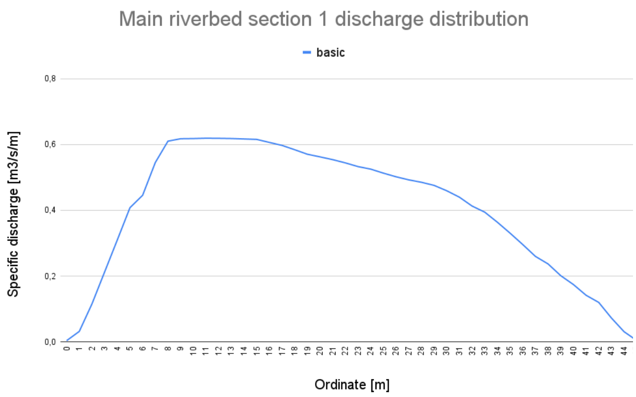


Figure 3.8: Mery Site - Discharge distribution at cross-section 1

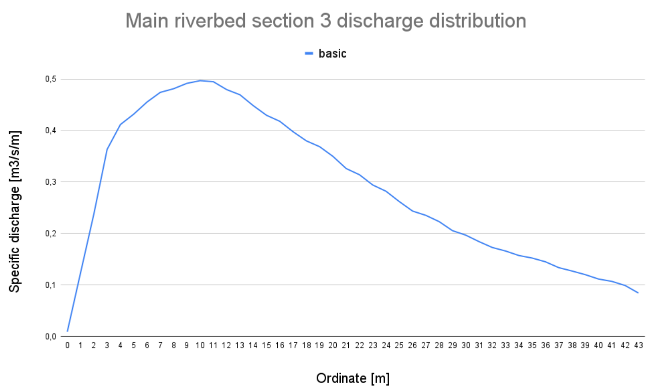


Figure 3.9: Mery Site - Discharge distribution at cross-section 3

The main discharge is going towards the intake channel of the Kaplan turbine because the riverbed of the site is at the lowest levels at the left border due to the channel that was created in the past for shipping. In fact the main discharge follows the lowest riverbed parts neatly. The riverbed is represented in figure 3.12

The vectorial representations of discharge at specific parts of the site are represented in the appendix in figures C.8, C.9 and C.10. The vectorial distributions show that in front of the openings of the weir and the Archimedes screw the vectors change the direction toward the outlet of the simulated area, which are the incisions for the case of the weir. The zoom on the main river part shows that the flow is not strong enough towards the screw to guide the fish towards a safe migration route.

The distribution at cross sections for the weir and in the main riverbed at the section 2 are shown in figures C.11 and C.12. On the main river cross-section the discharge is high on the left and on the right border but low in the middle. This is because the main flow is running along the left border as stated before. The pike in discharge on the right side is due to the Archimedes screw and the lowered topographic height just in front of it. The lower discharge at the middle part shows that the flow is not favoring migration towards the screw. In regard of the distribution at the cross-section in front of the weir the discharge is high in front of the openings of the incisions.

3.2.2 Velocity

The second parameter that defines the migration route choice of smolts is the velocity. The velocity distribution over the whole site is represented in figure C.13. The distribution pattern is the same as for the discharge.

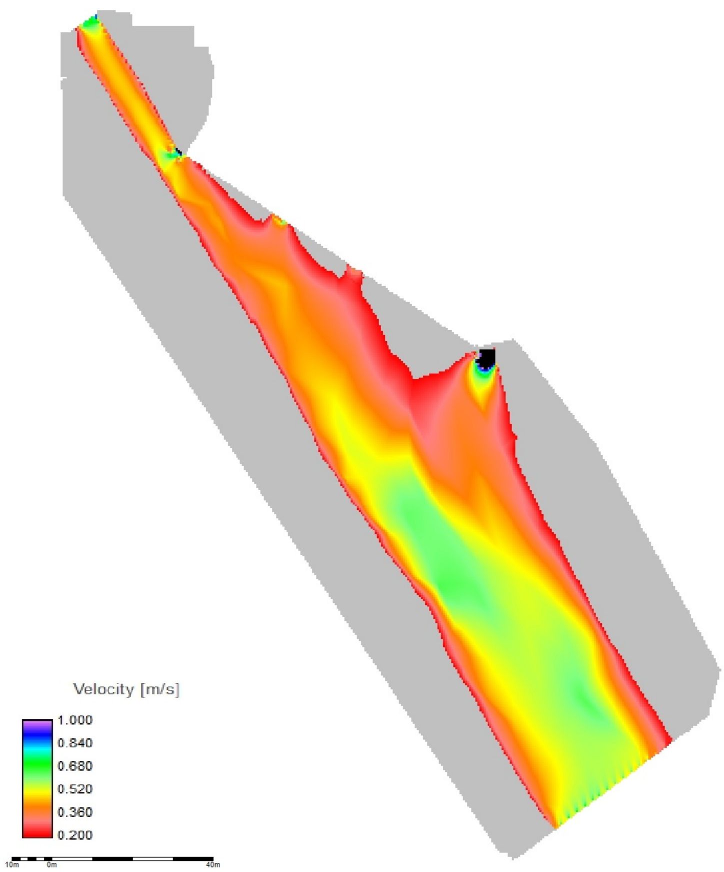


Figure 3.10: Mery Site - Water velocity favoring migration

While the discharge was not defined with specific values in the research articles, the velocity was defined with concrete values. Thus in figure 3.10 the velocity range that favors migration is represented. It can be seen that the velocity favoring migration average of $0,5[m/s]$, represented in yellow, is nearly continuous only towards the Kaplan channel. Towards the direction of the Archimedes screw the velocity is reduced. This underlays the conclusions taken at the section of the discharge, that the discharge favors migration towards the intake channel of the Kaplan turbine.

Zones of low flow velocity need to be avoided due to the augmentation of predation in those areas. Over the site this condition is fulfilled, but when the solutions for improvement are simulated those low velocity zones need to be avoided.

3.2.3 Water depth

Another parameter with concrete values favoring migration that is described in research is the water depth. Figure below 3.11 shows the water depth over the whole site. From this figure it is visible that the water depth on the left border is the deepest with values up to a depth of $3,23[m]$. In front of the Archimedes screw is a located sag resulting in higher water depth at this point, which may result from the construction of the screw. The initial water level is set at $75,788[m]$ above sea level.

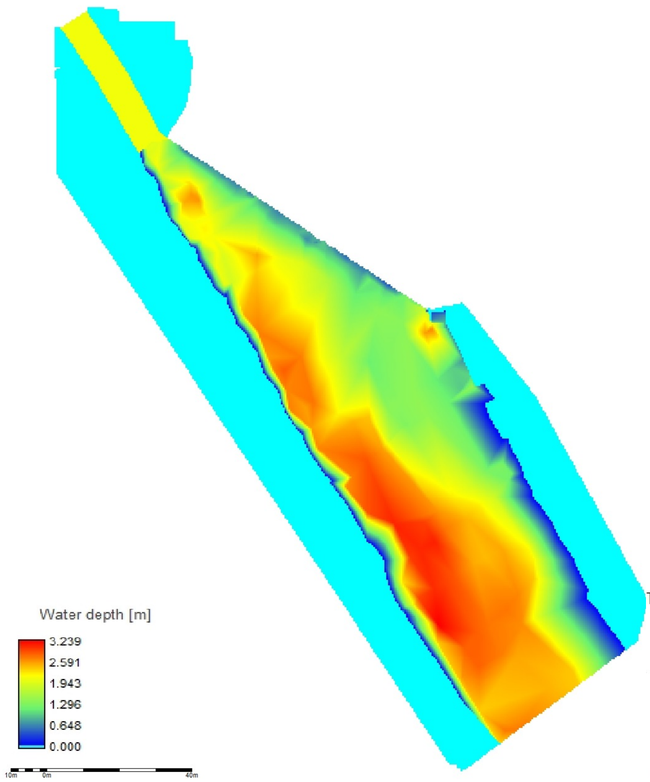


Figure 3.11: Mery Site - Water depth

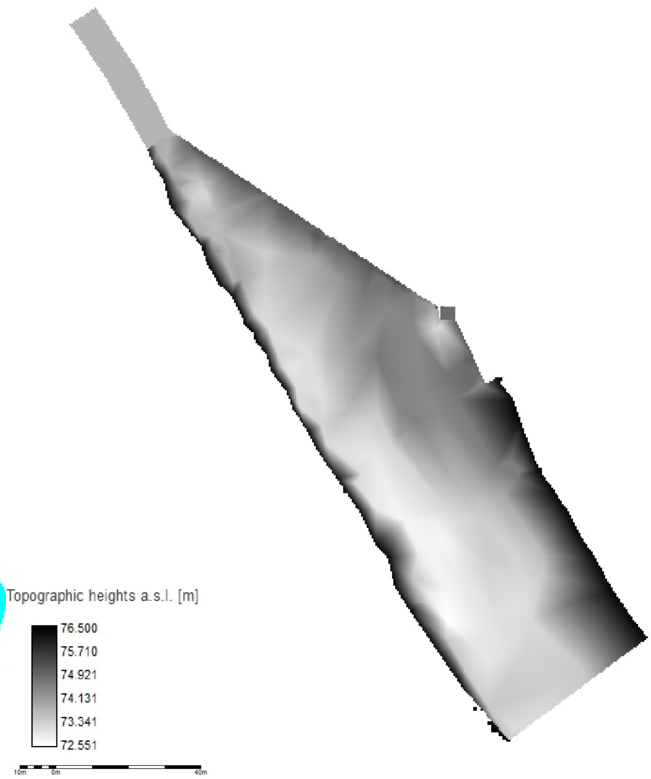


Figure 3.12: Mery Site - Topographic heigth

3.2.4 Channel

The hydrodynamic parameters in the channel leading towards the Kaplan turbines are crucial for a good performance of the electricity production for the Kaplan turbine. The discharge of the channel in the initial configuration is represented in figures C.14 and 3.13.

In order to reduce the effects on the electricity production and to keep them stable, the aim is to keep the hydrodynamic parameters at the same level as they are right now.

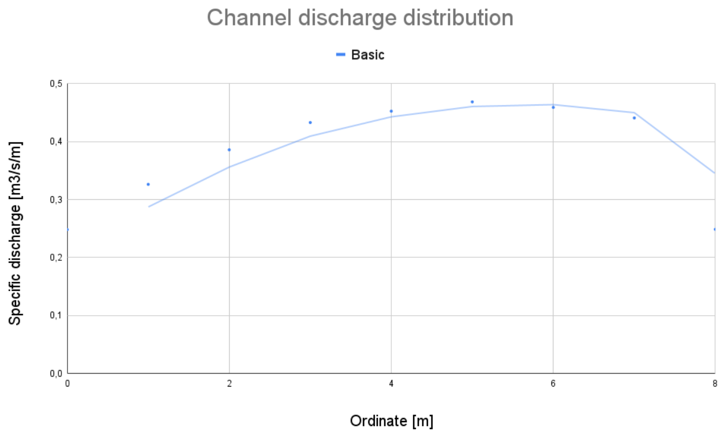


Figure 3.13: Mery Site - Discharge distribution in the channel

3.3 Conclusion

To conclude the analysis of the initial configuration the following points need to be considered to favor the downstream migration of Atlantic salmon smolts:

- Main flow directed away from intake channel of the Kaplan turbines
- Entrance possibility into the intake channel of the Kaplan turbine needs to be avoided
- Avoid zones of low water velocity under $0,2[m/s]$
- Minimal water depth of $0,2[m]$
- Maintain energy production at the same level.

Chapter 4

Results & Discussion

1 Basic solution simulation

1.1 Preliminary analysis of different components

This chapter examines different solutions to change the main discharge running into the channel from the Kaplan turbines towards a favorable migration route for the salmon smolts. Thus different approaches are examined:

- Influence of incisions
- Influence of hydraulic constructions

There are 2 goals performing this changes, first the influence of hydraulic constructions aims to lead the main flow towards the Archimedes screw and the right side of the weir. The incision gate opening should help the hydraulic construction for a better guidance of the main flow.

The second goal investigated is set for the case that the entrance of the intake channel is equipped with a bar rack to prevent the smolts from entering. In this case no constructions are built to lead the main flow towards an other direction, but the first incision gate should work as a bypass in front of the new build rack.

1.2 Influence of Incision

This section first study's the influence of the incision as they are implemented, in a second step some geometrical changes are investigated to develop a higher influence of the incision on the discharge distribution. The width and the maximal opening depth of the as-built incisions are represented in the table 4.1. The depth describes the maximal opening of each gate, the incisions are numbered from the left edge of the weir next to the intake channel of the Kaplan turbine to the right edge next to the Archimedes screw.

	Incision			
	1	2	3	4
Width [m]	0,5	3	3	0,5
Depth [cm]	22,3	37,5	25,2	37,6

Table 4.1: Incision gates - Geometric parameters

1.2.1 Incision opening

To analyse the influence of the incision openings, each opening is simulated with the maximal opening depth. The specific discharge on the cross-sections in front of the weir, at the intake channel and at the main riverbed section 2 is then plotted on different figures to get an overview of their influence on the discharge distribution.

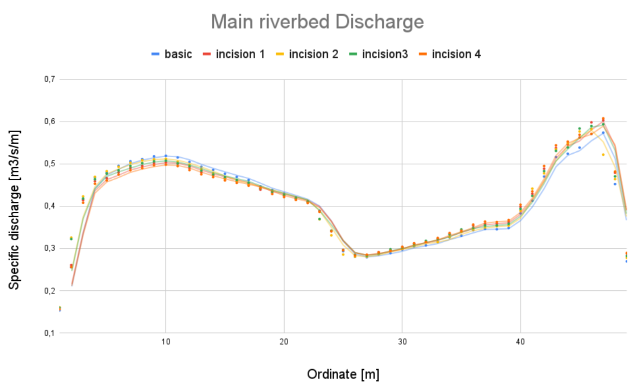


Figure 4.1: Mery Site - Discharge distribution due to incision gate openings at the cross-section main riverbed section 2

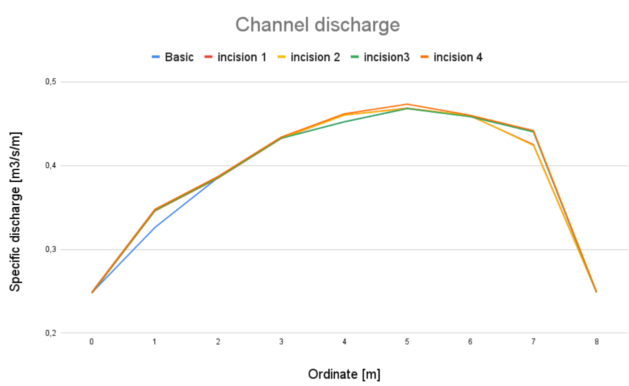


Figure 4.2: Mery Site - Discharge distribution due to incision gate openings at the cross-section in the intake channel

Figure 4.1 representing the discharge in the main riverbed shows that the influence of the incision gate opening on the discharge distribution is limited. Only minor changes are noticeable for the opening of the 4 incisions. On the left side of the riverbed the specific discharge is lowered while on the right side it is increased compared to the initial configuration. The 1^{st} and 4^{th} incisions create the highest difference in discharge distribution although in general their influence are very low. Figure 4.2 representing the specific discharge in the intake channel shows that the opening of the gates has no major influence on the discharge distribution.

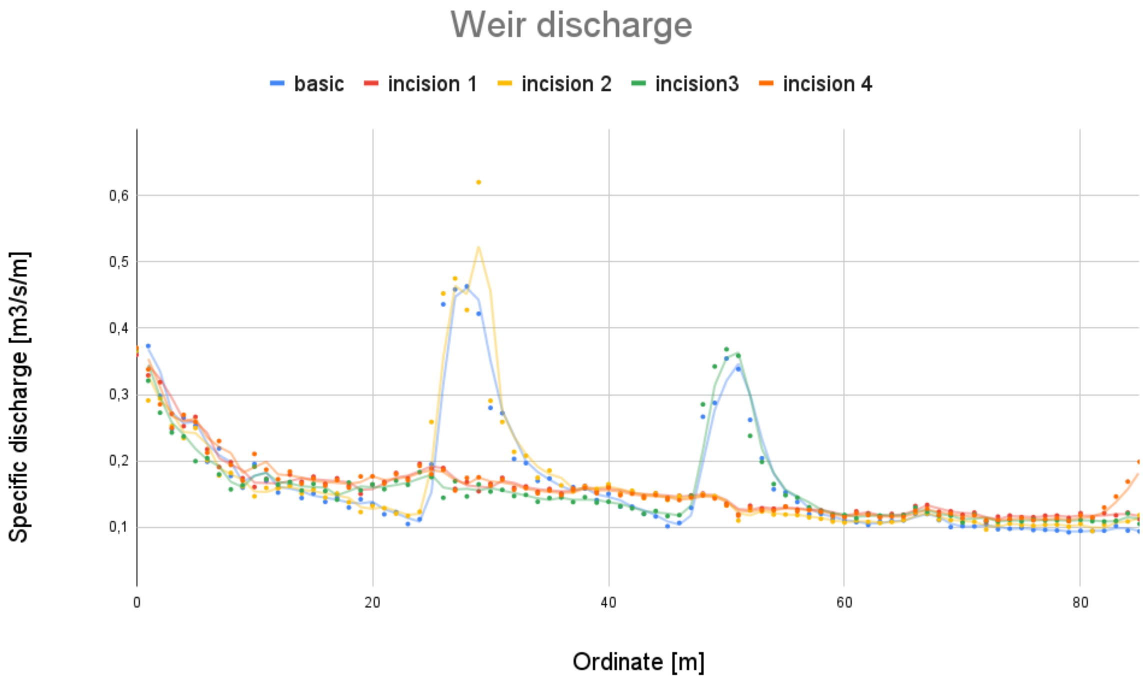


Figure 4.3: Mery Site - Discharge distribution due to incision gate openings at the cross-section in front of the weir

Figure 4.3 shows that the specific discharge of the openings is high when the gates are opened which is logic as the water can pass at a lower altitude and thus more can pass. It shows also that the opening of the incision at the gate 2 and 3 is a bit higher as for the initial configuration. For the 4^{th} incision a clear difference is observed compared to the initial configuration because this incision was closed for that simulation.

1.2.2 Geometrical changes

Next step is to change the geometric outlay of the incision gates to increase their influence on the discharge distribution on the site. Therefore some simulations are performed with a deepened opening depth of $0,5[m]$ for each of the incision gates.

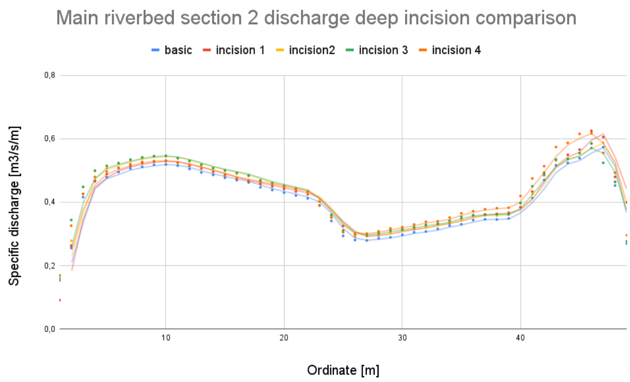


Figure 4.4: Mery Site - Discharge distribution due to deepened incision gate openings at the cross-section main riverbed section 2

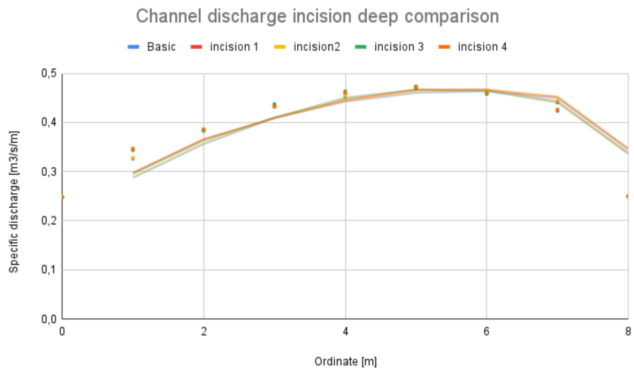


Figure 4.5: Mery Site - Discharge distribution due to deepened incision gate openings at the cross-section in the intake channel

In the figure 4.4 at river cross-section 2, it can be observed that the discharge is raised most on the right border for the openings of incision 1 and 4. While the opening of the incision gate 1 has the highest influence on discharge distribution on this part of the river section at the previously investigated incision openings. The second highest discharge is achieved by the incision gate number 4. In contrast to the previous observations for the case of an as-built opening depth, the discharge over the whole cross section is raised by all the incisions except for a few metres along the left border. The incisions 1 & 4 have the smallest influence on the discharge from the left border to the middle of the cross section 2.

Figure 4.5 shows no major influence on the discharge in the intake channel of the Kaplan turbine compared to the initial configuration.

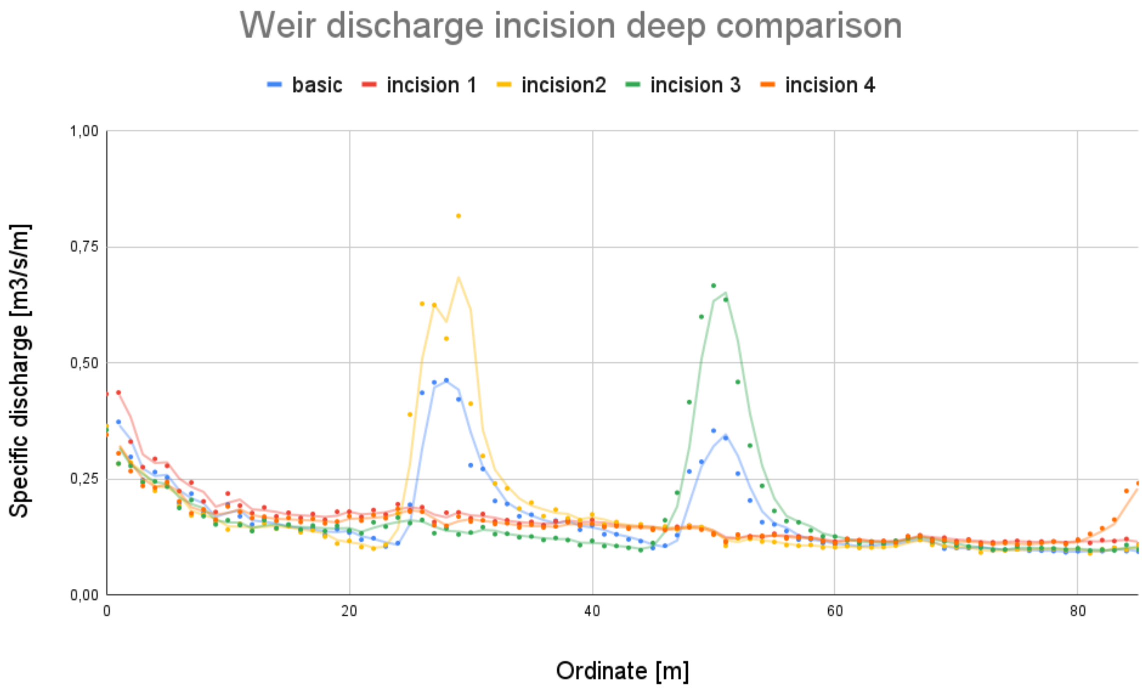


Figure 4.6: Mery Site - Discharge distribution due to deepened incision gate openings at the cross-section in front of the weir

For the figure 4.6 a huge difference to the basic simulation is seen for the specific discharge at the incision gates 2 & 3. Compared to the basic configuration the discharge has nearly doubled and when comparing it with the discharge distribution from the maximal gate depth as-build, the discharge raised too. The discharge at the incision gate 4 shows no big difference compared to the as-built simulation, same counts for the incision gate 1 which has a bit higher discharge passing through.

1.3 Influence of hydraulic constructions

This section combines the analysis of constructive changes to the site. 2 different approaches are investigated, the construction of flow guides and the conversion of the riverbed. The specific discharges are plotted at the intake channel, and on the 3 sections of the main riverbed.

1.3.1 Flow guide construction

3 different outlays of flow guide structures are tested:

- guiding wall (figure 4.7)
- 2 guiding walls (figure 4.8)
- embankment (figure 4.9)

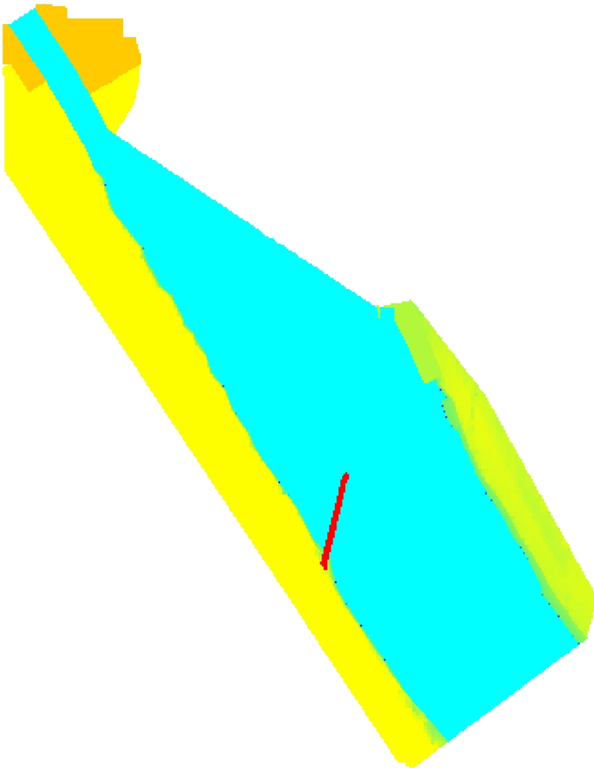


Figure 4.7: Mery Site - Guiding wall configuration

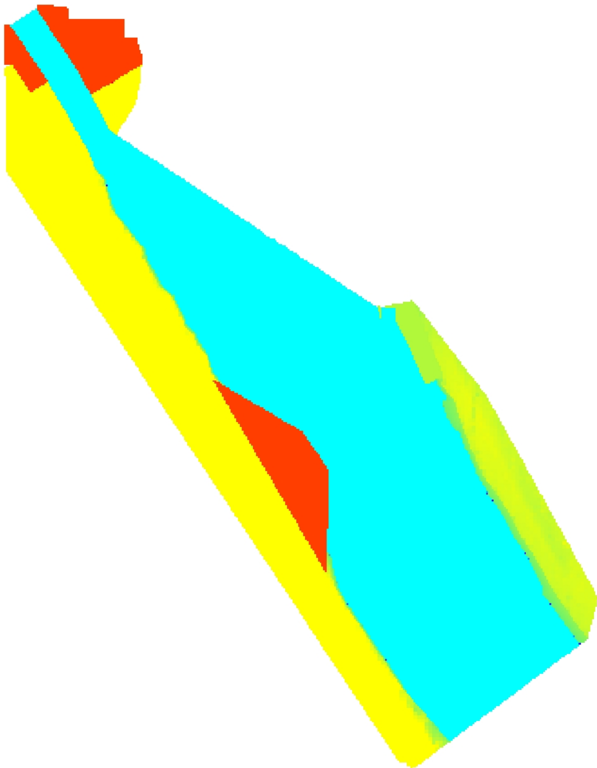


Figure 4.8: Mery Site - Embankment configuration

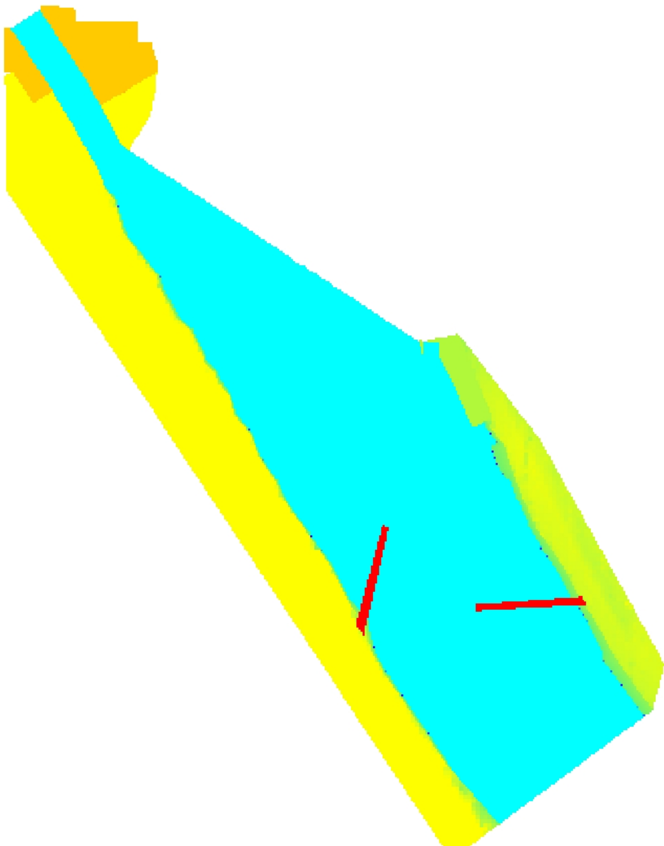


Figure 4.9: Mery Site - 2 guiding walls configuration

The optimal layout of the flow guide was defined performing a few simulations beforehand. First 3 different positions for small walls on the left river border are tested in order to determine the optimal placement. From the 3 placements on the border the middle one is retained. Then there were tests performed with inclined and perpendicular walls in relation to the river border, to determine which have a better flow guidance and produce a smaller area of low flow and recirculation. These tests showed that the better option is to use inclined walls. Finally there were 2 simulations to try finding the optimal length of the wall and the most favorable length is with a distance of approximately $10[m]$ to the border.

1.3.2 Topographic changes

For the outlays of the site with a change in the topography, 2 different approaches are investigated:

- Connection (figure 4.10)
- New channel (figure 4.11)

The first method consists of using the existing channel on the left river border and reducing the river bed height towards the Archimedes screw, the excavated material material can then be used to fill the deep parts on the left side of the riverbed leading towards the intake channel. This method needs less intervention on the riverbed and thus guarantees that the overall riverbed rests stable.

The second method consists in the redistribution of the complete riverbed upstream of the site, by excavating a new channel along the right border and filling the existing channel with the excavated materials. This method needs a lot more interference with the existing riverbed and thus destabilizes the whole area, which could lead to the flush out of the material in case of a flood. The excavated and refilled volumes are represented on table D.1.

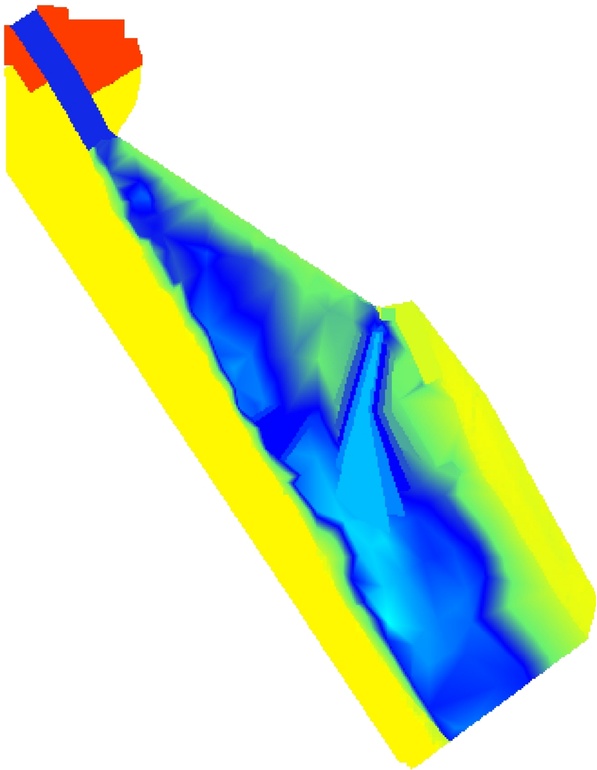


Figure 4.10: Mery Site - Connection configuration

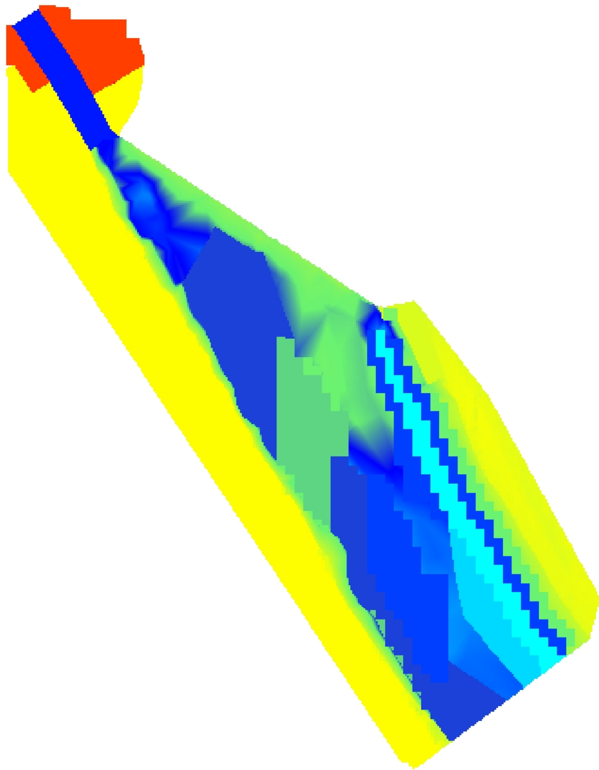


Figure 4.11: Mery Site - Channel displacement configuration

1.3.3 Comparison of constructions

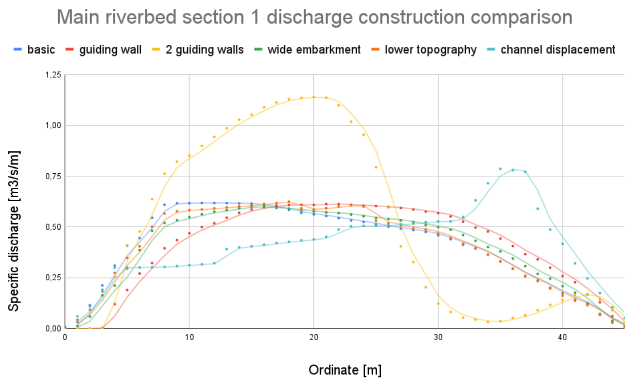


Figure 4.12: Mery Site - Discharge distribution due to constructions at the cross-section main riverbed section 1

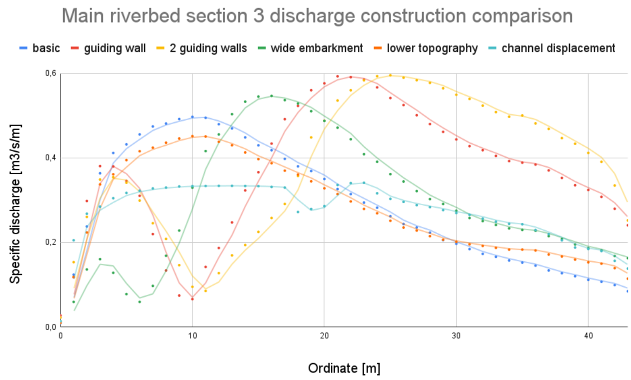


Figure 4.13: Mery Site - Discharge distribution due to constructions at the cross-section main riverbed section 3

Figure 4.12 shows the discharge distribution at the main riverbed section 1. The methods using 1 guiding wall, an embankment or the connection of the existing shipping channel to the Archimedes screw have no huge influence on the discharge from the basic configuration of the site. The method using 2 walls is increasing the discharge by a huge amount on the left border because of the influence from the upstream wall and a huge reduction on the right border is observed. The method of redistributing the channel on the right border is lowering the discharge on the left border and is augmenting the discharge on the right border.

In figure 4.13 the discharge at the cross-section main riverbed section 3 in front of the weir is represented. At this section all the methods present a huge difference in discharge distribution compared to the initial configuration. The least performing method is the connection of the shipping channel on the left border to the screw. It shows only a small reduction of the discharge on the left and only a small increase on the right side.
The method of executing a channel displacement shows a higher reduction of the discharge on the left side and creates higher discharge on the right side, while keeping the most regular overall discharge from all the methods.
The 2 methods of creating walls first create a rise in discharge on the left side of the cross-section which decreases directly after reaching the pike discharge. This is due to the recirculation area behind the flow guide, which is something that needs to be avoided because it encourages sedimentation and it can create zones of low velocity which leads to augmented predation. When considering the middle part of the section at about $10[m]$ the specific discharge rises again for those methods. At the right side of the section both methods create a huge discharge compared to the other analysed solutions.
The embankment method was tested to reduce the effect of recirculation and low flow velocity areas, but it only showed a small enhancement.

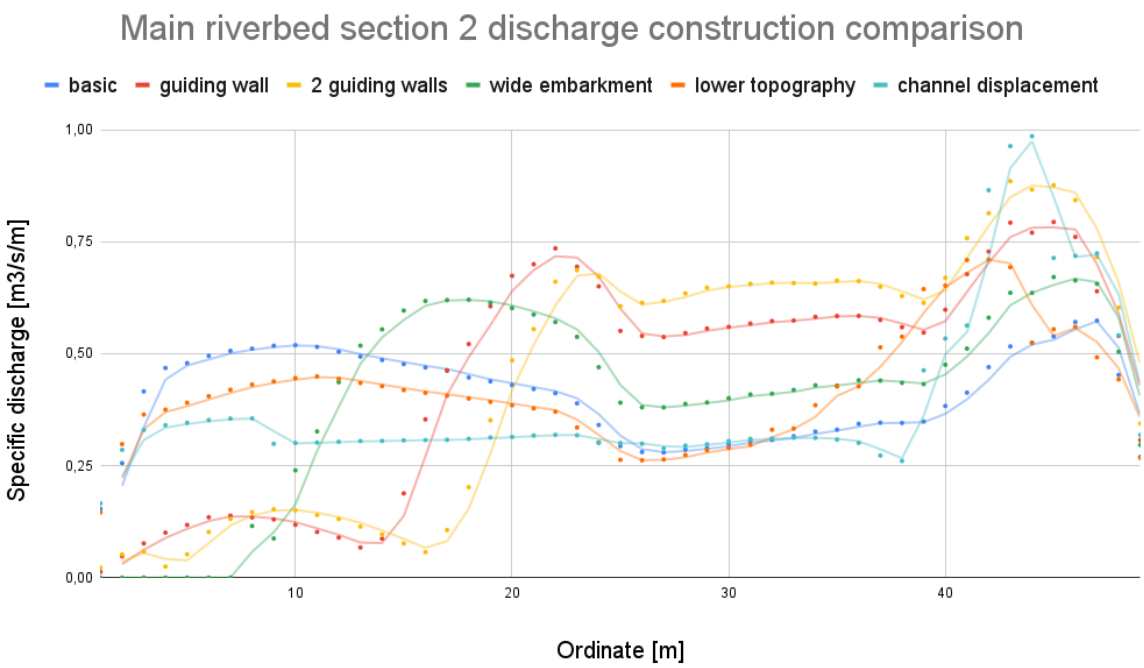


Figure 4.14: Mery Site - Discharge distribution due to constructions at the cross-section main riverbed section 2

Figure 4.14 demonstrates the discharge distribution at the main riverbed section 2, which is located directly in front of the Archimedes screw, shows huge differences from the initial

configuration.
On the left border the 3 methods involving the simulation of flow guiding constructions show the highest reduction in discharge. The 2 methods using the remodelation of the topographic level on the other hand show a smaller reduction of the specific discharge.
At the middle section (from approximately $10 - 40[m]$) the construction methods show a rise in discharge while the topographic methods stay quite regular.
On the right border in front of the Archimedes screw intake all methods have a high rise in discharge, the best performing one is the redistribution of the shipping channel, the second is the method with the 2 guiding walls. The other methods are performing well compared to the initial simulation, but show a lower discharge in this area.

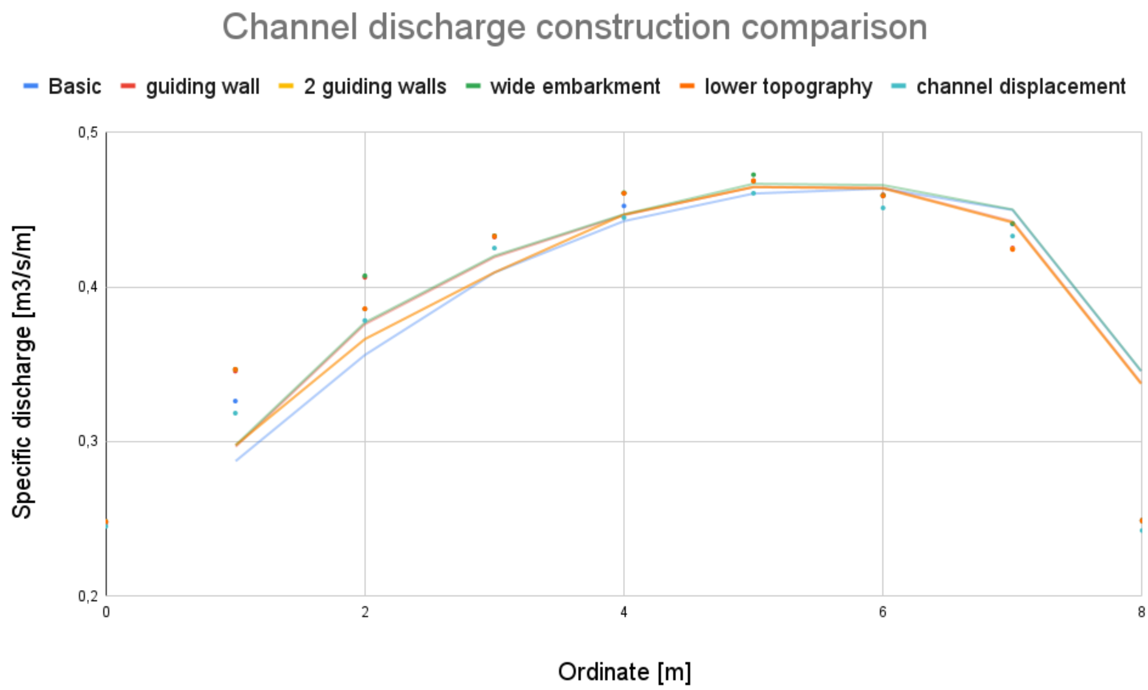


Figure 4.15: Mery Site - Discharge distribution due to constructions at the cross.section in the intake channel

Figure 4.15 displays the discharge distribution at the intake channel cross-section. The methods have no major influence on the discharge leading to the turbine.

1.4 Conclusion

1.4.1 Incision

The effect of the incision gate opening depth is quite limited on the discharge distribution, although combining them with the construction methods could favor the discharge outlay on the site. Therefore the next section investigates different combinations.

The gate with the most favorable effect leading the discharge at the main riverbed section 2 on the right border is the incision 1 with a deepened opening. However, due to the position of the incision gate 1 it is not favorable to open this incision as it could lead the fish towards the intake channel of the Kaplan turbine. The incision gate 4 has the second best influence on guidance of the discharge towards the right border, due to its location next to the Archimedes screw this favors the discharge to guide the fish towards a safe migration route.

The incision 2 and 3 seem to have a good overall influence on the discharge, therefore these gates can be used in combination with the construction methods to lead the discharge away from the intake channel of the turbines.

Deepening the incision gates had a favorable effect on guiding the discharge distribution towards the right river and weir side.

It can be concluded for the incision gates that a few combinations of the as-build and deepened incision gates 2, 3 and 4 in combination with the 2 most valuable constructive methods need to be compared.

Even though that the incision 1 is not suited to combine it with the constructive methods, it could present the possibility to establish a method on its own. In combination with the construction of a trash rack/ fish guidance rack in front of the intake channel of the turbines the incision could work as a bypass. Therefore different outlays of this incision are simulated.

1.4.2 Construction

Concluding on constructive methods, the most efficient method of changing the topographic level, is the construction of a new channel along the right border as it seems to be the most favorable solution to improve the downstream migration. In the approach of the site the discharge is concentrated on the right border and creates the highest discharge of all the simulated methods in front of the screw, this should favor the fish to first arrive at the intake of the Archimedes screw. Another strong point of this method is that it also has an almost regular and low discharge over the whole site from the Archimedes screw up to the intake channel. As all the other methods no major influence on the discharge in the channel itself is observed.
Thus with the combination of an incision gate opening at the right or middle part of the weir this could be potentially a method to reduce fish entrance into the intake channel of the Kaplan turbines to nearly zero. Therefore this method will be analysed in combination with different incision gate combinations in the next section.

For the methods that need the construction of a flow guiding structure, the best performing method was the construction of 2 flow guiding walls. This method creates the second highest

discharge on the right border in front of the Archimedes screw intake and it has the highest discharge along the weir. As all the other methods this one has no influence on the discharge in the intake channel of the Kaplan turbine.
Although it is performing neatly in regard of discharge distribution this method will need further investigations regarding the recirculation behind the walls.

As for the use of embankments there is also recirculation detected even if they are lower, thus the following section only focus on walls as the problems associated with recirculation is not the aim of this research. As it is done for the topographic method this method will be combined with different opening combinations of the incision gates to guide the fish towards a safe migration route.

2 Combining solutions

In this chapter possible combinations of the solutions from the previous section are investigated. The constructive solutions of building 2 flow guiding walls and of the channel displacement are combined and analysed with different incision gate opening combinations. For this reason the following combinations are simulated:

- 2 flow guides + incisions 2 & 4
- 2 flow guides + incisions 3 & 4
- 2 flow guides + deep incisions 2 & 4
- 2 flow guides + deep incisions 3 & 4
- 2 flow guides + deep incisions 2, 3 & 4
- channel displacement + incisions 2 & 4
- channel displacement + deep incisions 2 & 4
- channel displacement + incisions 2, 3 & 4
- channel displacement + deep incisions 2, 3 & 4
- channel displacement + closed incisions

Performing these combinations the aim is to create a disruption of the main flow pattern that is going towards the intake channel of the Kaplan turbine.

For this section the discharge is the main focused parameter, first in a qualitative and then in a quantitative manner. If there is no major difference observable between the different combinations, the velocity favoring migration or the water depth are considered too.

For the tests of the best performing combination of incisions with the flow guides, a large amount of combinations are tested. The channel displacement is then tested with the 2 best performing combinations of the flow guides.

As mentioned at the previous section, the incision 1 is not included in these combinations as it is placed too close to the intake channel and would shunt a higher discharge towards this unfavorable part of the site.

For the case of the construction of a new bar rack at the beginning of the intake channel from the Kaplan turbine, the incision 1 will work as a by-pass. Therefor the incision 1 is simulated for different geometrical changes:

- wide incision 1
- cubic incision 1
- complete incision 1

The best performing combination for each of the constructive change and the best outlay of the incision 1 are analysed in more detail as final solutions.

As for this section no significant differences can be observed at the existing cross-sections in the main riverbed 2 new sections are added, section 4 and 5. On addition because the influence of the incision 1 outlays is only limited to a small ares 2 cross-sections are added next to the entrance of the intake channel of the Kaplan turbine. Their locations are shown in figure 4.16 and their exact coordinates are represented in table C.1.

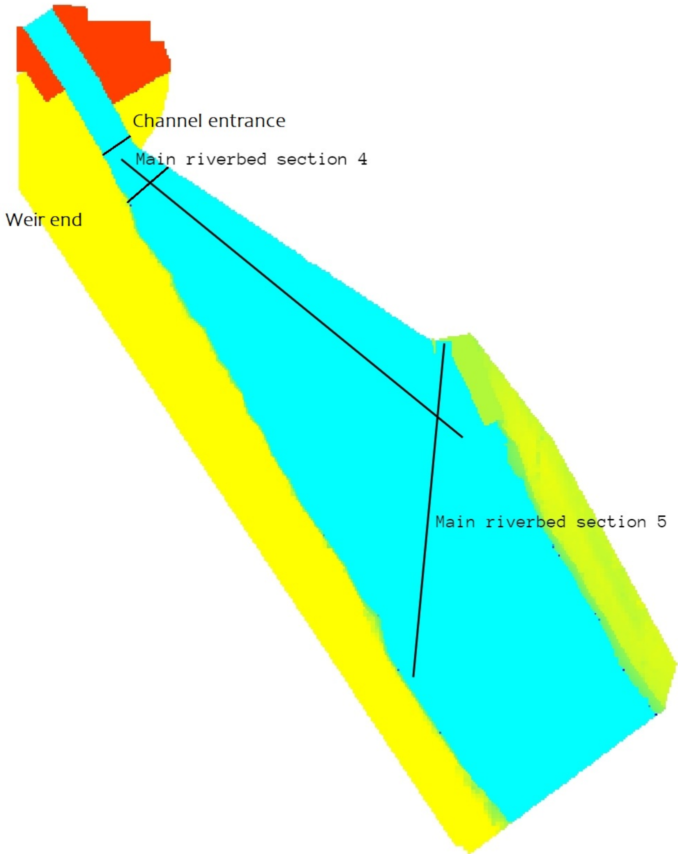


Figure 4.16: Mery Site - Additional cross-sections

2.1 2 flow guides + incision gate opening combination

First combinations of 2 flow guiding walls with different incision openings are compared. Qualitative figures show the main discharge over the whole site while quantitative figures give exact values at the cross-sections.

2.1.1 Qualitative observations

First the figures below represent the overall discharge distribution over the whole Mery site. The goal of mixing the constructive methods with different incision gate opening combinations is to ensure that the main flow is not going towards the intake channel from the Kaplan turbine. Thus on these graphical figures the flow represented in yellow and green has to represent a cut in the direction of the channel.

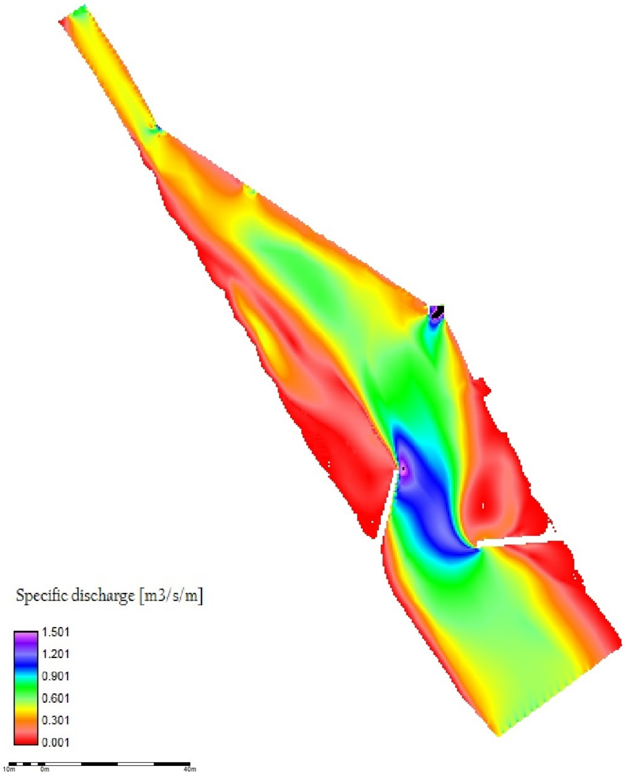


Figure 4.17: Mery Site - 2 Flow guides + incisions 2, 4

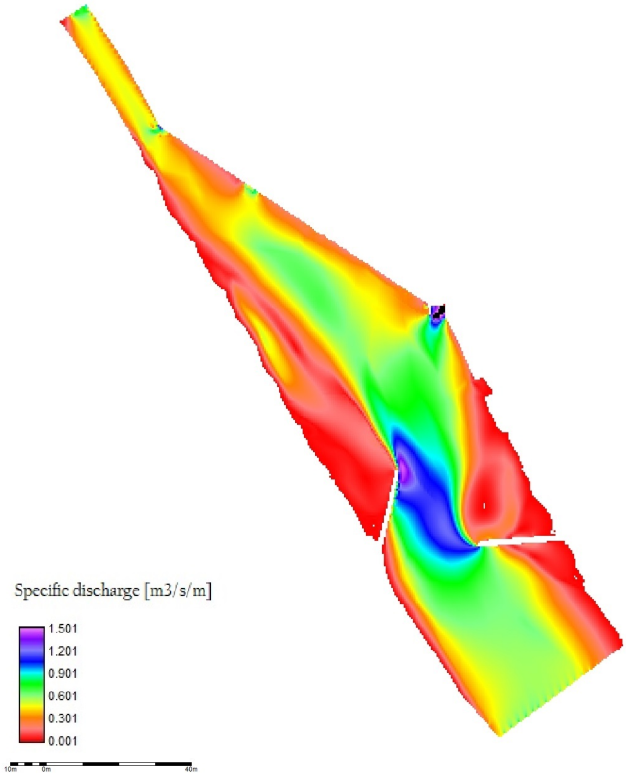


Figure 4.18: Mery Site - 2 Flow guides + deep incisions 2, 4

Figures above show the influence of the incision gates 2 & 4 on the discharge distribution. The left figure 4.17 is simulated with the as-built incision gate depth, while the right figure 4.18 represents the discharge with deepened incision openings.

For the approach area of the site no mayor difference is observed between both. Then for the region between the 2 flow guiding walls the discharge distribution seems the same for both combinations too. The same counts for the region in front of the Archimedes screw, as only slight differences can be observed. The region in front of the weir shows minor changes at the right side of the weir, also due to the influence of the incision gate 4 a little bit less discharge is going towards the incision 2 in case of deepened incisions. In front of the incision gate 2 it can be seen that the deepened version shows a better continuation of the flow towards the gate, while the flow leading towards the intake channel from the turbines is represented by a more fade yellow which means less discharge is running towards it.

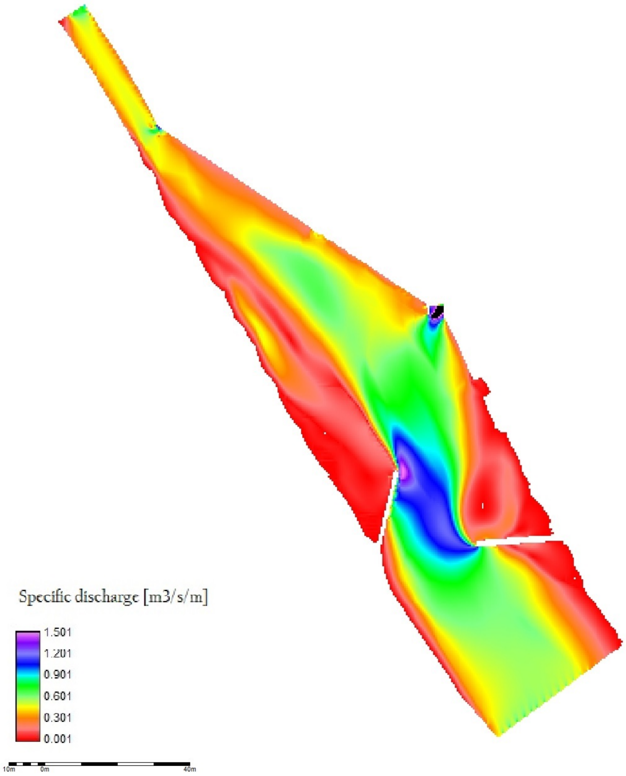


Figure 4.19: Mery Site - 2 Flow guides + incisions 3, 4

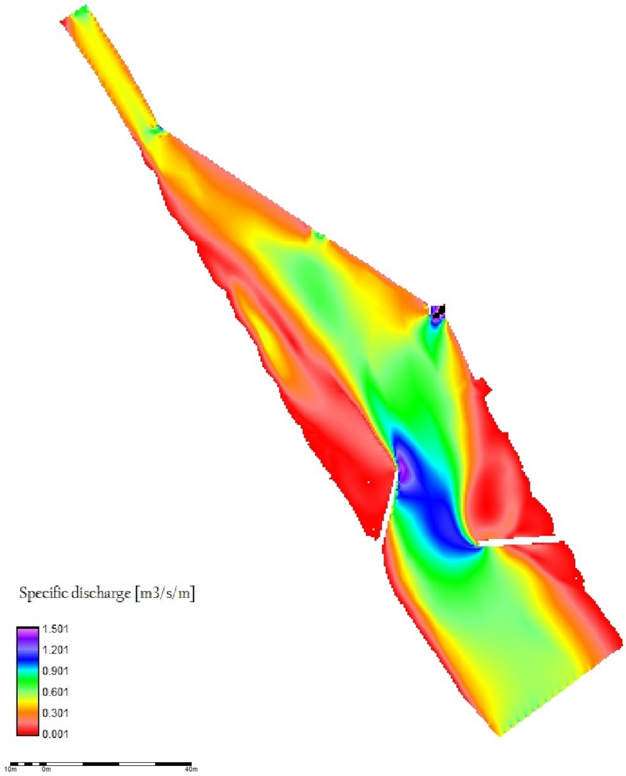


Figure 4.20: Mery Site - 2 Flow guides + deep incisions 3, 4

Figures above represent the simulation outcome for a combination with the opening of the incision gates 3 & 4. Again on the left figure 4.19 is represented the discharge with an as-built gate depth and on the right figure 4.20 with deepened openings.

As for the previous openings there is no visible change at the approach area. At the area between the flow guiding walls a small change in the discharge is observed, the deepened openings seem to have a reductive effect on the discharge at this area as the center is more blue. In front of the Archimedes screw there is no difference observable. For the region in front of the weir we can clearly see that the flow is guided better to the deepened incision 3 then towards the actually build one. Another important observation is that the flow towards the intake channel is reduced as the yellow/green area is shortened for the deepened outlay.

It has to be pointed out that the green region goes past incision 3 which is unfavorable because this can guide fish past the save migration routes. When smolts arrive at this point they could follow the remaining flow going towards the intake channel of the Kaplan turbine.

As for both of the combinations analysed so far the deepened incisions showed a better behavior, the combination of using the incisions 2, 3 and 4 is only done with deepened incisions.

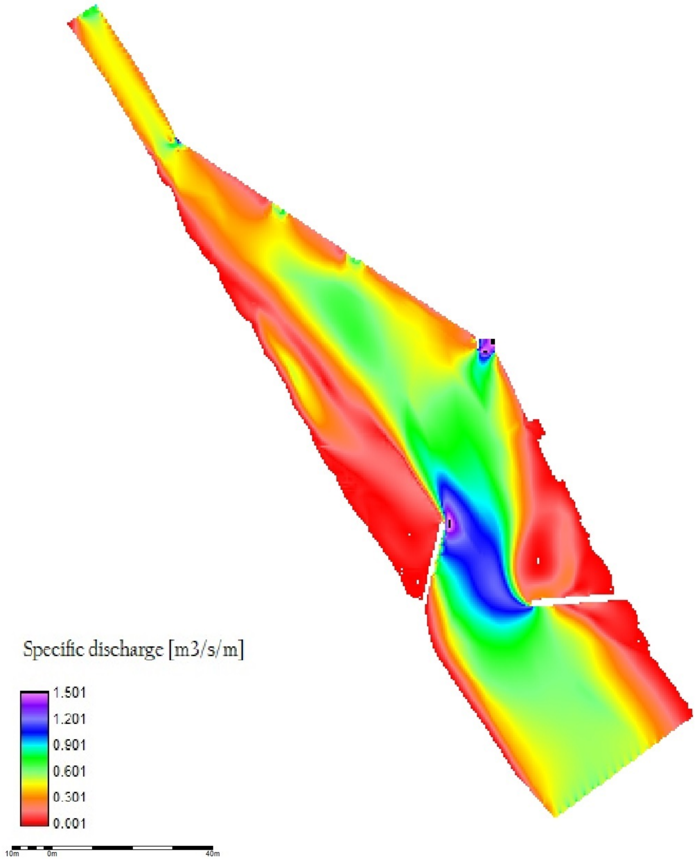


Figure 4.21: Mery Site - 2 Flow guides + deep incisions 2, 3 & 4

Figure 4.21 shows the distribution due to the opening of deepened incisions 2, 3 and 4. I can be seen that the approach area does not differ from the other solutions. The area between the 2 flow guides are also similar to the other combination, the same counts for the intake of the Archimedes screw. In front of the weir the incision gate 3 is well connected to the main flow. For the incision 2 the discharge seems also quite continuous. The rest of the discharge leading towards the intake channel from the Kaplan turbines has a lower discharge section next to the closed incision 2. Thus this method seems to be the best solution to avoid that the flow guides the fish towards the Kaplan turbines.

2.1.2 Quantitative observations

To focus further on the mentioned observations made at the previous subsection the values at all the cross-sections are displayed and discussed.

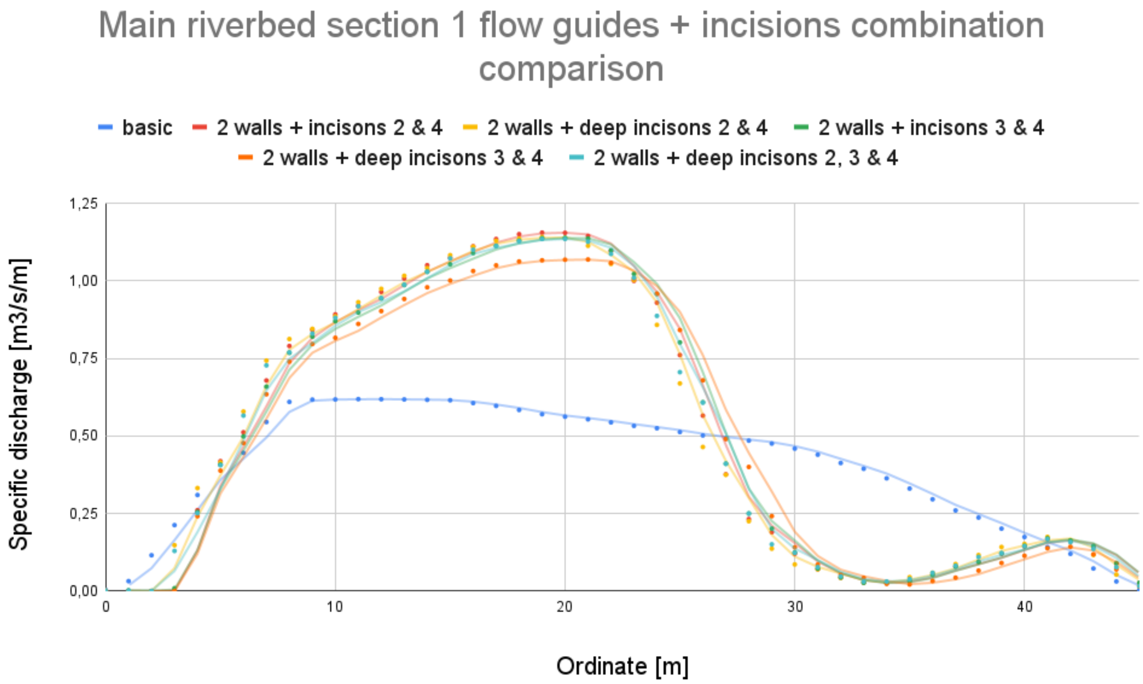


Figure 4.22: Mery Site - Main riverbed section 1 flow guide + incision comparison discharge distribution

Figure 4.22 above shows the discharge distribution over the cross-section 1 in the main riverbed. All the combinations have the same look except the combination with the deepened incision gates 3 and 4, which has a lower discharge on the left part from approximately $5-25[m]$ of the section. On the right side the discharge is very low for all the methods as this part is strongly influenced by recirculation from the right flow guide.

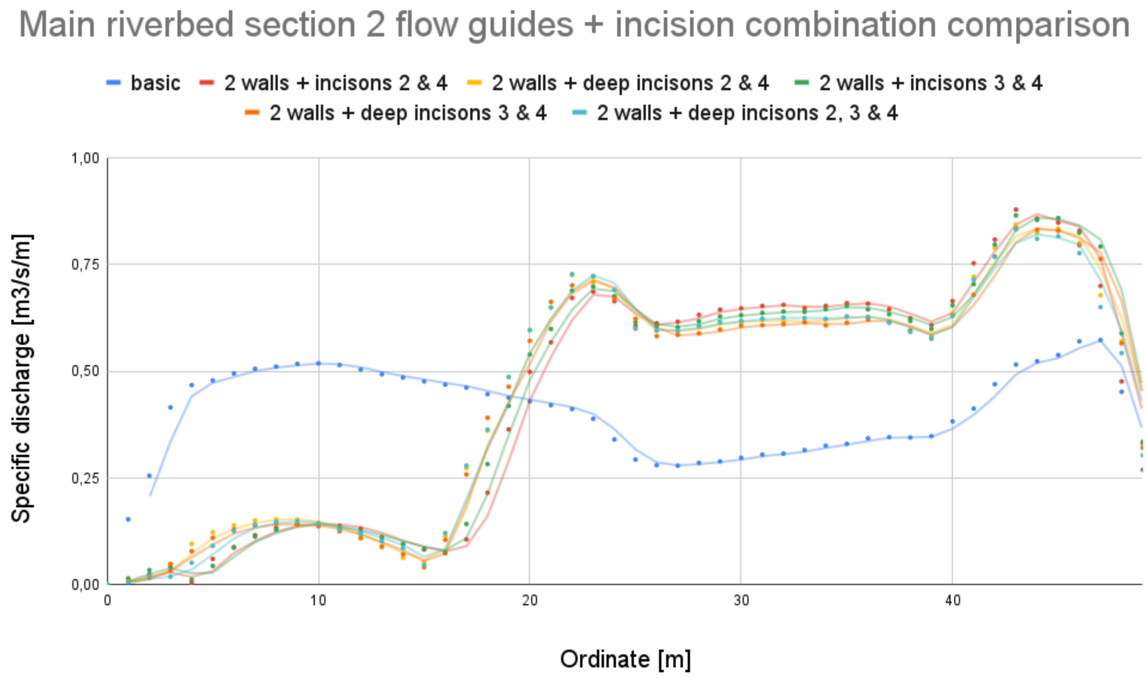


Figure 4.23: Mery Site - Main riverbed section 2 flow guide + incision comparison discharge distribution

Figure 4.23 represents the discharge distribution at the main riverbed cross-section 2. The left part from $0 - 15[m]$ is very low because it is located in the recirculation area behind the left flow guide. A huge rise can be observed in the middle of the section as it is located where the main flow is guided by the left flow guide. On the right side of the section at $40[m]$ another rise is observed due to the influence from the intake of the Archimedes screw. On the middle section the combination with the as-built incisions 2 and 4 has the highest discharge,. The second highest discharge is observed for the combinations of as build incisions 3, and 4. For the right part in front of the Archimedes screw the highest discharge is produced again by the combination of the as-build incision gates 2 and 4. The second highest discharge on that part of the cross-section is achieved with the combination of the gates 3 and 4.

Thus for a high discharge leading towards the Archimedes screw the best suited option is the combination of the as-built incisions 2 and 4.

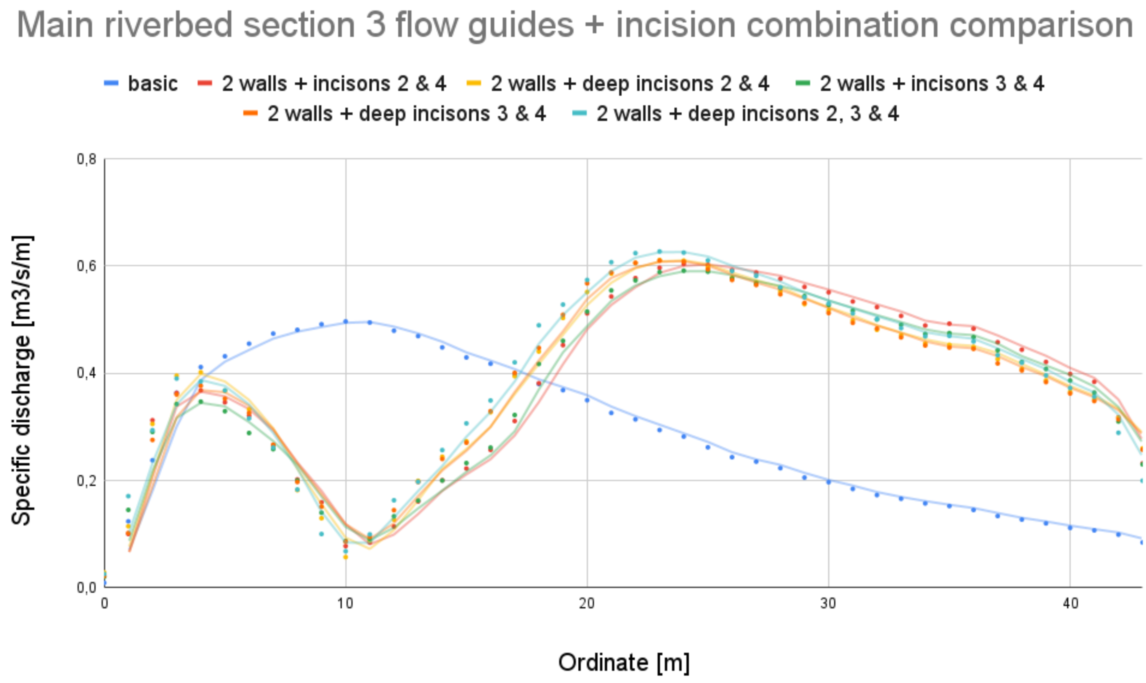


Figure 4.24: Mery Site - Main riverbed section 3 flow guide + incision comparison discharge distribution

The next riverbed cross-section located directly behind the intake of the Archimedes screw and at the beginning of the weir is represented in figure 4.24. The first pike in discharge located on the left side of the section up to $10[m]$ is due to recirculation. From about $10[m]$ to approximately $23[m]$ there is a rise in discharge that can be observed. The main flow is located from $20-30[m]$ as the discharge is the highest with values above $0,5[m^3/s/m]$ for all the combinations. The method using the combination of deepened incision gates 2, 3 and 4 has the highest values, while the methods of the as-built incisions have the lowest. However, all methods perform quite similar. For the right side of the section the representations shows that the method with the as-built incisions 2 and 4 hast the highest values next to the weir.

The fact that the discharge is highest for the deepened methods, especially when combining the incision gates 2 and 3, is logic because when the opening is deeper the discharge they can lead through is higher for the same water level.

Thus the best suited method seems to be the combination of the incisions 2 and 4 as-built as it underlines the fact that with this combination the main flow is guided to the Archimedes screw.

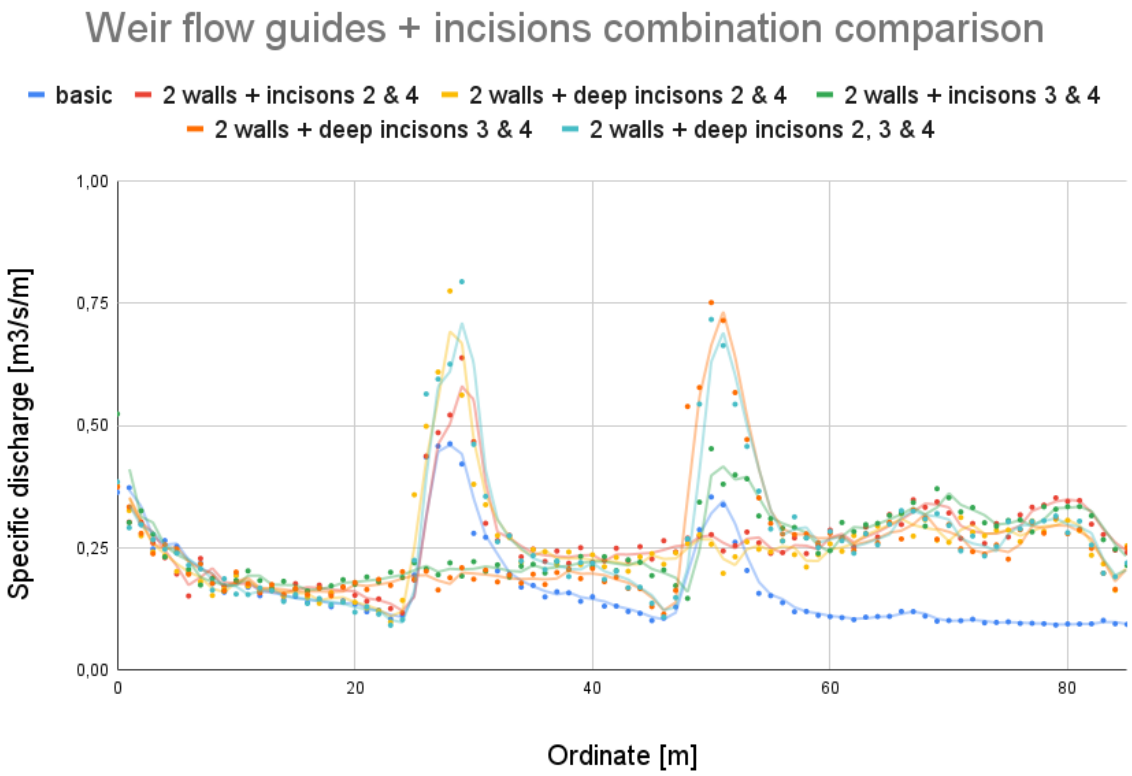


Figure 4.25: Mery Site - Weir section flow guide + incision comparison discharge distribution

Next the discharge in front of the weir is represented in figure 4.25. In this figure it can be seen that on the left part of the section from $0 - 20[m]$ the lowest discharge is observed for the methods combining the deepened incisions 2, 3 and 4. The difference is only very small. At the incision gates 2 the method using the deepened incisions gates 2,3 and 4 produces the highest discharge. In front of the incision 3 the highest discharge is achieved with combining the deepened gates 3 and 4. On the right side of the weir the highest discharge is achieved for the as-built incisions 2 and 4. Another aspect to state is that the discharge on the left side is pretty similar to the initial configuration while the discharge on the right side of the weir is much higher as for the initial configuration.

Thus it can be deduced that the combination of as-built incisions 2 and 4 or the combination of deepened incisions 2, 3 and 4 have the best overall effect on the discharge in front of the weir.

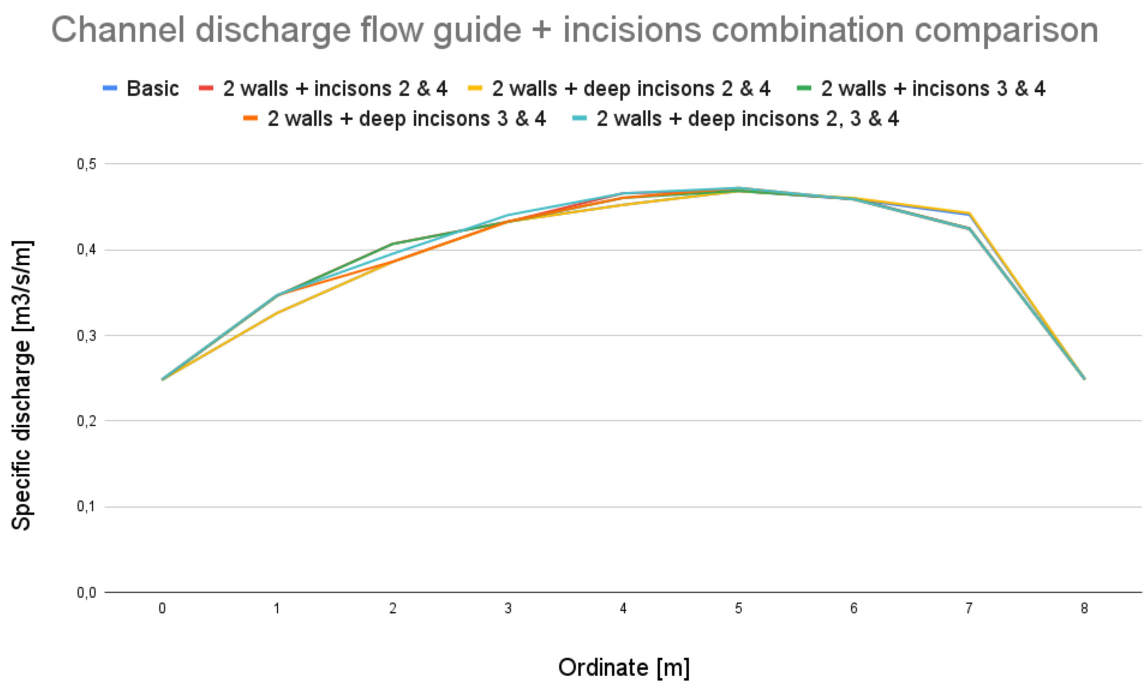


Figure 4.26: Mery Site - Channel section flow guide + incision comparison discharge distribution

As for all the other simulations the discharge in the intake channel of the Kaplan turbines is similar for all combinations. It has to be mentioned that this is due to the fact that the discharge at the turbine is fixed so only minor influences from upstream changes can be detected at this part of the site.

2.1.3 Interim Conclusion

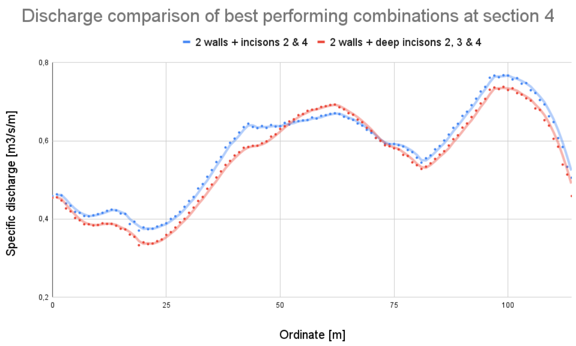
As of now it is not clearly visible which method performs best. For the quantitative analysis it seems that using deepened incision gates 2, 3 and 4 was performing best to develop a cut in the flow towards the Kaplan turbine. While the method using the as-build incisions 2 and 4 is the best solution to help the flow guides pushing the flow towards the Archimedes screw and the right part of the weir. As it is not 100% clear which method represents the best results new sections have to be analysed to quantify the discharge and to see if it is really disrupted. Another factor analysed is a qualitative analysis of the discharge direction.

In figures D.1 and D.2 the vectors representing the flow direction are depicted, only a slight difference is observed next to the Archimedes screw. In front of the intake there are only a few vectors that are directed slightly more in north direction. Between the guides there is no visible difference.

Hence it can be concluded that there is no combination that outperforms the other.

These figures D.3 and D.4 represent the flow directions in form of vectors in front of the weir. It can be observed that the combination of as-built openings 2 and 4 and deepened openings 2, 3 and 4 present a similar flow pattern on the right side of the zoom. The main flow which is represented in green is wider for the case of the deepened incisions as it is influenced by the deepened incision gate 3. In front of the incision 2 there are 2 vectors that show more towards the incision for the deepened combination.

Thus for this section the combination using deepened incision gates 2, 3 and 4 perform a little bit better.



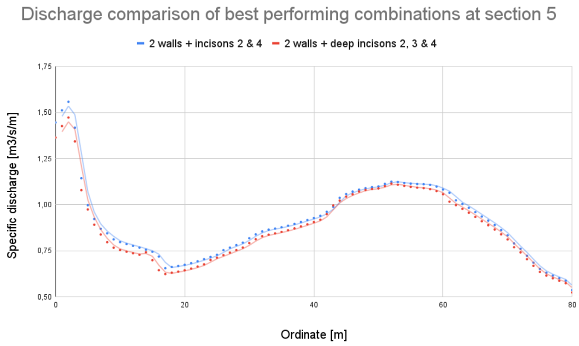


Figure 4.27: Mery Site - Discharge comparison of best combinations at section 4

Figure 4.28: Mery Site - Discharge comparison of best combinations at section 5

In figure 4.27 the discharge is displayed for the cross-section 4 from the intake channel of the Kaplan turbine along the weir towards the Archimedes screw. The combination of deepened incisions 2, 3 and 4 has a lower discharge overall except for the region in front of the incision 3. This shows that the discharge going towards the Kaplan turbine is lower using this method. Another favorable effect is that some of the discharge is going towards the incision 3.

Therefore this combination has better effects on the flow because it reduces the flow and thus fish migration behavior towards this direction.

The last figure of this section 4.28 shows the discharge distribution from the inlet of the Archimedes screw towards the left river border just in front of the passage between the 2 flow guides. It can be observed that when arriving at the crucial area the discharge for both methods is the same. When approaching the Archimedes screw the discharge of the combination of as-built incisions 2 and 4 is slightly higher then the discharge of the deepened incisions. Only directly in front of the screw a noticeable difference is visible on the figure but it is still quite small.

For that reason there is no method that favors smolt migration behavior better than the other at this cross-section.

2.1.4 Conclusion

To conclude the analysis of combining different incision gate openings and 2 flow guides, the method using deepened incisions at the incisions 2, 3 and 4 is best suited to favor fish migration towards the Archimedes screw or over the weir as it produces quite high discharges at the incision gates, and the discharge on the right weir side is also augmented. Another strong point using this method is that is creates the lowest proportion of discharge going in the direction of the intake channel from the Kaplan turbine.

A weak point using this method is the additional cost that is needed to rebuild the incisions.

2.2 Channel displacement + incision combination

As for the previous section the most influential solutions was the one using the incisions 2 and 4 or the incisions 2, 3 and 4 in this section the combination of using the incision 3 and 4 are not investigated. Another discovery made at the first simulations is that no area with a flow towards the intake channel from the Kaplan turbine is observed, therefore a solution without opening any of the incisions is investigated as well.

2.2.1 Qualitative observations

In general it can be stated that for all the openings the main flow is leading towards the Archimedes screw and the initial discharge leading towards the intake channel from the Kaplan turbine is disrupted. Thus all the methods analysed show a favorable discharge distribution in terms of guiding the smolts towards a fish-friendly migration route.

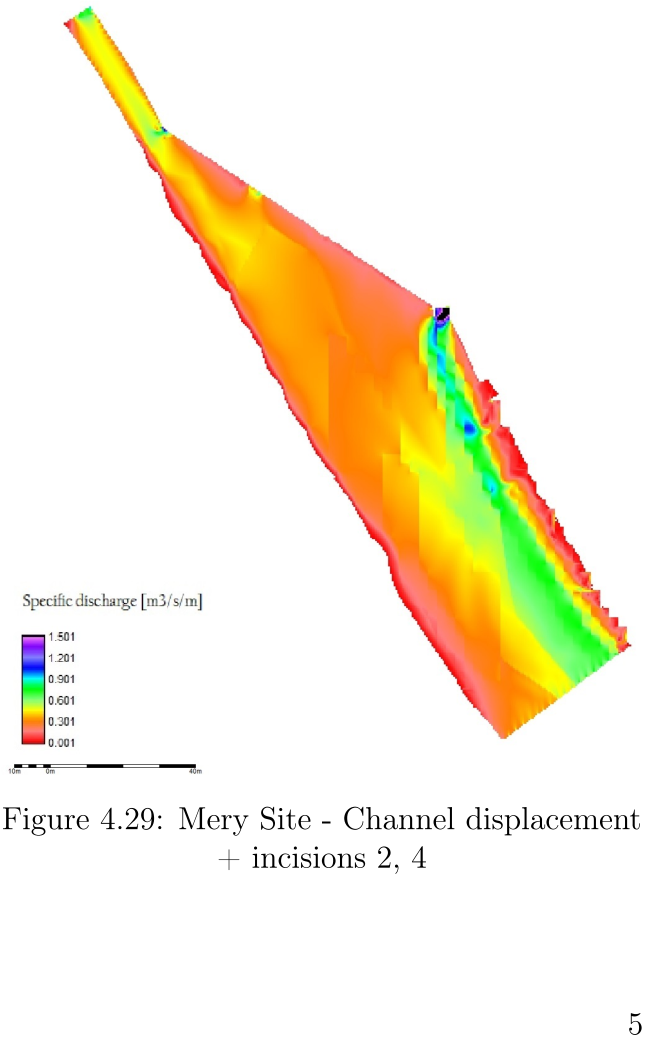


Figure 4.29: Mery Site - Channel displacement + incisions 2, 4

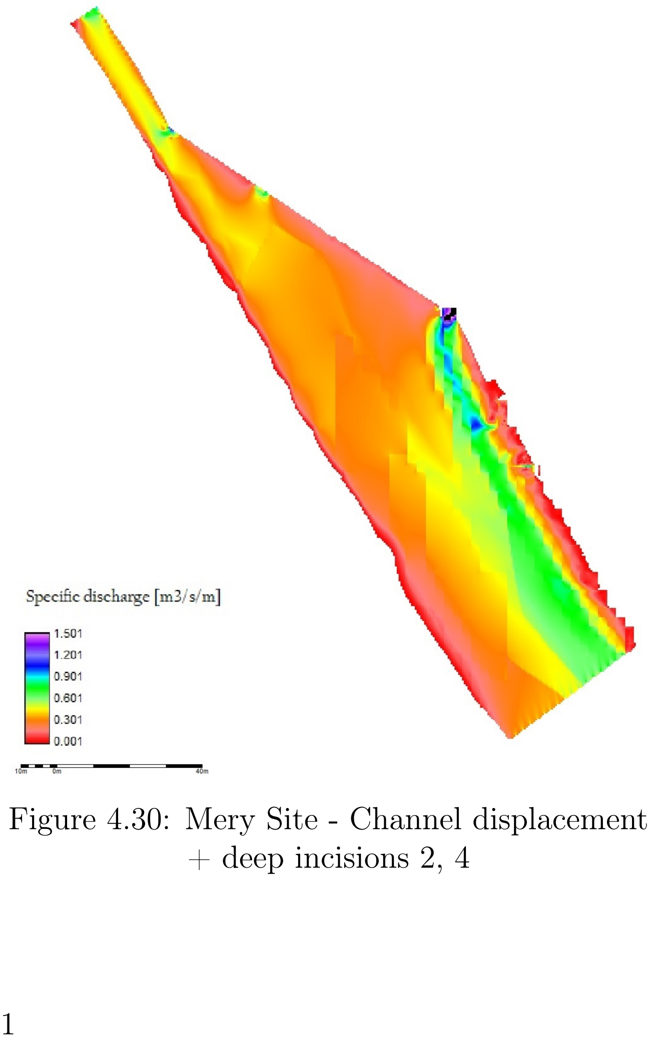
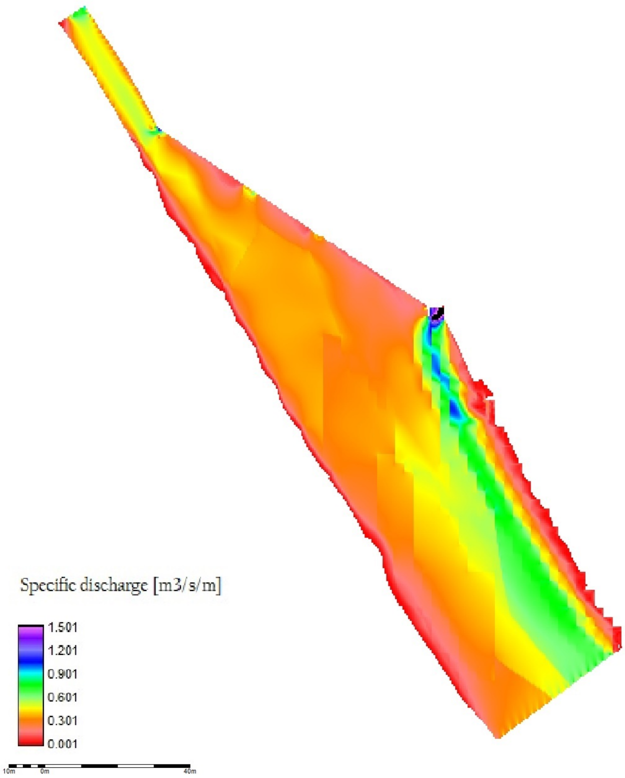


Figure 4.30: Mery Site - Channel displacement + deep incisions 2, 4



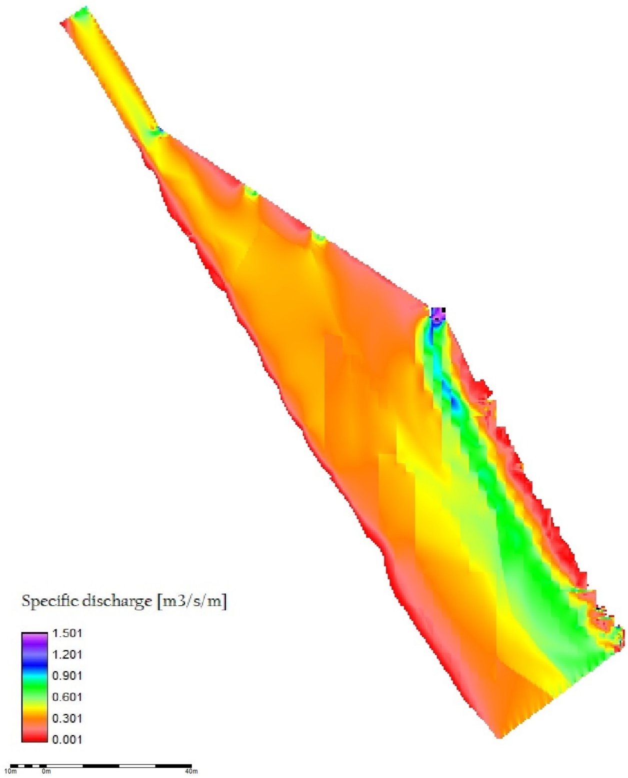


Figure 4.31: Mery Site - Channel displacement + incisions 2, 3 and 4

Figure 4.32: Mery Site - Channel displacement + deep incisions 2, 3 and 4

In the figures above 4.29, 4.30, 4.31 and 4.32 there is no major difference observable. The only observation to make is that the first combination shows a slightly lower discharge on the left part in front of the weir leading towards the intake channel of the Kaplan turbine.

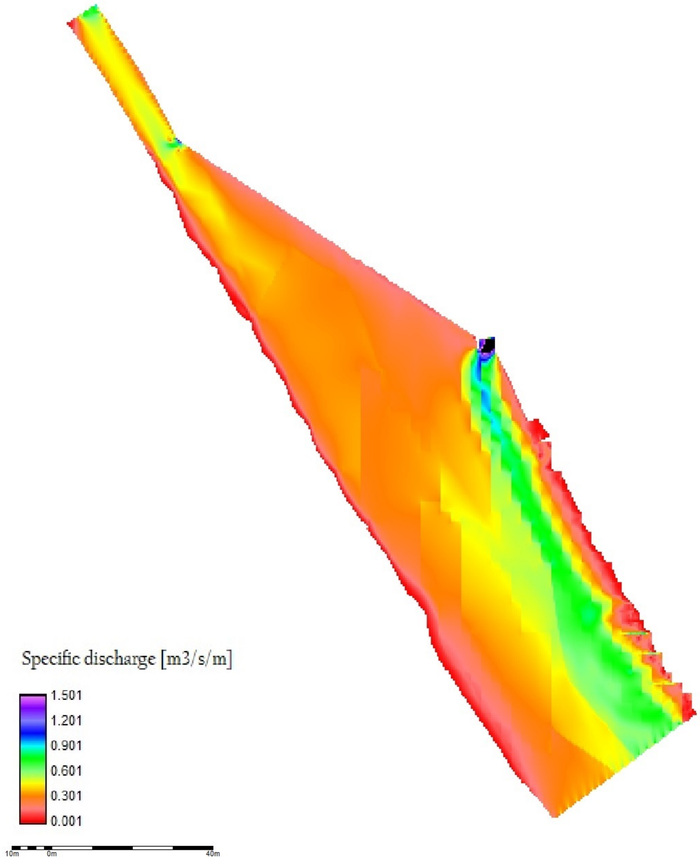


Figure 4.33: Mery Site - Channel displacement + closed incisions

Figure 4.33 represents the discharge with all the incisions closed, it has the lowest discharge on the left part leading towards the turbine as the yellow part is the most faded from all 5 combinations.

2.2.2 Quantitative observations

As for the qualitative observations no difference of influence on the discharge is observed, this subsection focuses on the quantitative analysis at the cross-sections.

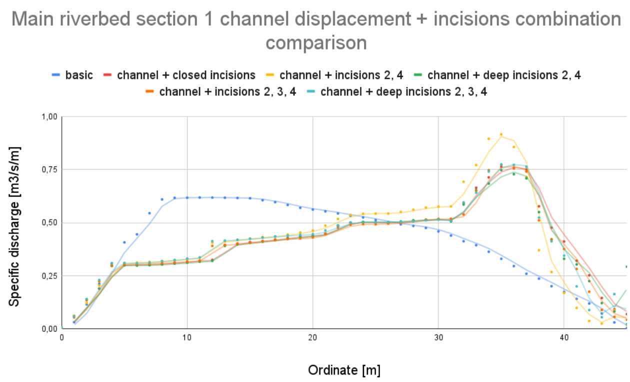


Figure 4.34: Mery Site - Main riverbed section 1 channel displacement combinations

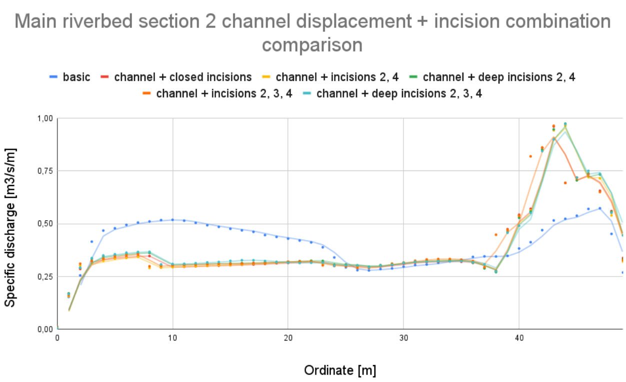


Figure 4.35: Mery Site - Main riverbed section 2 channel displacement combinations

In figure 4.34 the only combination with a higher flow on the right edge of the riverbed is observed with the as-built openings 2 and 4. The other combinations all perform in a same manner, without a major difference.

For the next cross-section in the main riverbed in front of the Archimedes screw, which is represented in figure 4.35, no huge difference for any of the combinations is observable in terms of maximal value. Only a displacement to the right can be observed for the methods using the combination of deepened incisions which therefore push the main discharge slightly towards the right side of the riverbed.

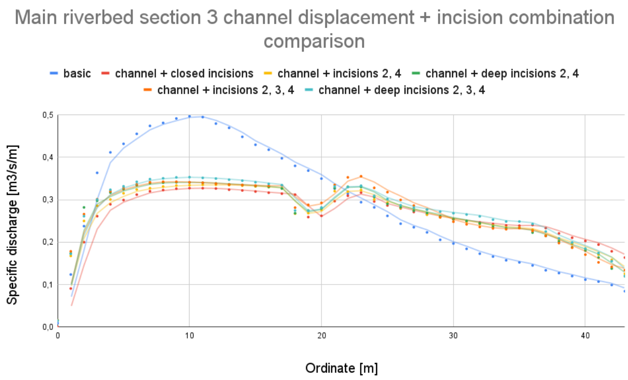


Figure 4.36: Mery Site - Main riverbed section 3 channel displacement combinations

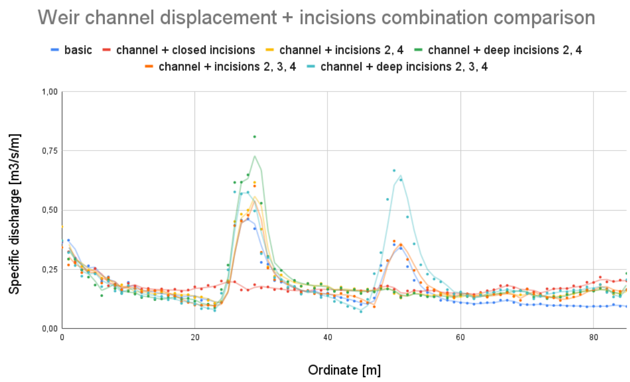


Figure 4.37: Mery Site - Weir section channel displacement combinations

Figure 4.36 shows that for all the incision gates combinations the discharge at the main riverbed section 3 directly behind the Archimedes screw is distributed in a same way. In between the different combinations there is no major difference observable.

Figure 4.37 represents the discharge directly in front of the weir, as observed for the other methods the discharge is high in front of an incision if the corresponding gate is opened, but no major difference is observed for the gates. Another small observation is that for the combination with no incision opened the discharge is higher towards the right side of the weir.

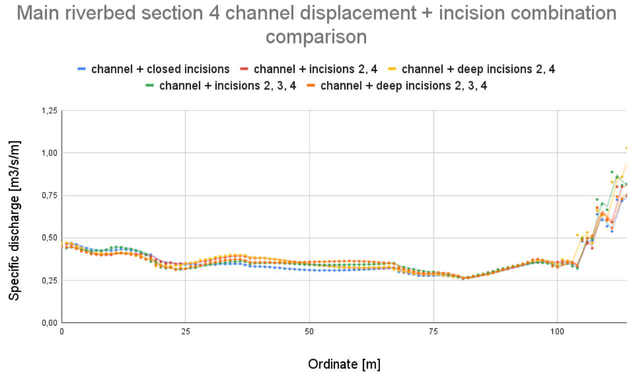


Figure 4.38: Mery Site - Main riverbed section 4 channel displacement combination

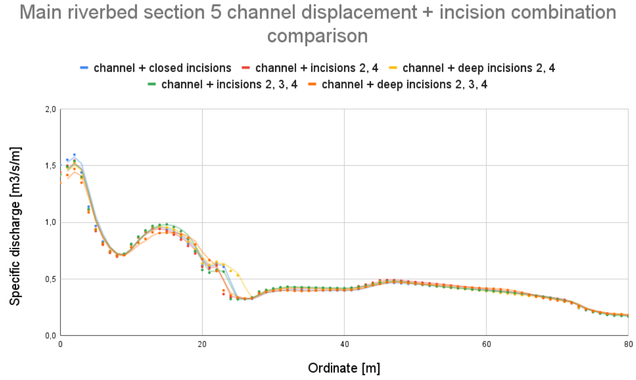


Figure 4.39: Mery Site - Main riverbed section 5 channel displacement combination

The cross-sections for the river bed at sections 4 and 5 are represented in the figures 4.38 and 4.39. For both of the sections no clear change of the specific discharge is observed. Thus there is no combination that outperforms the other as the discharge leading towards the Archimedes screw is the same and also in terms of interruption of the flow towards the intake channel from the turbine the methods perform in a similar way. Although it can be said that the method with all the incisions closed might produce the best results as the discharge in the mid section from the cross-section is the smallest and in front of the Archimedes screw and the right side of the weir, the discharge of this combination is the highest, even if those are minor differences.

2.2.3 Interim Conclusion

As with the focus only on the discharge no conclusion on the best performing method is observed, the next most crucial parameters are the velocity and the water depth. Therefore the velocity favoring downstream migration is plotted on the following graphs. The grey cells represent a zone with a velocity less then 0,2 [m/s], this zone is avoided by fish because such low velocities cause disorientation and favor predation.

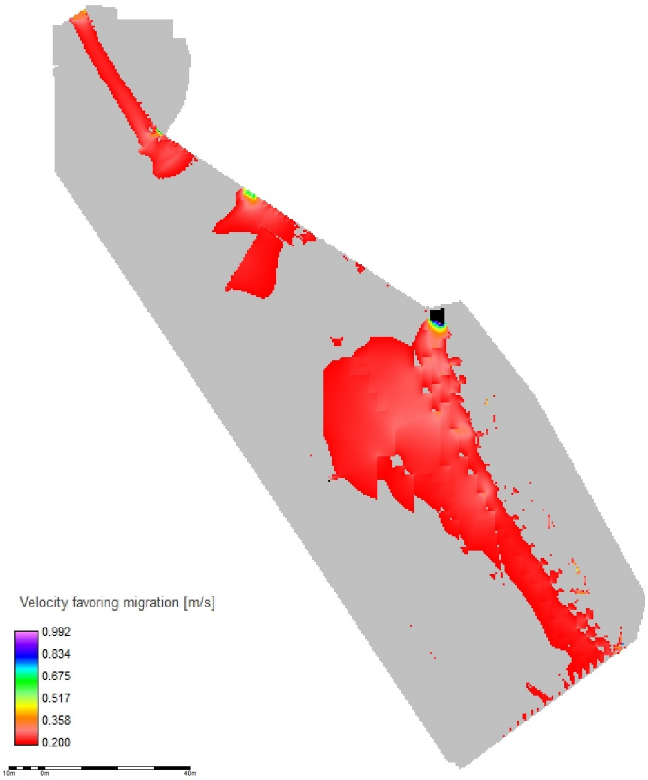


Figure 4.40: Mery Site - Velocity favoring downstream migration - channel displacement + incisions 2, 4

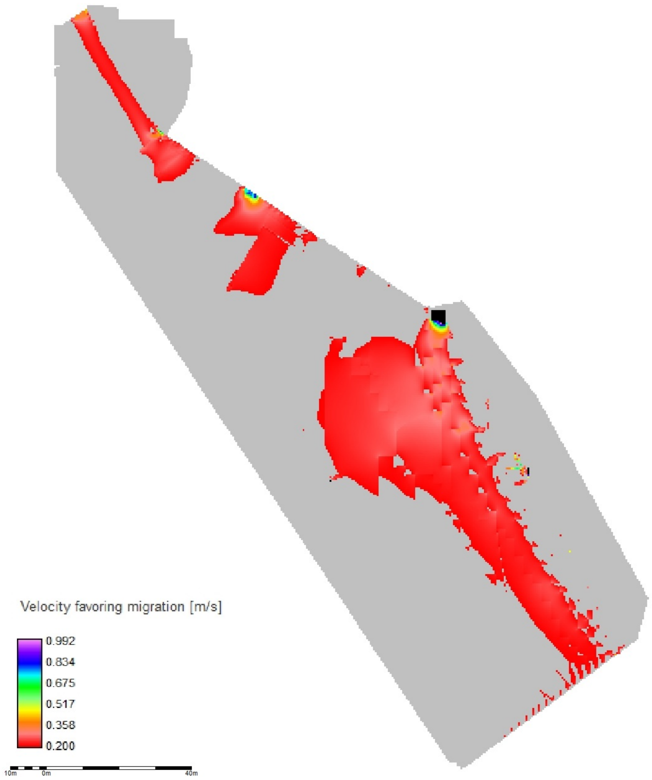


Figure 4.41: Mery Site - Velocity favoring downstream migration - channel displacement + deep incisions 2, 4

In the figures above, the velocity is plotted for the combination of a channel displacement with an opening of the as-built in figure 4.40 and with deepened incisions 2 and 4 in figure 4.41. A clear cut in the velocity is observed after the zone next to the Archimedes screw. For the case with deepened incisions the zone influenced of the incision 2 is larger and also the zone influenced by the intake of the Kaplan turbines compared to the as-built layout.

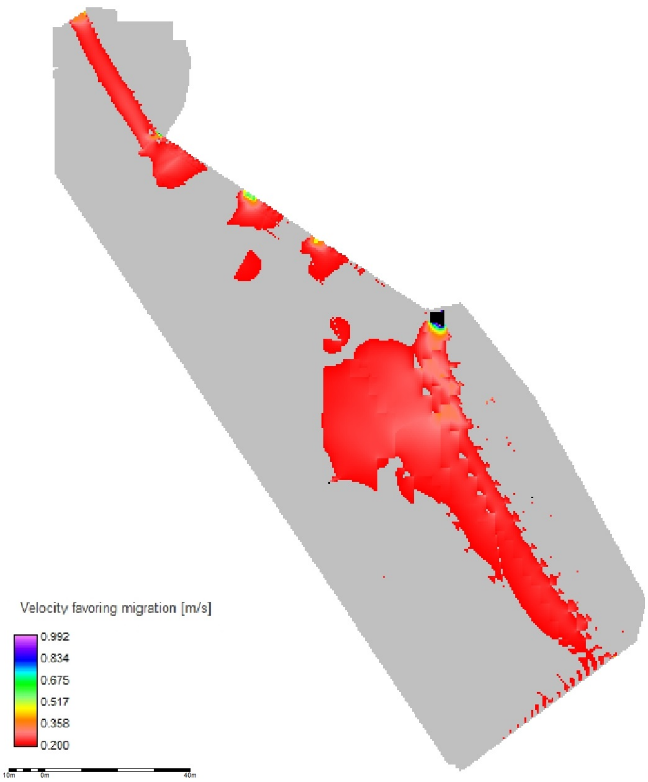


Figure 4.42: Mery Site - Velocity favoring downstream migration - channel displacement + incisions 2, 3, 4

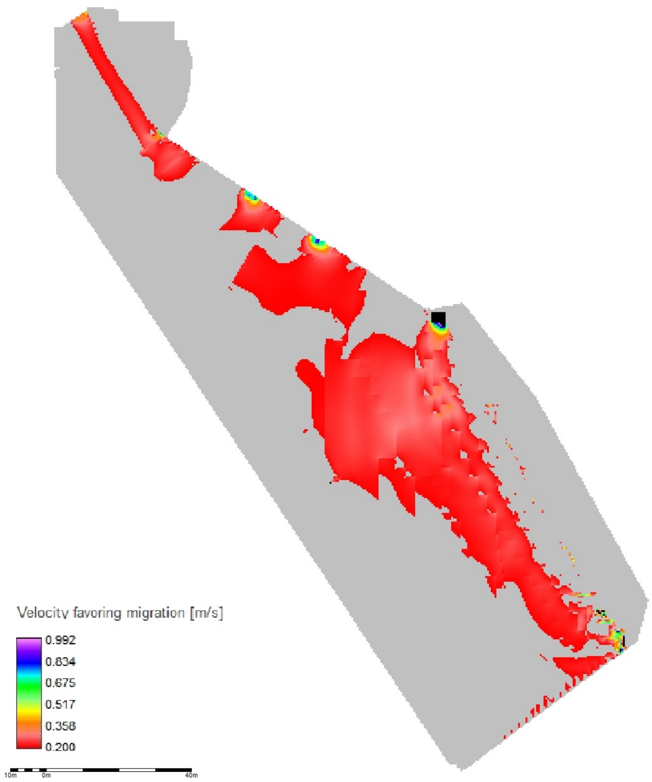


Figure 4.43: Mery Site - Velocity favoring downstream migration - channel displacement + deep incisions 2, 3, 4

These figures represent the velocity of the combinations of as-built (figure 4.42) and deepened incisions 2, 3 and 4 shown in figure 4.43. Compared to the previous figures the zone next to the Archimedes screw is larger. The influence of the incision 3 is a lot bigger for the deepened incision combination and connects to the approach zone next to the screw. The zone of influence of the incision 2 is smaller as the zone of the previous combinations, but is not connected to the upstream parts. The influence of the intake channel is bigger for the as-build layout.

Thus the combination with the deepened incisions has the advantage to lead fish that passed the influence region of the Archimedes screw towards the incision gates which are classed as a favorable migration route.

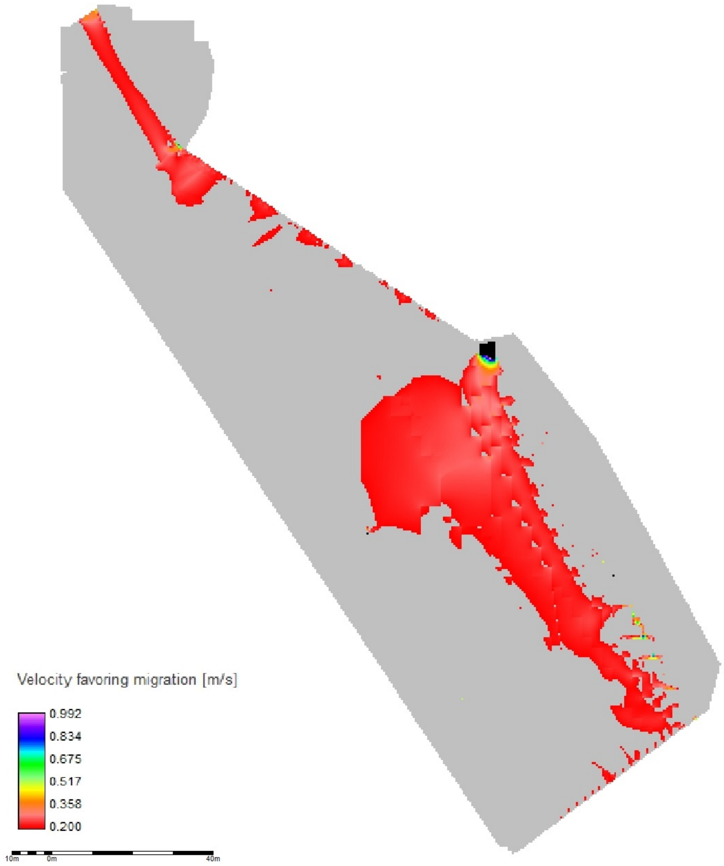


Figure 4.44: Mery Site - Velocity favoring downstream migration - channel displacement + closed incisions

The last representation of favorable velocity regions is represented for the case with all the incisions closed in figure 4.44. This outlay has the widest cut between the approach zone and the intake channel from the turbine. Another observation is that it has small zones with favoring velocity all along the weir which could be due to a more regular flow over the weir because the water level should also be higher.

Thus the methods that are performing best in terms of velocity are the combination of deepened incisions 2, 3 and 4 or all of the incisions closed. The method with closed incisions has the advantage that the velocity has no continuous favorable pattern further downstream as the Archimedes screw. Another favorable point is that because of the velocity distributed along the weir fish that arrive at the Archimedes screw and swim along the weir could be lead to take the weir as migration route. On the other hand the method using the deepened incisions has the advantage that if the smolts pass by the screw there is a bigger area leading them towards an other safe migration route although these regions don't show the exact direction in which the smolts are guided. To define which is the best in terms of water depth that favor fish to use the weir the water depth is plotted in front of the weir.

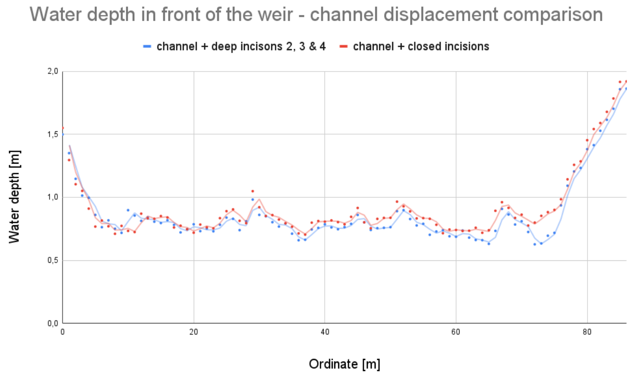


Figure 4.45: Mery Site - Weir section water depth - Channel displacement combinations comparison

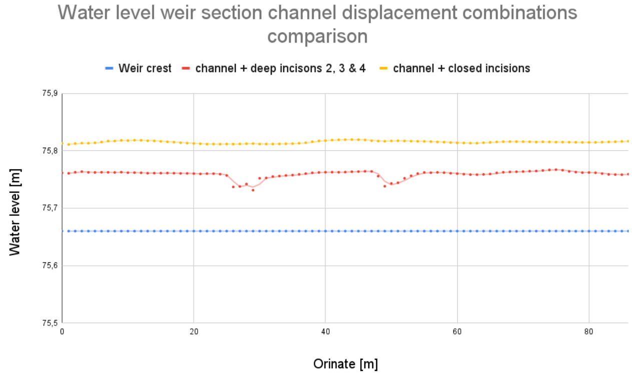


Figure 4.46: Mery Site - Weir section water level - channel displacement combinations comparison

Figure 4.45 represents the water depth at the weir cross-section and figure 4.46 shows the water elevation of the channel combinations and the weir crest. The left figure shows that the depth is higher for the combination of all incisions closed except for the part next to the intake channel of the Kaplan turbine. The right figure shows that the water level is higher for the closed incision is higher over the whole site. It has to be pointed out that the incision openings are missing on the figure and therefore the difference comes when comparing the level to the depth on the left weir side. This favors a passage over the weir on the middle and right side, as the water depth passing over the weir used by fish has to be as high as possible. Another positive aspect is that because of the higher water level more water could be dedicated to energy production reasons.

2.2.4 Conclusion

The conclusion that can be made in terms of choice for an optimal guiding of smolts to a safe downstream migration route is not easy as the method using the closed incision and the method using deepened incisions favor migration on the site in different manners. However as it is stated in the research that fish follow the main flow, when 2 main flows are present they choose the flow which corresponds on which side they are released. Since the channel is placed on the right border and there has to be a connection upstream to connect it to the channel which is in place on the left border, the fish from both sides are guided to the right border when approaching the site. Furthermore, the cut of favorable velocity is focused more towards the Archimedes screw for the combination with closed incisions. Next comes the fact that velocity favoring migration is in a favorable range all along the weir and the water depth next to the weir is higher for the closed incision combination. Those conditions are all favorable to guide the migrating smolts towards a safe route which is the Archimedes screw or the weir. Finally it can be stated that the outlay of the site with all the incisions closed is the best performing combination with the realisation of a channel displacement in the main riverbed.

2.3 New rack + incision 1

This method aims to increase the discharge of the incision 1 in front of the new placement of the bar rack to guide fish past the Mery station. The incision 1 can be seen as some kind of bypass in this configuration. Figure 4.47 represents the outlay of this method.

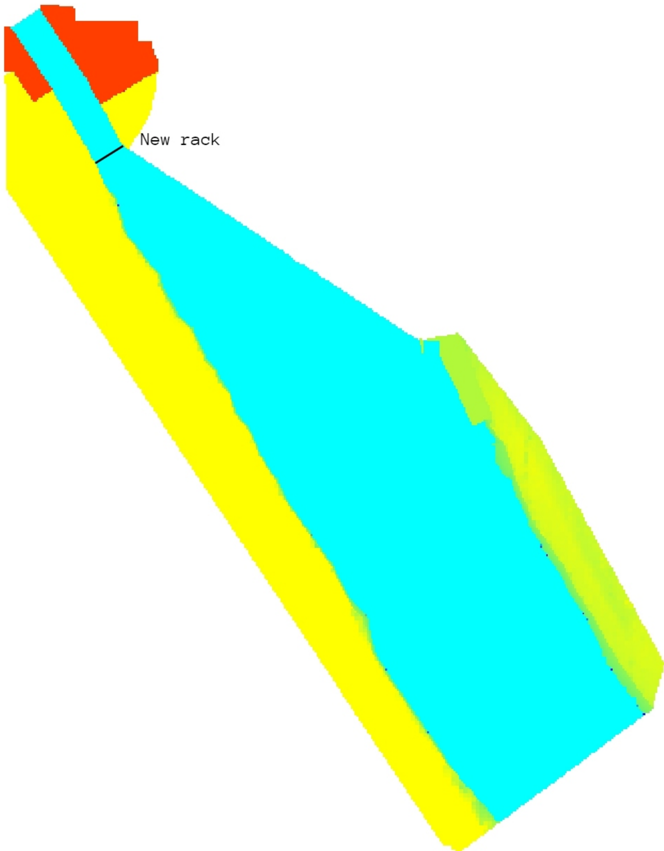


Figure 4.47: Mery Site - New placement of trash rack configuration

Thus to analyse this method, to favor downstream smolt passage at the Mery site, the only incision which is opened is the incision 1 itself.

		Incision outlays		
		Cubic	Wide	Complete
Width	[m]	0,75	1	0,25
Depth	[m]	0,75	0,5	1,96

Table 4.2: Incision layouts tested

Table 4.2 shows the geometric parameters of different layouts from the incision 1 analysed. The first test is performed with a deepened depth of $0,5[m]$ and a width of $1[m]$. The second test is performed using a cubic layout with a width and depth of $0,75[m]$. The last layout is inspired by research and uses a thin width of $0,25[m]$ and an depth reaching until the bottom of $1,96[m]$.

2.3.1 Qualitative analysis

In the figures the specific discharge is represented for different configurations of the incision 1.

For figures D.5, D.7 and D.9 there is no difference observable between the 3 outlays. The figures D.6, D.8 and D.10 represent a zoom on the section with the incision 1. For this area there is only a slight difference observable with the highest discharges represented at the configuration with the narrow incision and a depth reaching to the bottom of the weir until the topographic height of the riverbed.

2.3.2 Quantitative analysis

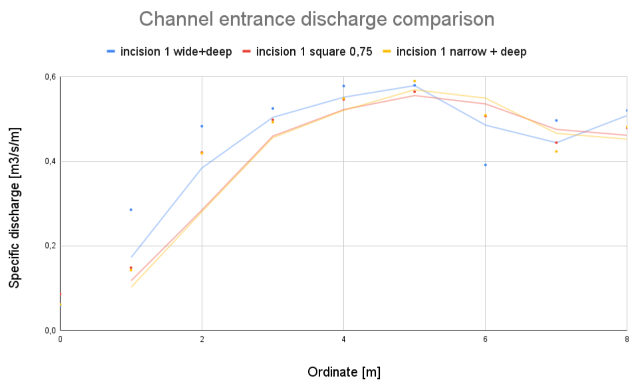


Figure 4.48: Mery Site - Channel entrance discharge incision 1 comparison

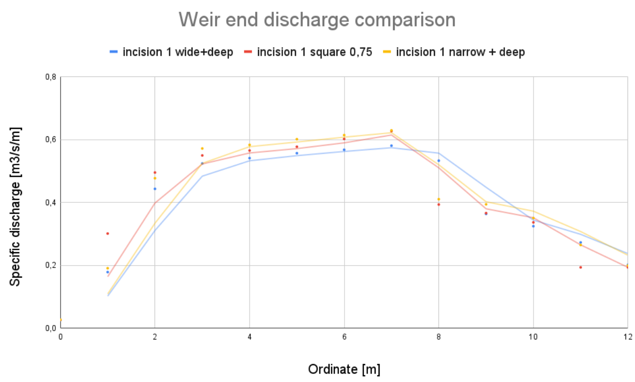


Figure 4.49: Mery Site - Weir end discharge incision 1 comparison

Figure 4.48 shows the specific discharge distribution at the entrance of the intake channel while the figure 4.49 shows the specific discharge distribution at the end of the weir next to the incision 1. It can be seen that for the channel entrance the specific discharge is higher in general for the wide outlay. At the weir end section the discharge reaches the highest value for the complete incision outlay.

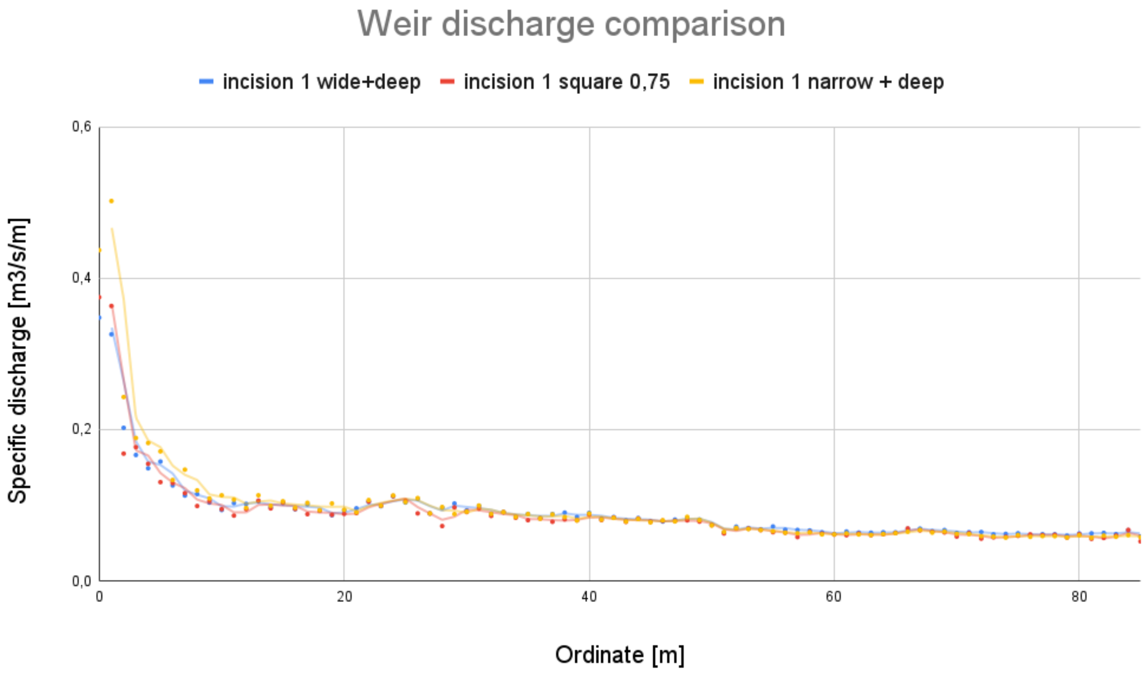


Figure 4.50: Mery Site - Weir discharge incision 1 comparison

Figure 4.50 represents the specific discharge at the weir cross-section. It shows that the discharge is the highest for the outlay of the complete incision in front of the incision gate. For the rest of the weir, the discharge stays the same for all the configurations.

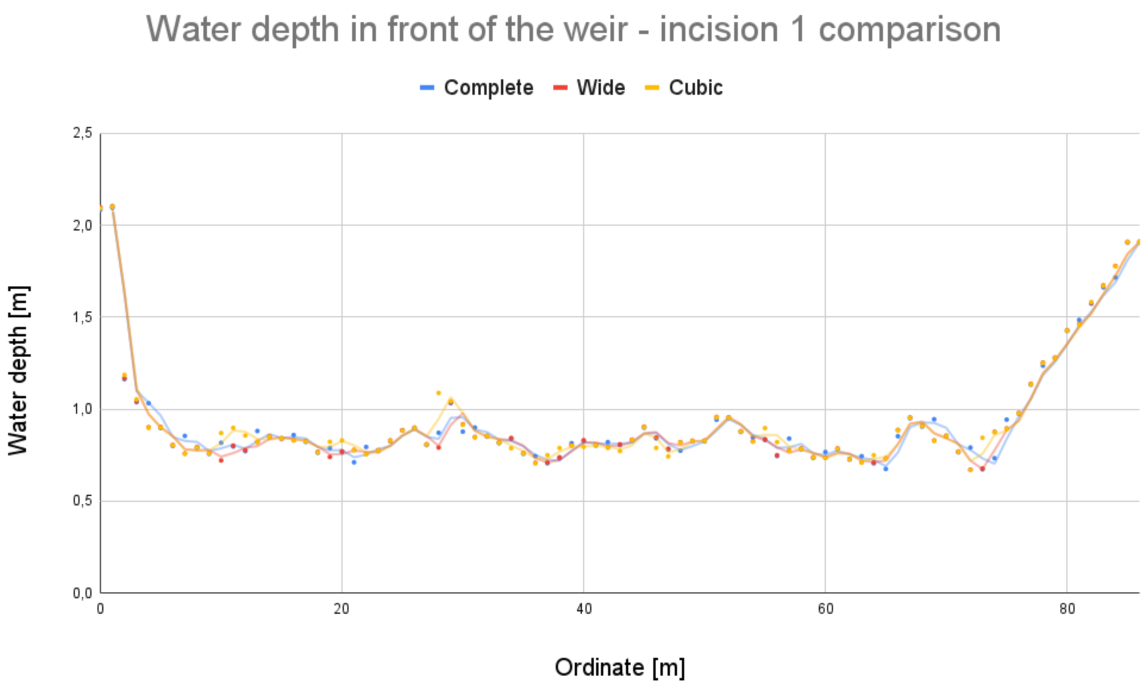


Figure 4.51: Mery Site - Water depth in front of Weir incision 1 comparison

Figure 4.51 represents the water depth in front of the weir. The depth seems to be quite similar for all of the incisions.

2.3.3 Conclusion

Thus there is no major difference observable for the different outlays except for the discharge in front of the incision 1. From a fish migration perspective the most valuable solution by far is the complete incision outlay as with this the fish can migrate with all possible water levels. Another strong point is that with this outlay the migration is also achieved for other species as eels for example.

3 Final comparison

At this section the best performing solutions are compared at 3 different discharge scenarios. As the previous sections only used 1 discharge, in this section there are 2 more investigated. As it is known that when the discharge is really high there is no problem in terms of downstream migration as the main flow is directed towards the weir and the water depth passing over the weir is deep enough. Therefore lower discharges are the most crucial. The lowest additional discharge is defined by taking a discharge with the minimal discharge going through the energy production facilities majored by 10% as represented on the table 4.3 below.

Calculation of minimal inflow debit		
Archimedes	6,4	[m3/s]
Kaplan	3,3	[m3/s]
10 % majoration	1,0	[m3/s]
Total	10,7	[m3/s]

Table 4.3: Discharge scenario 2 calculation

The other additional discharge is taken higher as the initially used, but smaller as the discharge leading the main flow completely over the weir, thus the table 4.4 shows the discharges as inflow of the site used and the corresponding discharge going out through the hydroelectric turbines.

	Discharge		
	Scenario 1	Scenario 2	Scenario 3
	[m3/s]	[m3/s]	[m3/s]
Inflow debit	18,4	10,7	26,5
Kaplan turbine	3,3	3,3	6,4
Archimedes screw	6,5	6,4	6,6

Table 4.4: Discharge parameters

Each scenario is analysed separately to see the behavior of the different configurations at the specific discharge simulated. For each scenario first the discharge is investigated, then the velocity and finally the water depth. Those hydraulic parameters are the dominant factors guiding smolts in their downstream migration behavior.

3.1 Scenario 1

The first discharge scenario is the one analysed already under the previous sections.

3.1.1 Discharge

The specific discharge is the first parameter analysed, because it is the main parameter that defines large scale migration behavior as smolts tend to follow the main flow until reaching an obstacle.

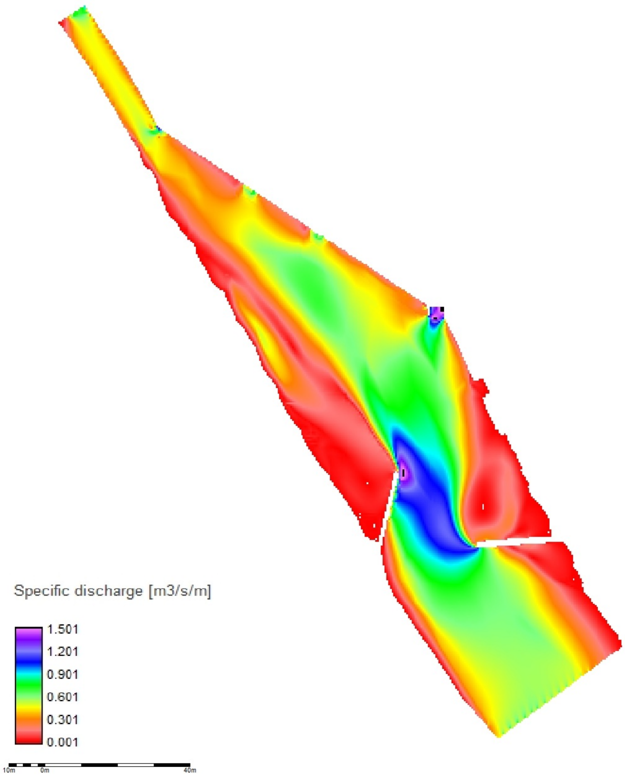


Figure 4.52: Mery Site - 2 guiding walls specific discharge scenario 1

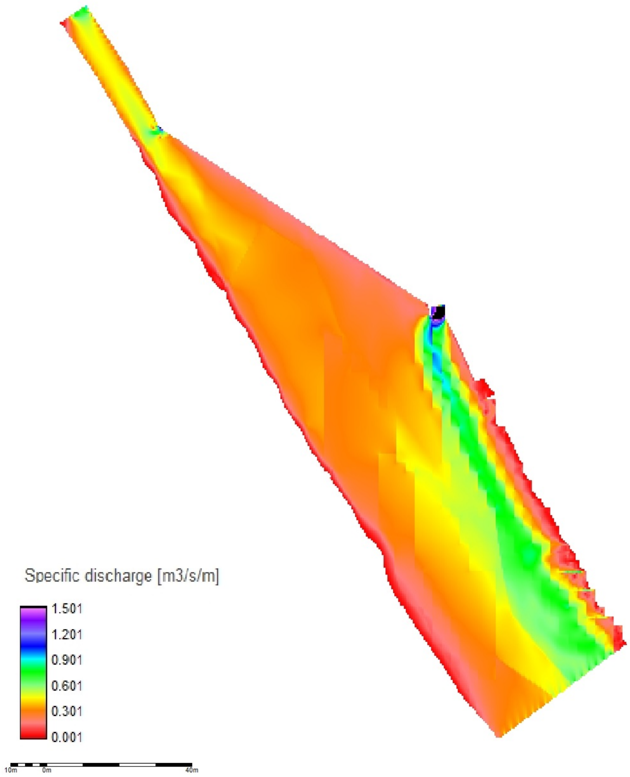


Figure 4.53: Mery Site - channel displacement specific discharge scenario 1

The figures 4.52 and 4.53 represent the specific discharge for the Mery site for the outlay with 2 flow guiding structures on the left and a channel displacement outlay on the right.

It can be seen that for the case of flow guides the main flow is guided towards the Archimedes screw but it is also flowing further towards the incision gates 2 and 3. From the incision 2 towards the intake channel of the Kaplan turbine the discharge is significantly lower.

On the other hand the method with a channel displacement guides the main flow towards the Archimedes screw, but with this outlay there is no main flow going further towards the intake channel.

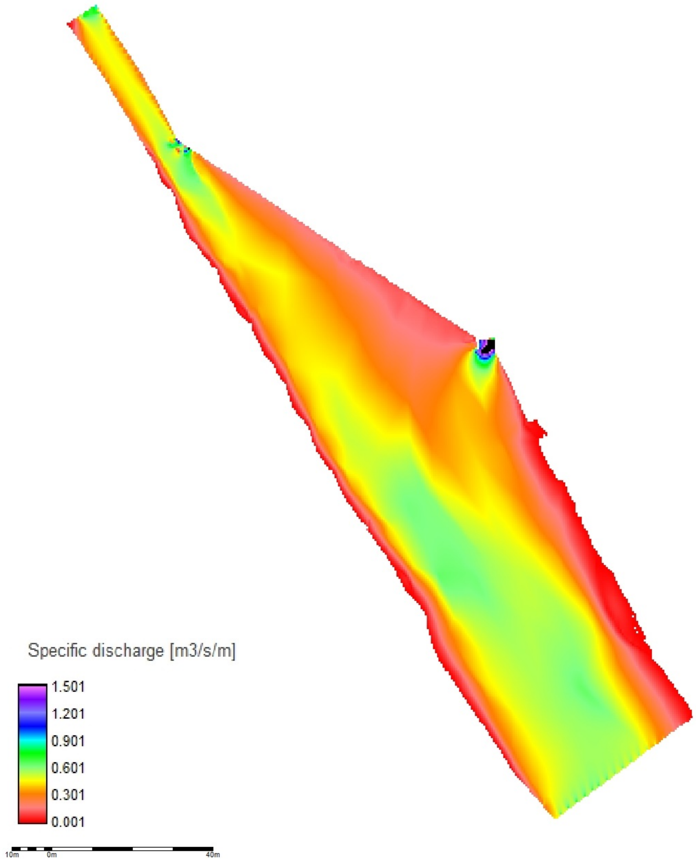


Figure 4.54: Mery Site - incision 1 specific discharge scenario 1

Figure 4.54 represents the main flow in the case of the outlay with a trash rack combined with a modified incision 1. It can be observed that the main flow is basically in the same shape as for the initial configuration as the site is nowadays. The only difference is that the main flow in the area next to the intake channel of the Kaplan turbine is larger.

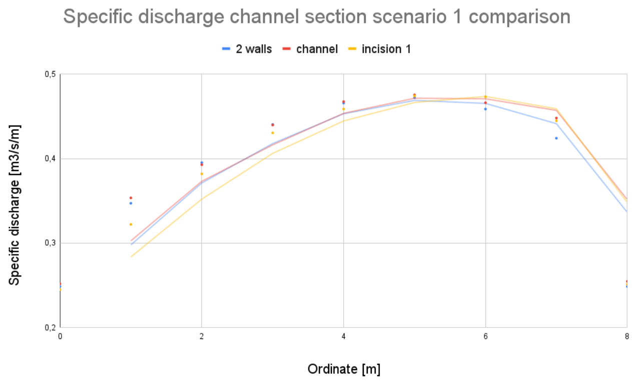


Figure 4.55: Mery Site - Channel section specific discharge scenario 1 comparison

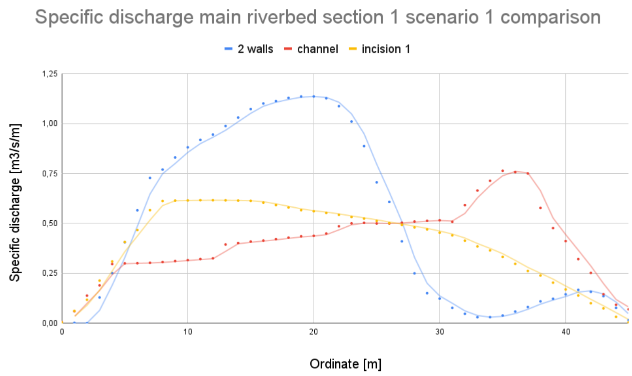


Figure 4.56: Mery Site - Main riverbed section 1 specific discharge scenario 1 comparison

Figure 4.55 represents the specific discharge distribution in the intake channel of the Kaplan turbine. It shows that there is no major difference between the different outlays.

In the next figure 4.56 the discharge is represented at the main riverbed cross-section 1. The method using 2 flow guides has a much higher discharge on the left side because of the influence from the first flow guide and a lower discharge on the right side as it crosses the recirculation part behind the guide. The method using a channel displacement has the highest discharge on the right river border. The method with the new incision 1 shows that the specific discharge over the whole cross-section stays pretty regular. It is performing in between the 2 methods in terms of discharge distribution.

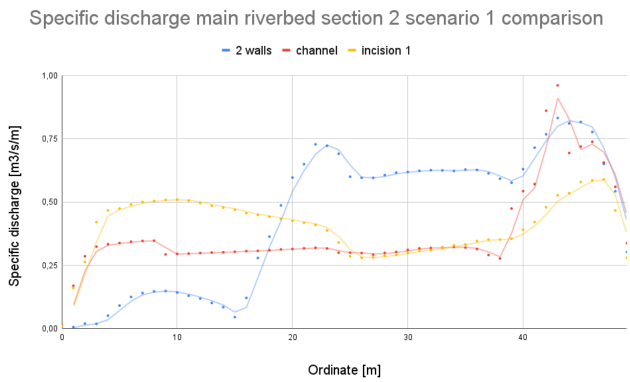


Figure 4.57: Mery Site - Main riverbed section 2 specific discharge scenario 1 comparison

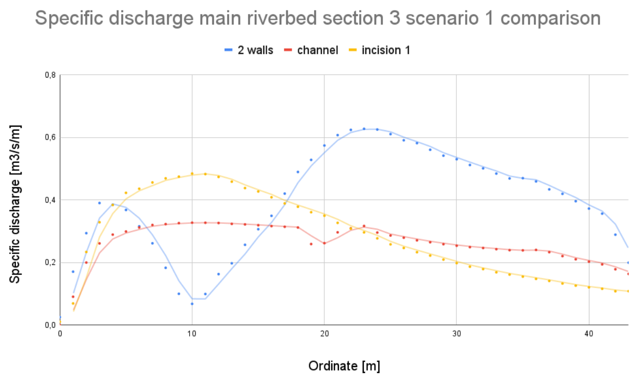


Figure 4.58: Mery Site - Main riverbed section 3 specific discharge scenario 1 comparison

Figure 4.57 shows the discharge distribution at the main riverbed section 2 in front of the Archimedes screw. The outlay with 2 flow guides has the highest overall discharge at the middle and right section. The channel outlay has the highest peak of specific discharge in front of the Archimedes screw, while the method of installing a bar rack with a changed incision 1 produces the highest discharge on the left river border.

Figure 4.58 representing specific discharge at the cross-section 3 of the main riverbed shows that for the method with 2 guiding walls the discharge is the highest on the right side and on the left side a peak is observable because it is situated at the recirculation area. The channel displacement method has a regular discharge which is slightly higher on the left border. At the left it creates the lowest discharge while on the right the discharge is slightly higher as the incision 1 method. This is because most of the discharge leaving the model is situated on the right part of the weir and the Archimedes screw.

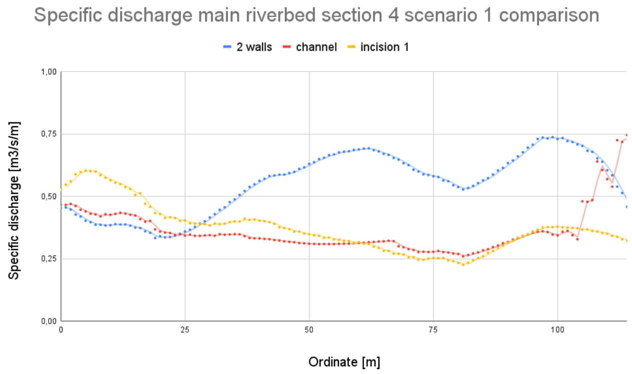


Figure 4.59: Mery Site - Main riverbed section 4 specific discharge scenario 1 comparison

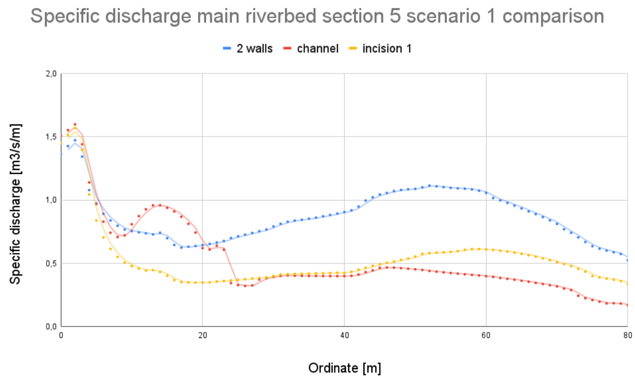


Figure 4.60: Mery Site - Main riverbed section 5 specific discharge scenario 1 comparison

The figures above show the discharge for the main riverbed cross-section 4 in figure 4.59 and section 5 in figure 4.60. It can be seen that the discharge is the highest in front of the Archimedes screw for all three methods.
The flow guide method has the highest overall discharge over both of the cross-sections, but also has the lowest discharge near the intake channel of the Kaplan turbine. For section 5 it has the highest discharge because the cross-section goes through the area in between the 2 guides. Using a channel displacement the discharge leading towards the screw is overall the highest as for section 4 it is highest on the right side and for section 5 it is the highest on the left side of the cross-section. Using this method the discharge on the rest of these cross-sections is quite regular.
The method using a bar rack with an incision 1 has the highest discharge in front of the incision 1 represented at section 4 and the second highest in front of the Archimedes screw represented at section 5. For the rest of both of these cross-sections this method keeps the specific discharge quite regular.

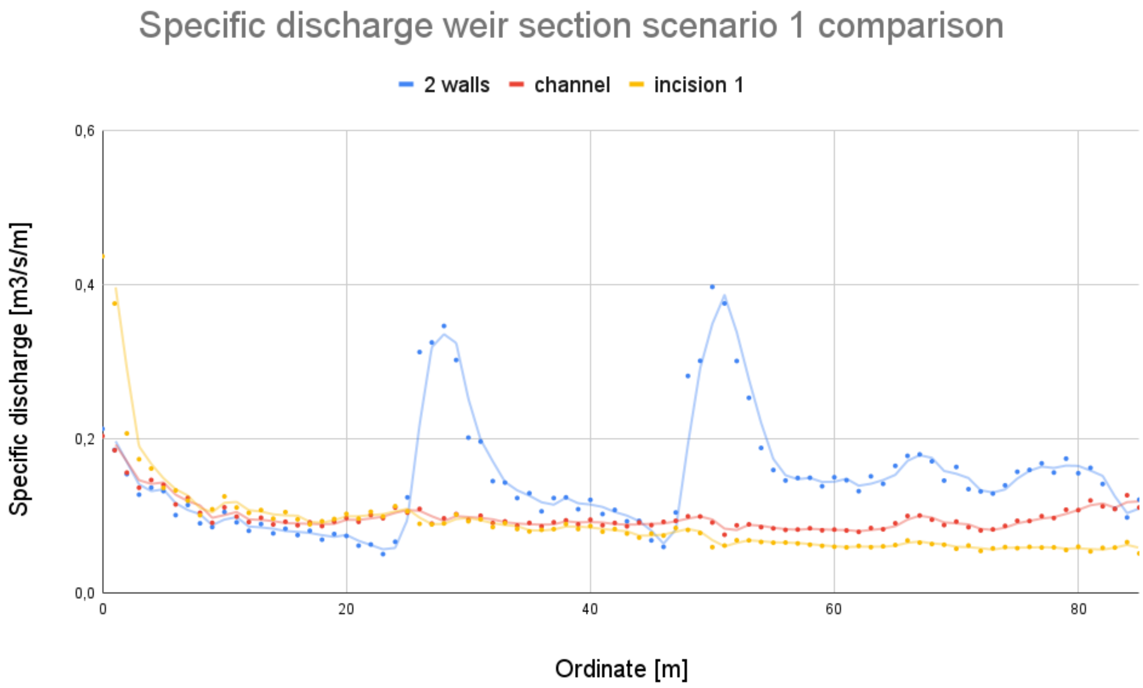


Figure 4.61: Mery Site - Specific discharge in front of the weir scenario 1 comparison

The last figure 4.61 represents the specific discharge passing over the weir. The method using the guiding walls produces the highest discharge passing over the weir on the middle section and on the right, with peaks in front of the incision 2 and 3, on the left this method has the lowest discharge passing over the weir.

The method using the new channel placement has the same outlay as the incision method which is quite obvious as none of the incisions 2, 3 and 4 are opened but the specific discharge is higher towards the right side of the weir.

The outlay changing the incision shows the highest discharge on the left in front of the incision 1 and the lowest discharge on the right side.

3.1.2 Velocity

Next the velocity favoring migration is observed. The following figures represent the area with a velocity favoring migration.

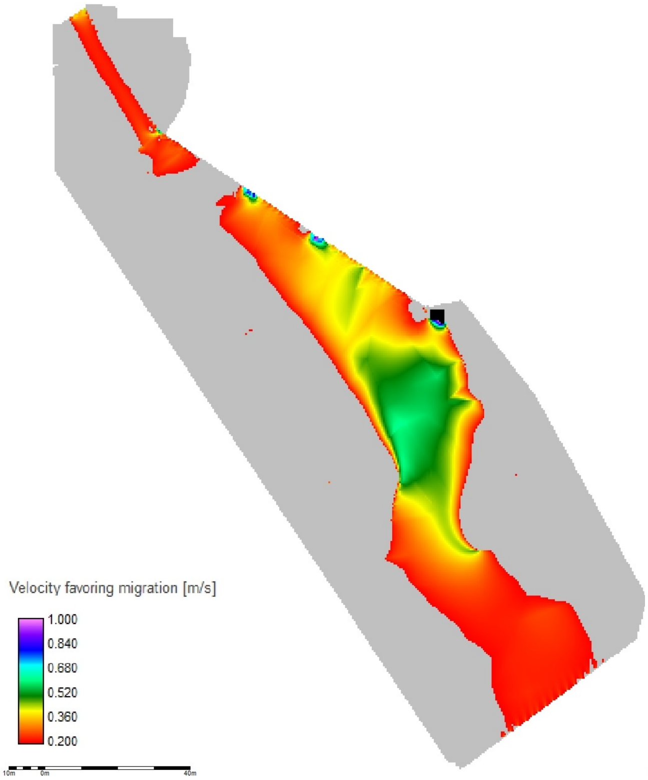


Figure 4.62: Mery Site - 2 guiding walls velocity favoring migration scenario 1

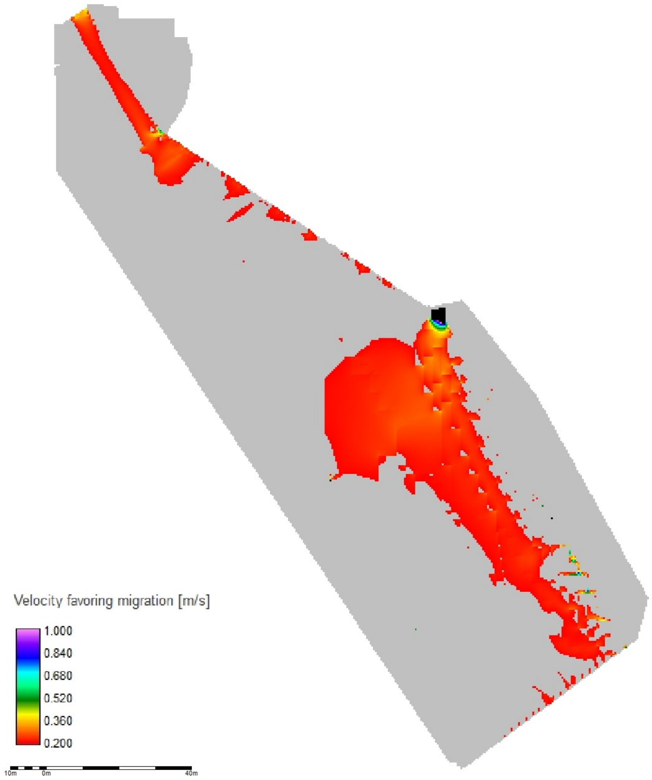


Figure 4.63: Mery Site - channel displacement velocity favoring migration scenario 1

In the first figure 4.62 the velocity in the range favoring migration is continuous over the most parts of the weir especially in front of the incision gates 2 and 3. It is also continuous from the approach zone, entrance of the system, until the Archimedes screw. Only between the intake channel and the incision 2 is a discontinuation observable.

The next figure 4.63 represents the downstream migration favoring velocity for the case of a channel displacement. It can be seen that the velocity leading towards the Archimedes screw is in a good range. After that the figure shows a huge discontinuation but has some favoring areas along the weir.

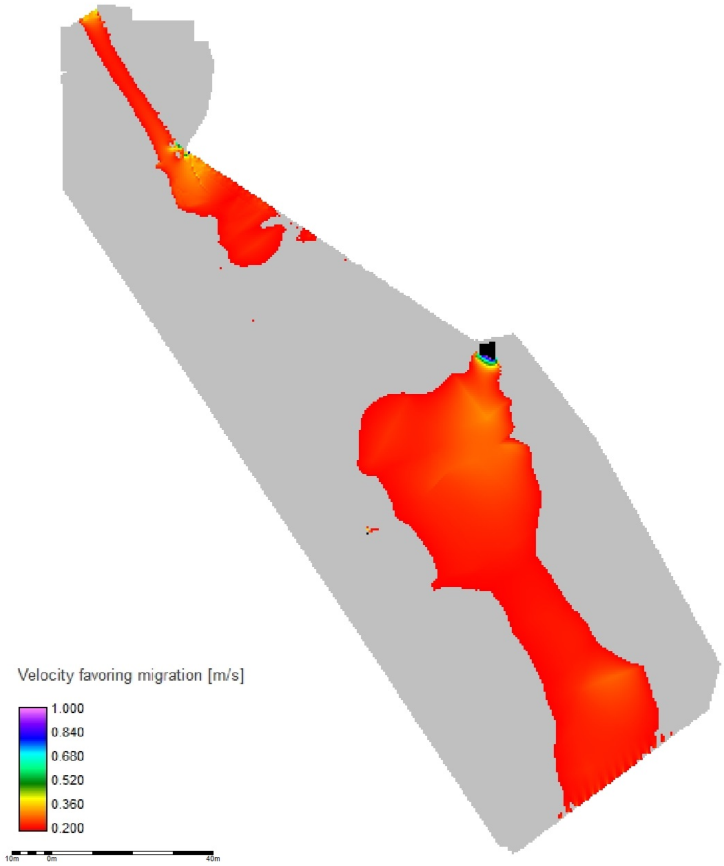


Figure 4.64: Mery Site - incision 1 velocity favoring migration scenario 1

The last figure 4.64 represents the favorable velocity for the outlay with the incision 1. It shows a continuation towards the Archimedes screw but also a huge discontinuation for the area after the screw. The area in front of the intake channel of the Kaplan turbine is the largest but there is no distribution of favorable zones in front of the rest of the weir.

3.1.3 Water depth

At this section the water depth favoring downstream migration is represented for the different outlays.

It can be seen in the figures 4.65, 4.66 and 4.67 that the water depth is favorable for the whole area, for every outlay of the site under hydraulic conditions from the scenario 1.

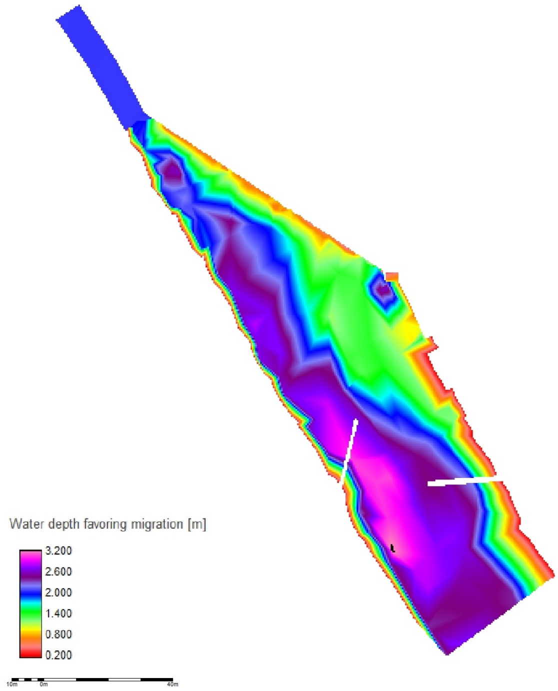


Figure 4.65: Mery Site - 2 guiding walls water depth favoring migration scenario 1

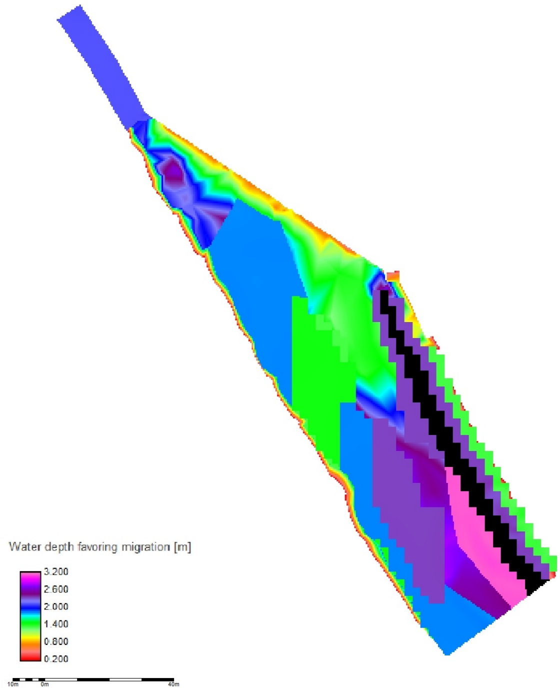


Figure 4.66: Mery Site - channel displacement water depth favoring migration scenario 1

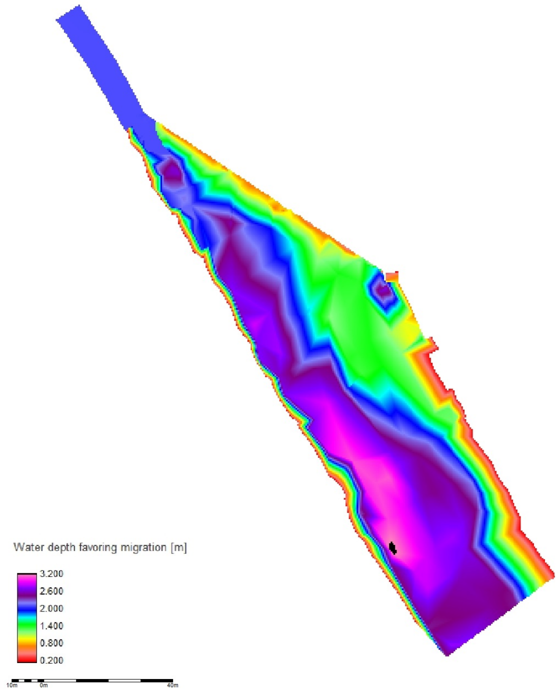


Figure 4.67: Mery Site - incision water depth favoring migration scenario 1

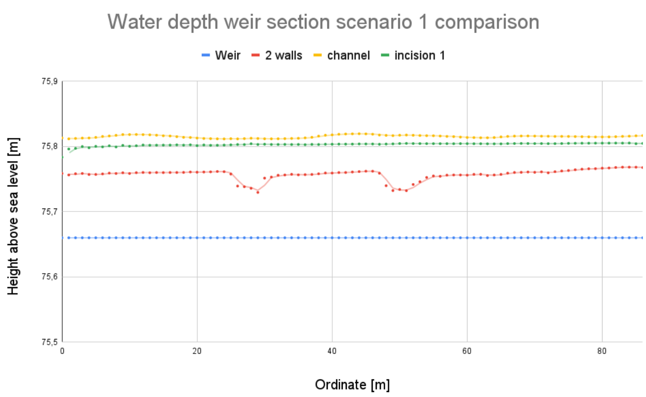


Figure 4.68: Mery Site - Weir section water level scenario 1 comparison

In figure 4.68 the water level is represented for each of the 3 outlays and also from the height of the weir. It can be seen that the depth of water running over the weir is the highest for the method using a new channel. However the method using a new incision performs also really well as it is only slightly lower. The outlay of 2 flow guides has the lowest depth, and with an even lower level at the incision gates. The representation of the incision gates is not shown on this graph as for the outlays of the incision 1 and the channel displacements the incisions 2, 3 and 4 were closed.

3.1.4 Conclusion scenario 1

Finally the conclusion for the scenario 1 can be taken.

While combining the observations from the discharge figures it can be deduced that the most effective of the methods in terms of discharge distribution favoring migration of smolts is the outlay with the channel displacement. This method does produce a generally high main discharge going towards the Archimedes screw and no main flow going further. Another positive thing is that the discharge going over the weir is still higher on the right side in front of the incision 4 compared to the other methods.

In a perspective of velocity the most favorable method is the one using a channel displacement too, as it has a quite large disruption of favorable velocity but still has some favorable velocity distributed all along the width of the weir. As fish tend to arrive in front of the Archimedes screw with this method they are mainly focused on the right side of the weir if they pass by the screw.

Lastly the best performing method in terms of water depth is the method using a channel displacement as it has the highest water level.

Thus the best method in regard of hydraulic conditions for downstream migration of Atlantic salmon smolts from scenario 1 is the method of using a new channel placement on the right river border with all the incisions closed.

3.2 Scenario 2

The scenario 2 is performed with the smallest intake discharge into the model with a discharge of $10,7[m^3/s]$. It represents the hydrodynamic parameters of the site under very low conditions.

3.2.1 Discharge

The first evaluated parameter is the discharge.

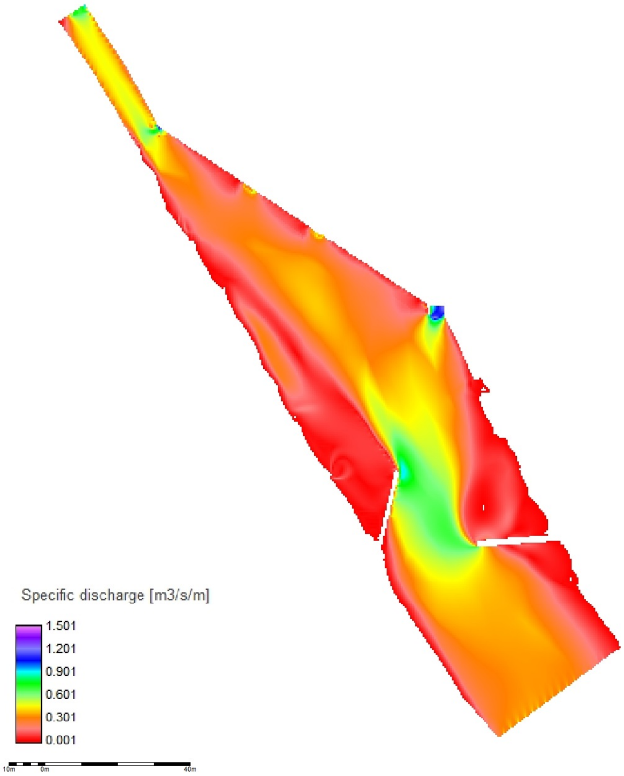


Figure 4.69: Mery Site - 2 guiding walls specific discharge scenario 2

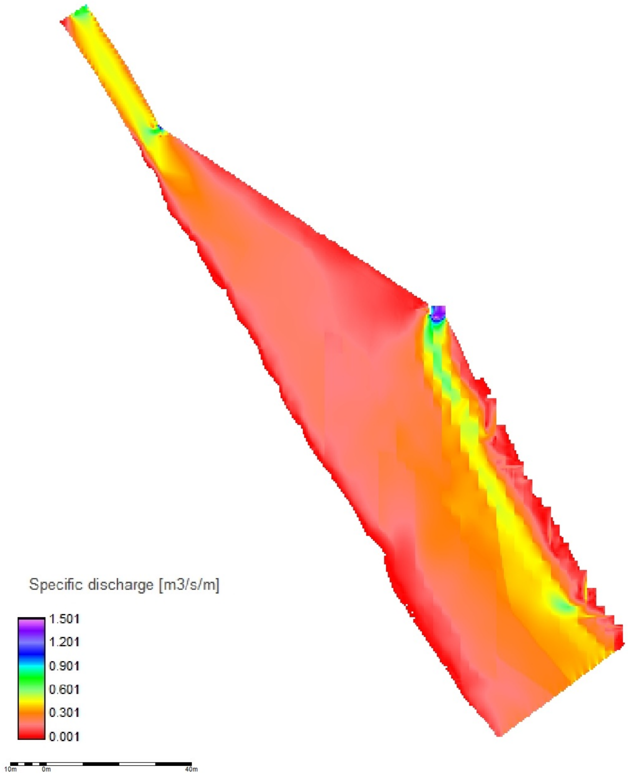


Figure 4.70: Mery Site - channel displacement specific discharge scenario 2

The first figure 4.69 represents the specific discharge distribution of scenario 2 with the outlay of the site with 2 flow guiding walls. It can be seen that the main flow is not completely continuous towards the Archimedes screw, nevertheless it is the highest in the area. Another observation is that there is no major connection of flow towards the weir and incision gates.

The second figure 4.70 shows the specific discharge distribution for the outlay of a channel displacement. It shows that the main flow is still continuous towards the Archimedes screw and no main flow is going further.

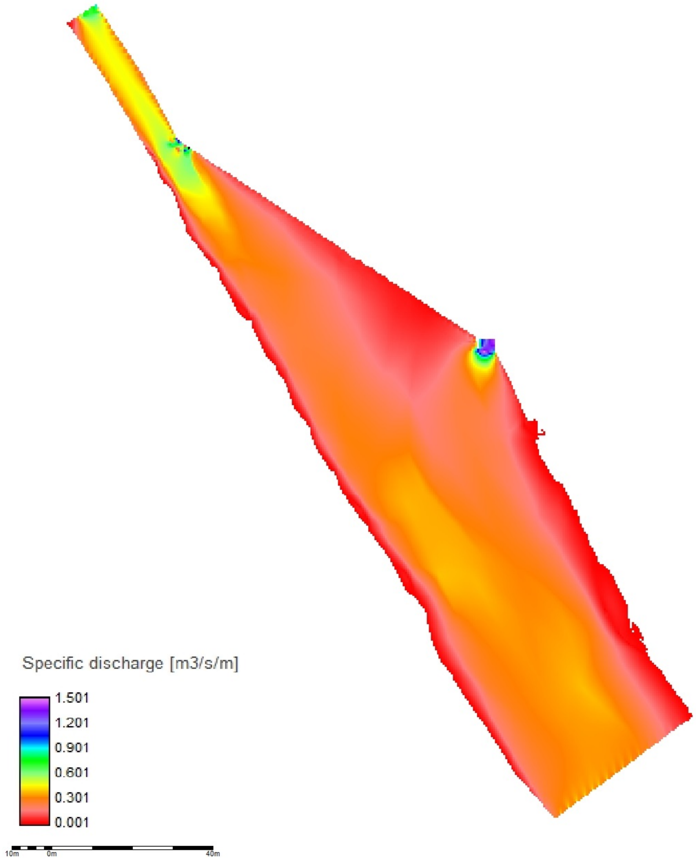


Figure 4.71: Mery Site - incision 1 specific discharge scenario 2

The last figure representing the specific discharge over the whole site 4.71 shows that there is no main flow but the flow over the whole site seems more or less evenly distributed.

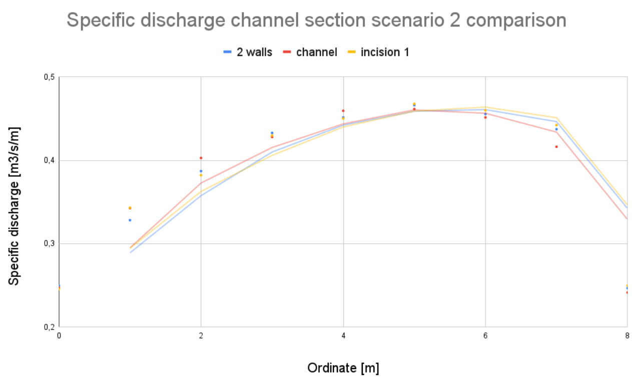


Figure 4.72: Mery Site - Channel section specific discharge scenario 2 comparison

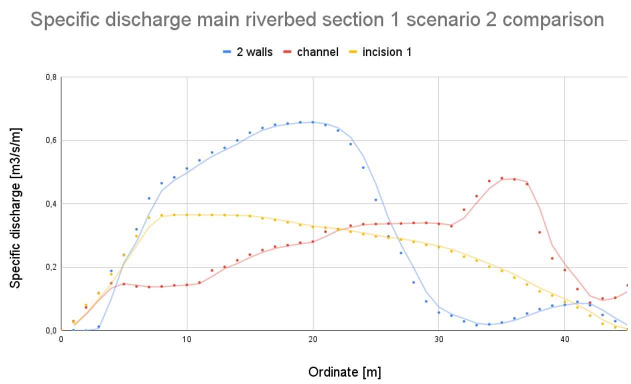


Figure 4.73: Mery Site - Main riverbed section 1 specific discharge scenario 2 comparison

The specific discharge at the channel cross-section is represented in figure 4.72. As for all the other cases no difference of the different outlays is visible.

Figure 4.73 shows the specific discharge distribution at the main riverbed cross-section 1. The allure of the different outlays is the same as for the simulation of scenario 1 which is illustrated in figure 4.56, but the values are not as high.

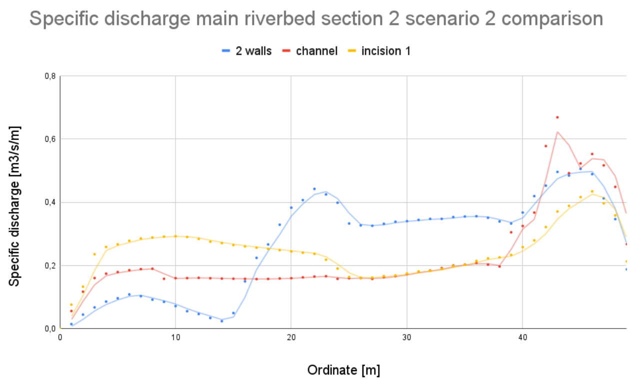


Figure 4.74: Mery Site - Main riverbed section 2 specific discharge scenario 2 comparison

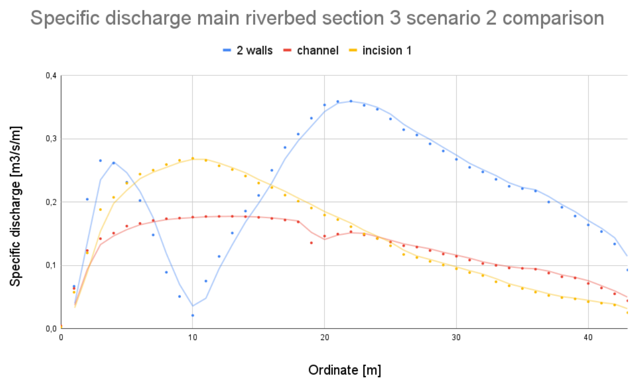


Figure 4.75: Mery Site - Main riverbed section 3 specific discharge scenario 2 comparison

The next figures 4.74 and 4.75 show the same specific discharge distribution as for the scenario 1 but also with lower values.

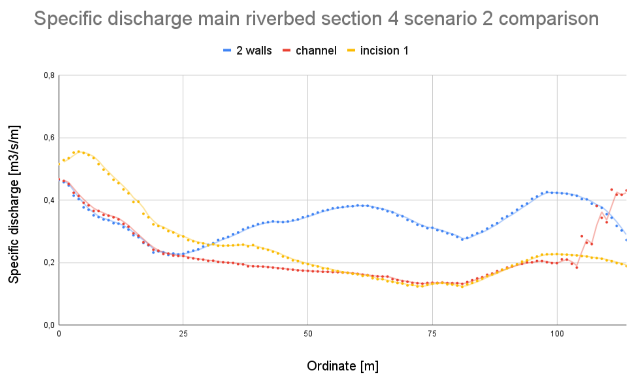


Figure 4.76: Mery Site - Main riverbed section 4 specific discharge scenario 2 comparison

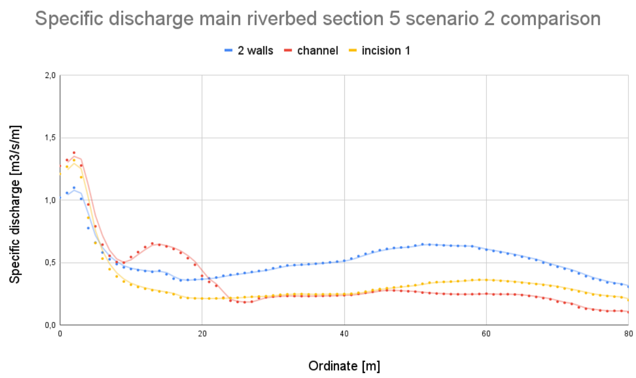


Figure 4.77: Mery Site - Main riverbed section 5 specific discharge scenario 2 comparison

The same observation is made for the figures 4.76 and 4.77.

Therefore the same conclusion for the discharge distribution at the site can be taken as for the scenario 1.

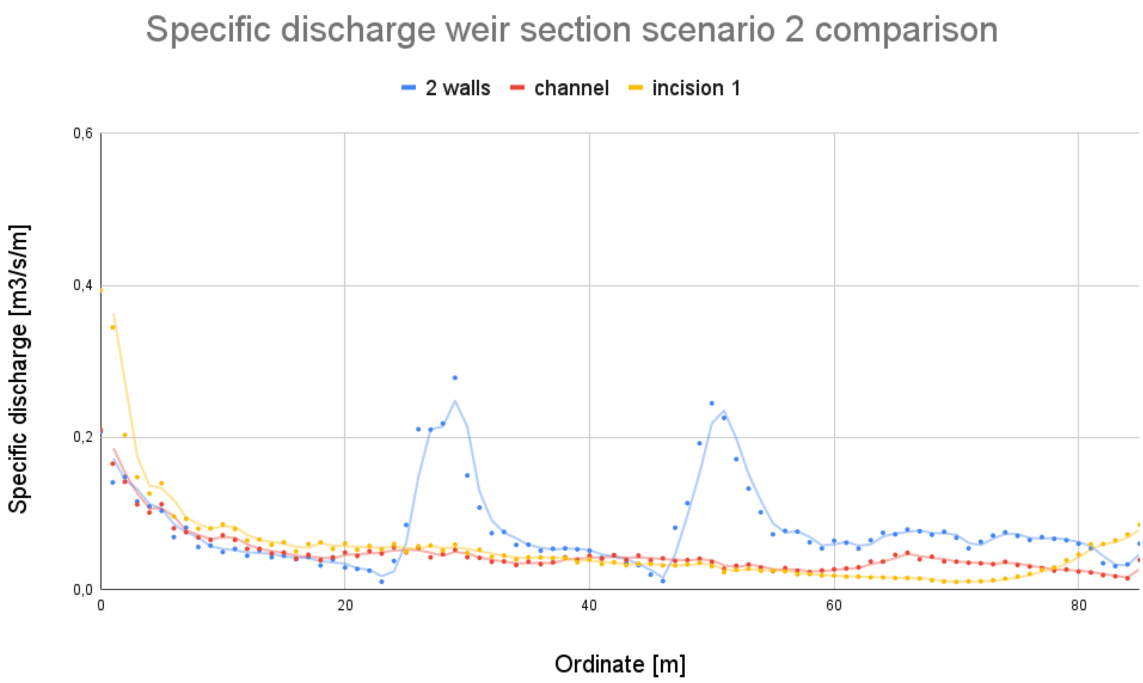


Figure 4.78: Mery Site - Specific discharge in front of the weir scenario 2 comparison

The last figure regarding discharge in front of the weir in figure 4.78, also shows a similar distribution as for the scenario 1 but with lower discharge values. The only difference can be observed for the right side of the weir where the outlay of 2 flow guide walls produces less high values compared to the 2 other outlays of the site.

3.2.2 Velocity

The next parameter analysed is the velocity distribution favoring migration.

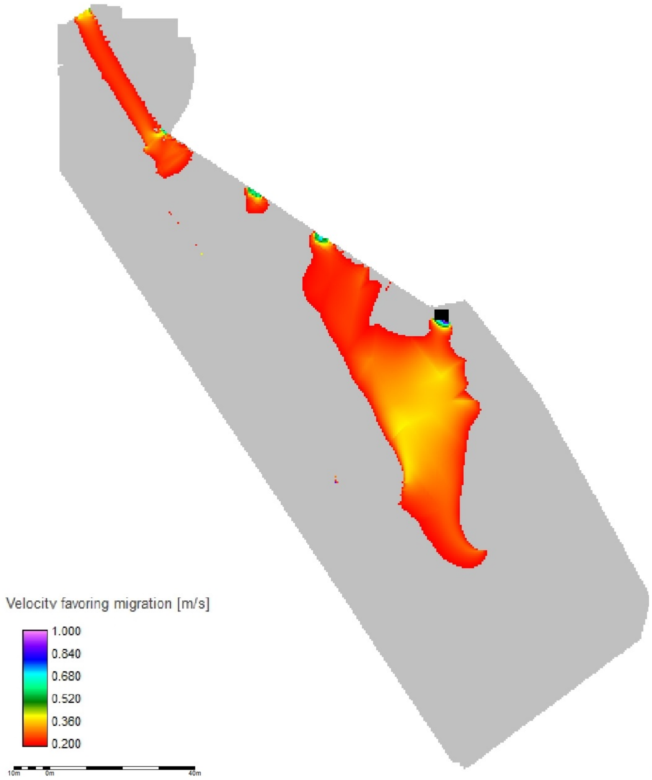


Figure 4.79: Mery Site - 2 guiding walls velocity favoring migration scenario 2

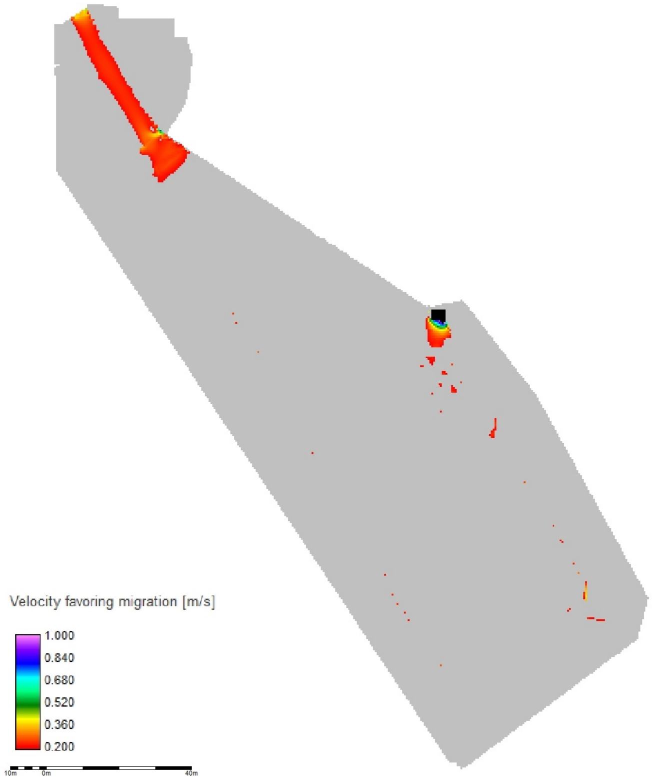


Figure 4.80: Mery Site - channel displacement velocity favoring migration scenario 2

Figure 4.79 shows a favorable velocity between the 2 flow guides which is continuous towards the Archimedes screw and also towards the incision 3. Although it is not continuous until the incision 2, the velocity leading into the model is not high enough to guide fish properly as the values are under $0,2[m/s]$.

On the right figure 4.80 it can be observed that the velocity over the whole site is not favorable for migration. There are only a few small areas in the region of the channel that show a favorable velocity. Along the weir there is no velocity favoring downstream migration observed at all.

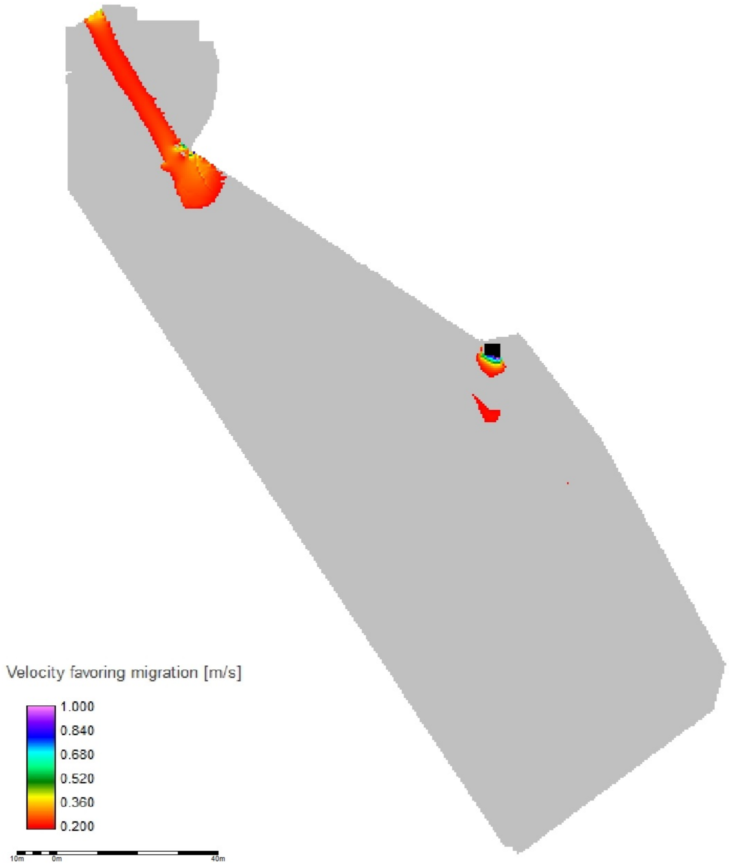


Figure 4.81: Mery Site - incision 1 velocity favoring migration scenario 2

On the last figure 4.81 representing velocity favoring migration it can be seen that nearly the whole site has unfavorable velocity values. Only in front of the Archimedes screw there is a small region within an acceptable range and in the intake channel of the Kaplan turbine.

3.2.3 Water depth

The last parameter analysed is the water depth.

The figures D.11, D.12 and D.13 represent the favorable water depth for migration of the Mery site similar to the scenario 1. Even for the very low hydraulic conditions the water depth is sufficient for whole the site regardless of the outlay of the site.

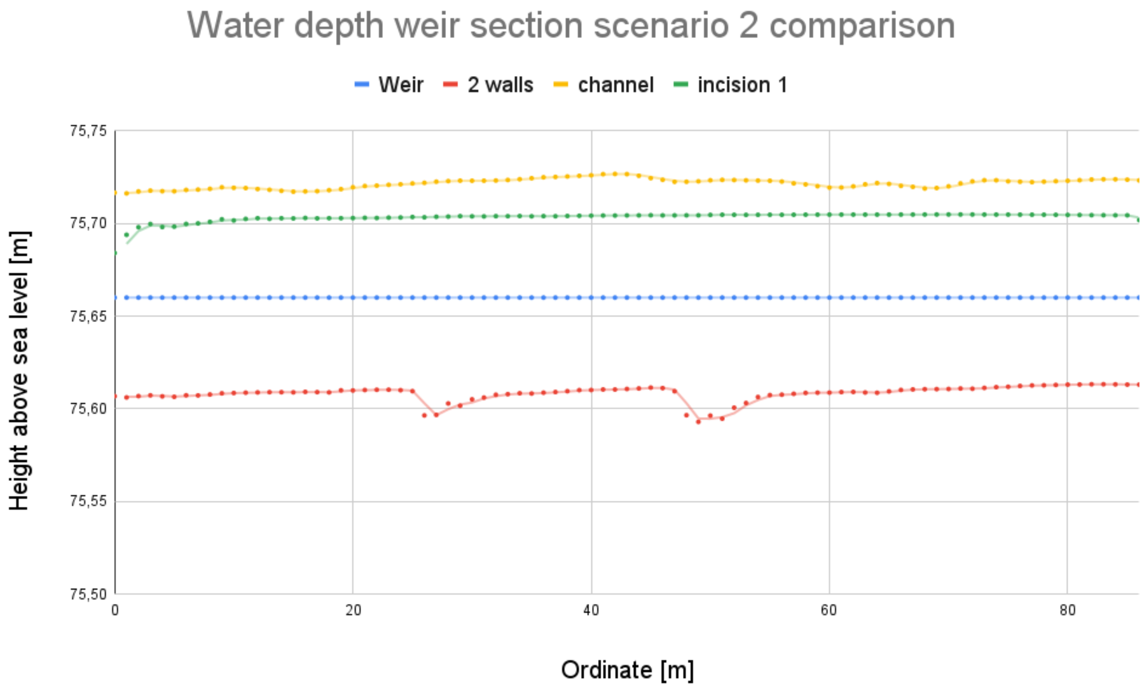


Figure 4.82: Mery Site - Weir section water level scenario 2 comparison

Figure 4.82 shows the water level in front of the weir for the 3 outlays and the height of the weir. It can be observed that the outlays of a new channel and of the incision gate generate a water level situated above the weir crest and thus fish can migrate over the weir. The highest water depth over the weir is observed for the channel outlay. The outlay using 2 flow guides has a lower water level as the weir crest, only in front of the incision openings the water can pass through the weir section.

3.2.4 Conclusion scenario 2

In terms of discharge the most favorable outlay combining the qualitative and quantitative observations the best performing method is the channel displacement as it is the only method that represents a continuous main flow to a secure migration path.

In regard of the velocity distribution the most efficient outlay is achieved with the construction of 2 flow guides. As when approaching the site the fish have to pass between the 2 flow guides and then are situated in a favorable zone of velocity which leads towards 2 favorable migration routes, the Archimedes screw and the incision 3.

Last the water depth is most favorable for migration in the case of the outlay using the channel displacement as it produces the highest water depth over the weir.

Finally it can be concluded that the most appropriated solution is achieved using the channel displacement method. It may be outperformed in terms of velocity distribution by the method using 2 flow guides but it is the best solution for the 2 other hydrodynamic parameters especially because the water depth for the flow guide outlay is not high enough at the weir. The specific discharge could be ameliorated by excavating the channel a little bit deeper in the middle or even with a more regular and smooth mesh.

3.3 Scenario 3

The last scenario analysed is simulated with an intake discharge of $26,5 [m^3/s]$.

3.3.1 Discharge

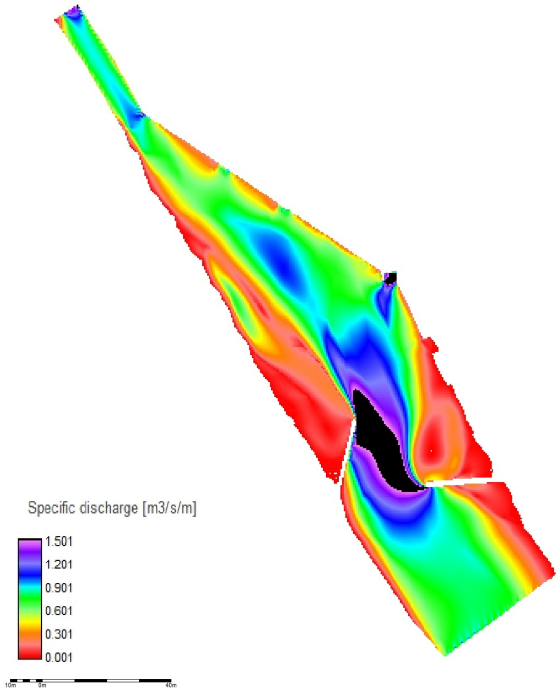


Figure 4.83: Mery Site - 2 guiding walls specific discharge scenario 3

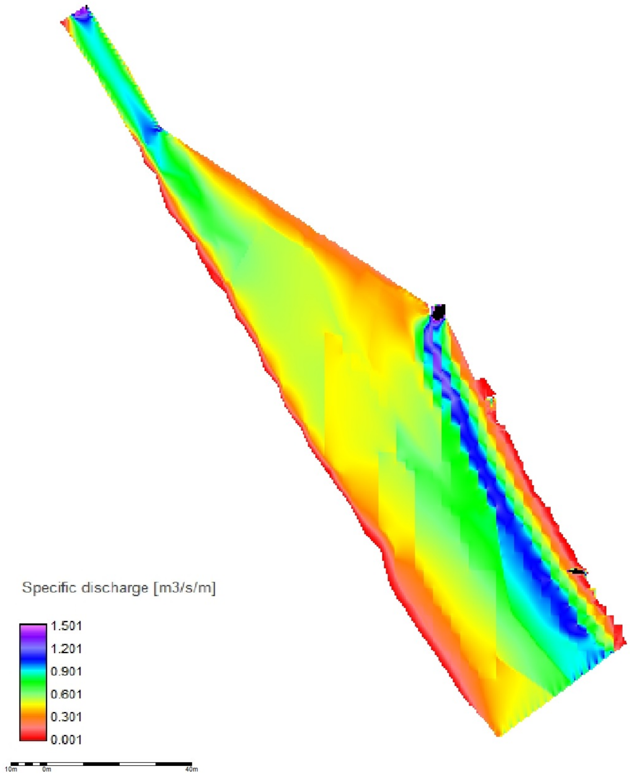


Figure 4.84: Mery Site - channel displacement specific discharge scenario 3

Figure 4.83 shows that the main flow is connected towards the intake channel of the Kaplan turbine and also toward the Archimedes screw, the weir and the incision gates 2 and 3 for the flow guide method.

The outlay with a channel displacement represented at the figure 4.84 has a main flow going towards the Archimedes screw. A high portion of the flow leads towards the intake channel of the Kaplan turbine, but a small disruption is seen in the area left of the Archimedes screw.

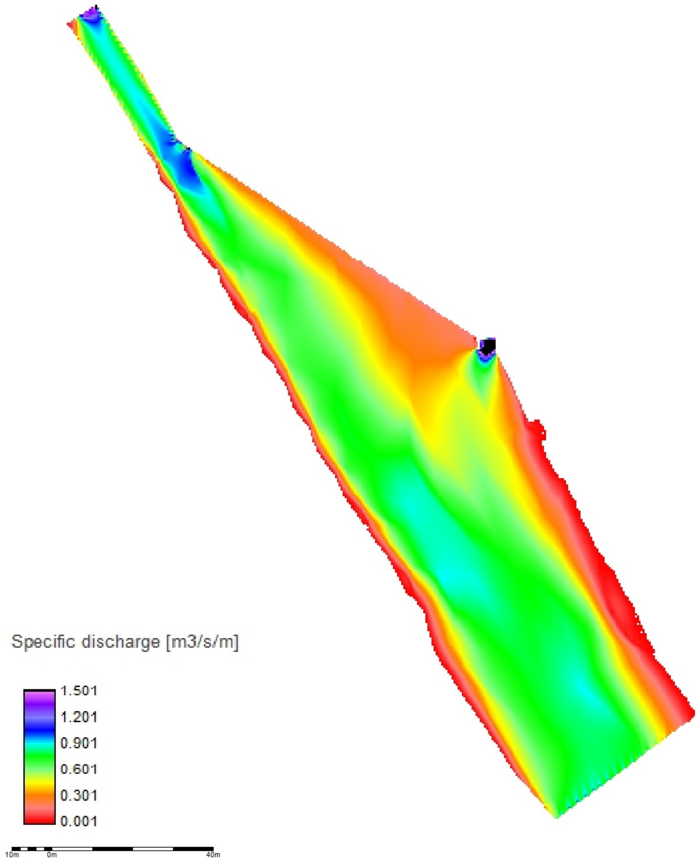


Figure 4.85: Mery Site - incision 1 specific discharge scenario 3

The last outlay with the incision 1 and a bar rack shown in figure 4.85 presents a main flow going towards the incision 1 and the intake channel. The flow directed towards the Archimedes screw is not completely connected as for the channel displacement method but the disruption is significantly smaller.

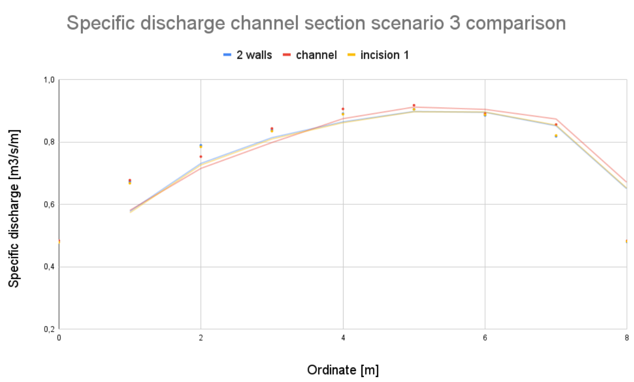


Figure 4.86: Mery Site - Channel section specific discharge scenario 3 comparison

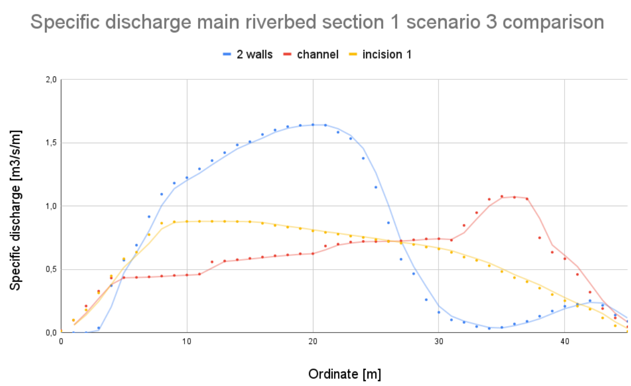


Figure 4.87: Mery Site - Main riverbed section 1 specific discharge scenario 3 comparison

Figure 4.86 representing the specific discharge in the intake channel shows again the same discharge regardless of the outlay of the site.

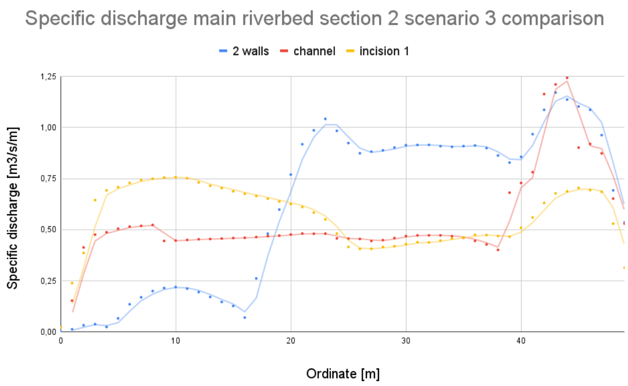


Figure 4.88: Mery Site - Main riverbed section 2 specific discharge scenario 3 comparison

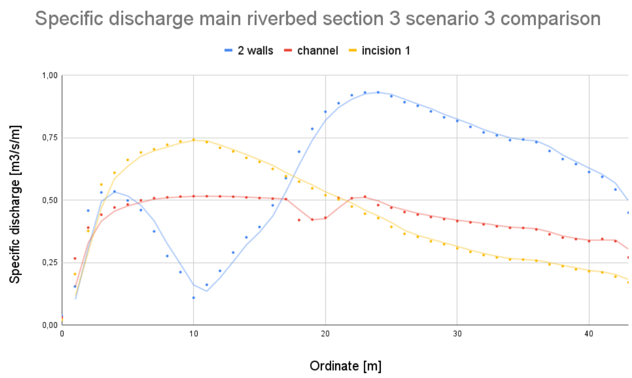


Figure 4.89: Mery Site - Main riverbed section 3 specific discharge scenario 3 comparison

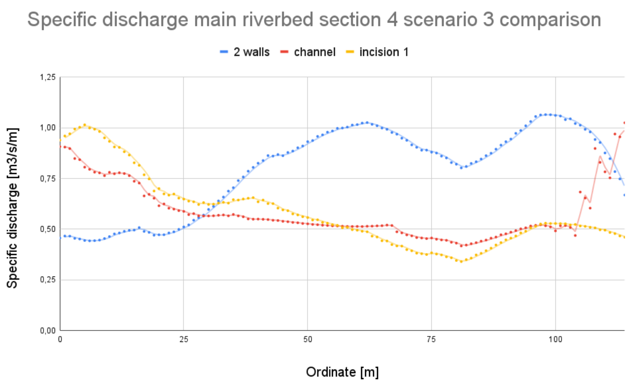


Figure 4.90: Mery Site - Main riverbed section 4 specific discharge scenario 3 comparison

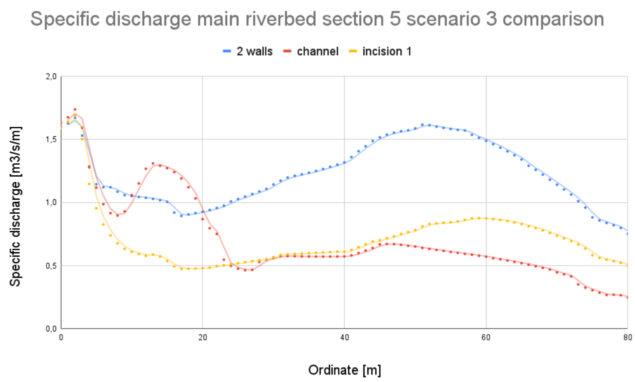


Figure 4.91: Mery Site - Main riverbed section 5 specific discharge scenario 3 comparison

The figures 4.87, 4.88, 4.89, 4.90 and 4.91 representing the specific discharge at the main riverbed cross-sections show the same distributions pattern as for the 2 other scenarios but with the highest observed values.

Thus it can be concluded that there is no difference in the distribution pattern of discharge for the 3 scenarios but only the values change. As long as the discharge flowing into the site does not exceed approximately $35[m3/s]$, so that the main flow goes over the weir.

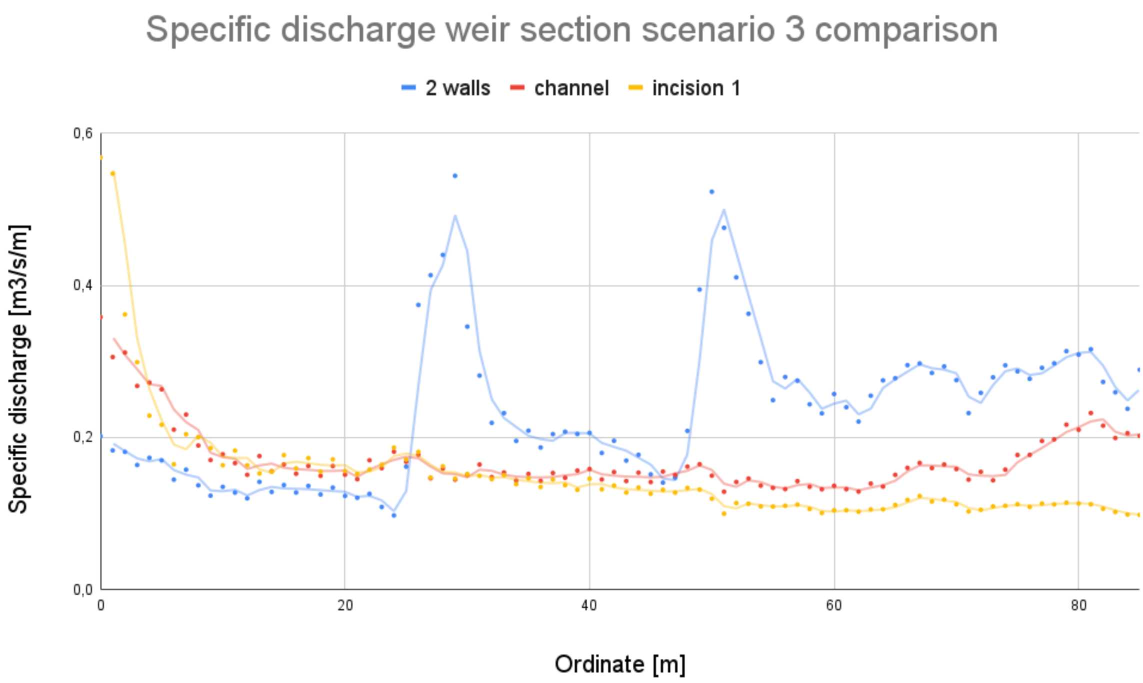


Figure 4.92: Mery Site - Specific discharge in front of the weir scenario 3 comparison

Figure 4.92 shows the specific discharge going over the weir. It shows that the discharge is highest in front of the incisions 2 and 3 for the case of 2 flow guides as the incisions are open. On the right side of the weir this method shows the highest discharge and the lowest on the left. The outlay of the site with a channel displacement also represents a high discharge on the right weir side. On the left side of the weir the specific discharge is highest for the incision 1 method as this is the only incision opened with this outlay.

3.3.2 Velocity

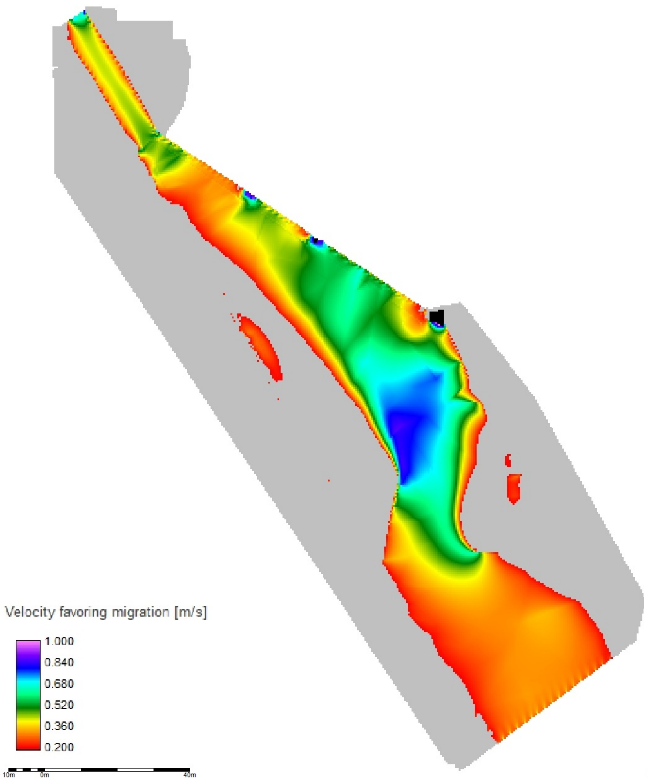


Figure 4.93: Mery Site - 2 guiding walls velocity favoring migration scenario 3

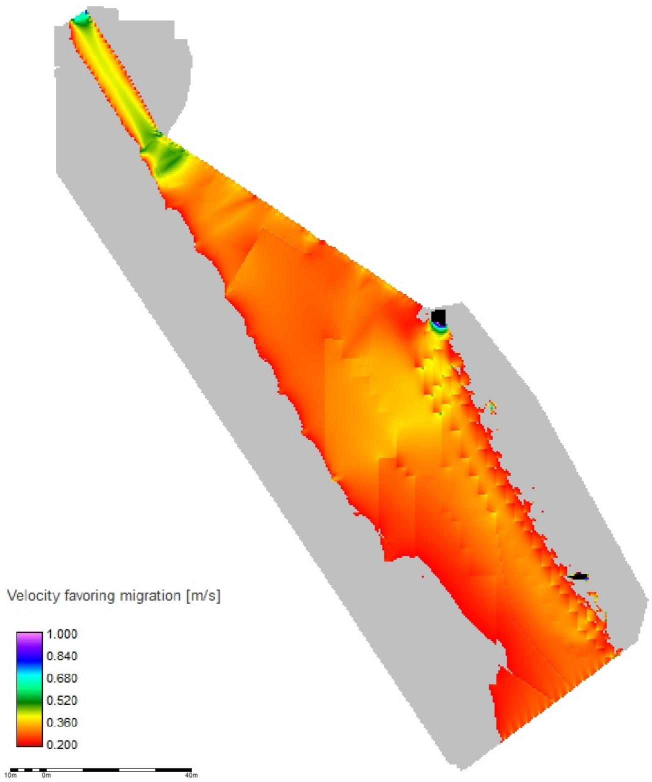


Figure 4.94: Mery Site - channel displacement velocity favoring migration scenario 3

In figure 4.93 the migration favoring velocity is continuous from the entrance of the model to the Archimedes screw, the weir until the Kaplan turbine, only areas behind the guides are not favorable for migration. Highest velocities are present between the flow guides and next to the incisions of the weir.

Figure 4.94 representing the velocity for the case of a new channel placement is distributed equally from the entrance of the system until the entrance of the intake channel of the Kaplan turbine. An acceleration of the flow is only observed at the intake channel of the Kaplan turbine.

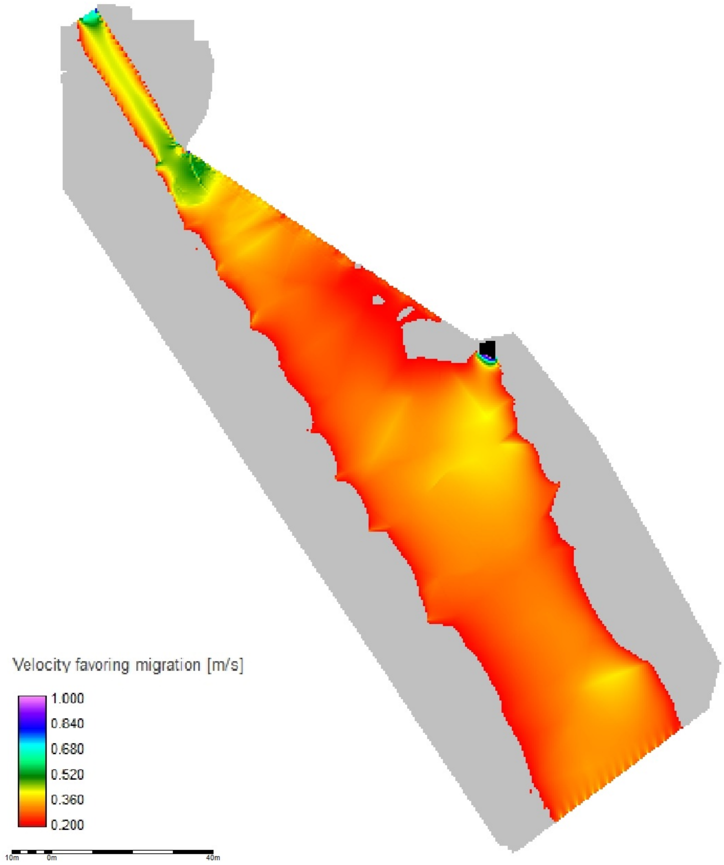


Figure 4.95: Mery Site - incision 1 velocity favoring migration scenario 3

The velocity favoring migration for the outlay of a complete incision is shown in figure 4.95. It can be seen that the velocity is distributed on the whole site except for a small area next to the Archimedes screw on the right side in front of the weir.

3.3.3 Water depth

As for the previous scenarios the water depth is favorable for migration over the whole site as it is represented in figures D.14, D.15 and D.16.

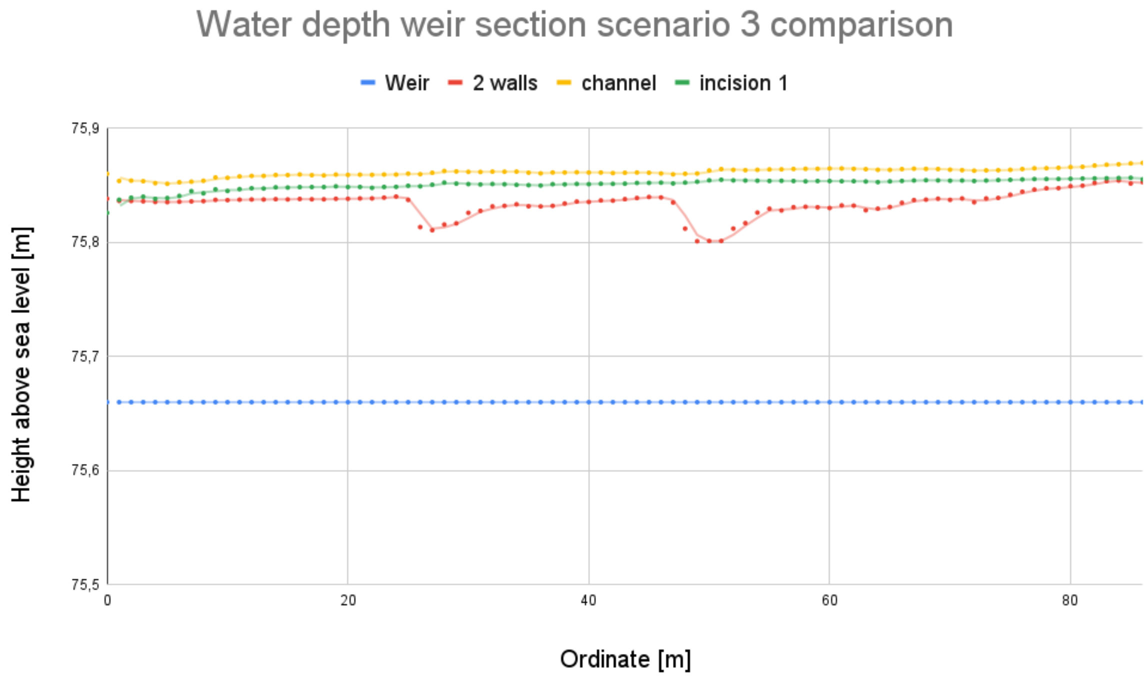


Figure 4.96: Mery Site - Weir section water level scenario 3 comparison

The last figure 4.96 represents the water level above sea just in front of the weir at the weir cross-section. It shows that the water level is nearly the same for every outlay, but as for the other scenarios the highest is achieved with the channel displacement and the lowest with the 2 flow guides.

3.3.4 Conclusion scenario 3

To conclude the analysis of the scenario 3 it can be observed that for the 3 methods the main flow is distributed best in the case of the channel displacement as it distributed the most on the right side leading towards the Archimedes screw and has the lowest portion leading towards the intake channel. Another strong point of this method is that it creates the best disruption of excess flow going towards the intake channel of the Kaplan turbine.

From the perspective of migration favorable water velocity there is no method that outperforms the others because the velocity over the whole site are in an acceptable range for all of the outlays tested.

In terms of water depth the most effective method is the one using a channel displacement as it creates the highest water depth at the weir.

Thus it can be concluded that the most effective method to guide fish towards a safe migration route is the one using a new channel displacement.

4 Discussion

The first results analyse the influence on the discharge of different incisions and some possible changes to the general outlay of the site by the implementation of constructive measures. This section showed that the site outlay with the most influence on the discharge is achieved by constructing 2 flow guides for constructive changes and with a new channel displacement for the topographic change methods.

With the most promising basic solutions, combinations of the site outlays with different incision openings are simulated. At this sections, observations showed that the most influential combinations are 2 flow guides with deepened incisions 2, 3 and 4, a channel displacement with all incisions closed and an incision 1 deepened until the bottom of the riverbed with the rest of the incisions closed.

The last section then also focused on analysing other hydraulic parameters as the velocity and the water depth along with the discharge for 3 different scenarios. Observing the different site outlays at the various scenarios the channel displacement is the most effective in terms of guiding fish towards a safe migration route relating to the hydrodynamic parameters.

It needs to be said that there are also other aspects to consider when optimizing a site. Therefore the table 4.7 below compares the 3 site outlays in terms of hydraulic efficiency in guiding fish and other factors needed to evaluate if the solution is viable. The different aspects are evaluated with 5 different classifications ranging from very bad to excellent, the table 4.5 represents the weight of each evaluation.

Excellent	**Good**	**Moderate**	**Bad**	**Very bad**
2	1	0	-1	-2

Table 4.5: Coefficient value

The hydraulic parameters favoring migration of the 3 final outlays of the Mery site are described in this research in the previous section. A summary of the different observations on the discharge, velocity and water depth for the 3 scenarios is shown in the table 4.6.

For scenario 1 the flow guides method is ranked as good because the main flow is deviated, but due to the fact that the main flow is going further than the location of the Archimedes, it is inferior to the channel displacement which is classed as excellent. As the incision method did not change the pattern of the main flow compared to the basic solution this method is considered as moderate as the fish can't enter the intake channel the discharge going towards the Kaplan turbine is not of significant. In terms of velocity distribution the most efficient method is the channel displacement which is classed as excellent. Because it presents the biggest gap in migration favoring velocity towards the intake channel of the Kaplan turbine. As the large scale behavior is defined by the main flow it guides the fish towards the Archimedes screw. Thus, as the velocity is distributed more over the whole weir the fish should be attracted to swim along the weir and choose this as migration route, as explained under the conclusions for scenario 1. The 2 flow guides method is classed as good because of the presence of a gap of migration favoring velocity between the incision 2 and the intake channel of the Kaplan turbine but the velocity is not distributed as evenly over the weir. The velocity distribution for the incision method is classed as good as a huge discontinuation is visible but no velocity is favorable along the right part of the weir, otherwise it would have been excellent. In the perspective of water depth favoring migration, the 3 methods are performing equally as for all the methods the whole site is in an acceptable range. The only difference is that the water level of the channel displacement method is the highest in front of the weir and therefore is classed as excellent, because the second highest water level is observed for the incision method this method is also classed as excellent as the difference is only minor. The flow guide method is classed as good as the water level is above the weir level but it is significantly lower then the 2 other methods.

For scenario 2 in terms of discharge the most efficient method is again the channel displacement as it produces the a main flow going towards the intake of the Archimedes screw and thus is noted with an excellent. The flow guides method shows a main flow going towards the Archimedes screw and a reduced flow leading to the area in front of the incision 3. It is considered to be good because the main flow is not going towards the intake channel of the Kaplan turbine. The incision method does not present any flow concentration and thus is considered as bad as the fish will distribute all over the area in upstream of the site. In regard of the velocity favoring migration the best method is the construction of flow guides as it is the only method that creates a continuous pattern going toward the Archimedes screw and the incision 3. Therefore this method is qualified as excellent. On the other hand the 2 other methods have no continuous velocity distribution and therefore are classed as very bad because fish are disoriented in such velocity conditions. For the water depth favoring migration all 3 methods show a favorable migration over most parts of the site. If the cross-section in front of the weir is considered, it can be observed that only the methods using closed incisions such as the channel displacement and incision methods have a water level higher then the crest of the weir. But the water-layer is not deep enough to favor migration, but the fish can still use the weir as migration route. Therefore these methods are classed as good. The flow guide method with its opened incisions although is performing bad because the water level is only high enough that there is some flow going through the incisions but not over the weir, which reduces the possibility of downstream migration routes for fish.

For scenario 3 the discharge distribution is most favorable for the method using a channel displacement which is qualified as excellent as the main flow goes towards the Archimedes screw and it also presents a disruption in the flow leading towards the intake channel of the Kaplan turbine. The 2 flow guides method is considered as very bad because the main flow divides into

2 flows. One leading towards the intake channel of the Kaplan turbine and the other towards the Archimedes screw. The incision outlay is considered as moderate as is does not change from the basic configuration of the site. In terms of velocity favoring migration all the methods perform bad, all of the have velocities all over the site going to the intake channel of the Kaplan turbines in the range that favours migration. Therefore all the methods are classified as bad. In terms of water depth all 3 methods are classed as excellent, because the water depth is sufficient all over the site for them and the water level is similar and higher than the crest of the weir.

Scenario	Flow parameters	Guiding walls	Channel	Incision
Scenario 1	Discharge	1	2	0
	Velocity	1	2	1
	Depth	1	2	2
Scenario 2	Discharge	1	2	-1
	Velocity	2	-2	-2
	Depth	-1	1	1
Scenario 3	Discharge	-2	1	0
	Velocity	-1	-1	-1
	Depth	2	2	2
Total		**4**	**9**	**3**

Table 4.6: Hydraulic parameters favoring migration summary

To conclude on the comparison of the hydrodynamic parameters favoring migration for large and fine scale behavior defined by the state of the art and the observed parameters from this research the most efficient method is the channel displacement method which is evaluated as excellent as it outperforms the other tested outlays in many aspects. The second best method which is the construction of 2 flow guides is classified as good as it presents some negative but more positive effects on the hydrodynamic parameters favoring migration. The incision method is classed as moderate as is does not change the parameters significantly compared to the basic simulation but does not present a deterioration neither. In comparison to the other methods it is also the one with the worst rating.

The possibility to enter the Kaplan turbine is only favorable for the incision in combination with a rack in front of the intake channel, thus it is qualified as excellent because with the right bar spacing the fish cannot pass. The 2 other methods still present the possibility that fish end up in the Kaplan turbine and therefore are classified as very bad options, even though that the hydrodynamic parameters should favor a passage through fish-friendly routes.

In terms of energy production the site configuration of flow guides with deepened incisions present a negative effect on the energy production compared to the other methods as it lowers the water level and thus is qualified as bad. The combination of a channel with closed incisions presents the most favorable effect on the water level of all the outlays and thus is qualified as good as it would be possible to use a higher discharge for energy production. The method with the combination of a new incision 1 and a bar rack is qualified as good even though it is only the second best in terms of water level. The placement of the rack, which makes it impossible for fish to pass, and the depth of the incision would allow to use a higher discharge in the Kaplan turbines and thus creating a water depth lower than the weir as the fish can still pass through the incision 1. The only limit here is to make sure that the velocity in front of the rack stays under $0,5[m/s]$ as the smolts would be pressed against the bars.

The next factor to choose the appropriate method is the complexity of construction, for the flow guide outlay the incisions on the weir have to be deepened and the flow guides need to be constructed in the river bed. Therefore it is a very bad choice as the main riverbed needs to be drained completely as the constructions are done at 3 different places on the site. The construction of a channel needs no changes on the weir but the new channel has to be excavated and the excavated material is used to refill the existing channel. Thus this outlay is considered as excellent in construction complexity as there is no drainage of the riverbed needed and no changes on the depth of the incisions needed. The incision option is considered to have a favorable construction complexity as the changes are only done at the most downstream part of the weir and the intake of the Kaplan turbine. During the construction period the lowest part of the site needs to be drained to do the works in a dry environment and the rest of the site is not influenced by the works.

The maintenance of the flow guides outlay is classed as bad because of the recirculation areas behind the guiding walls, where sedimentation occurs due to lower flow velocities and the accumulation of trash due to the recirculation itself need extra maintenance. The installation of a new incision 1 is also considered as bad as the bar rack needs a lot more cleaning as the one installed nowadays due to the smaller bar spacing. The channel outlay is considered as good as no difference from the situation as it is now is expected in terms of maintenance.

The costs of the flow guides outlay is considered as very expensive as it needs a lot of different works as drainage, construction of flow guides and the deepening of the existing incisions. The channel is considered as moderate as it basically only needs the use of a dredger, which is very expensive due to logistic and operational costs. However, no costs are involved for constructions and drainage. The incision outlay is considered as excellent as it only needs a small drained area and the works done are located at one point and thus can be done at once.

	Configuration		
	Flow guides	**Channel**	**Incision**
Hydraulic Parameters favoring migration	1	2	0
Possibility to enter Kaplan turbines	-2	-2	2
Energy production	-1	1	1
Estimated Construction complexity	-2	2	1
Estimated Maintenance	-1	1	-1
Estimated cost	-2	0	2
Total	**-6**	**4**	**5**

Table 4.7: Different factors influencing final choice

Considering all these factors the most favorable change for the site is the construction of a bar rack at the entrance of the intake channel of the Kaplan turbine combined with the reconstruction of the incision 1 with a depth reaching down to the riverbed of $1,96[m]$ and a width of $0,25[m]$.

It has to be pointed out that half these factors are estimations and therefore the construction complexity, maintenance and especially the cost may differ in weight. Dependent on how the assumptions to qualify these parameters are set, it is possible that the performance of a channel displacement method can overtake the incision method.

Chapter 5

Conclusion

To conclude this thesis, first general conclusions and their possible use for other projects are highlighted. Then some possible improvements are mentioned.

1 General conclusion

The aim of this research is to improve the downstream migration possibility of Atlantic salmon smolts at the Mery site. The main goal is to implement favorable changes to the site in terms of migration favoring hydraulic parameters while keeping the energy production at the same level or even improving it.

First analyses focused on the individual incision gates, therefore the influence of the as-built and deepened incisions are simulated. Observations made is that the influence of a single incision is quite limited on the main flow distribution. Only for deepened incisions at the weir cross-section in front of the incisions 2, 3 and 4 are observed.

The second step is the simulation of different constructive changes on the outlay of the site. Therefore 3 flow guide builds and 2 topographic changes are simulated. For the flow guide method the most favorable is the construction of 2 flow guiding walls as it has the highest influence on pushing the main flow towards the Archimedes screw. For the case of topographic changes the best suited is the channel displacement as the main flow is situated along the right river border. Therefor for the next section combinations of these 2 constructive changes with different incision gate openings are analysed.

Next comes the analysis of combinations and the analysis of the construction of a bar rack in the entrance of the intake channel from the Kaplan turbine. For the method using 2 flow guides the best combinations is observed using deepened incisions 2, 3 and 4 because the main flow is directed towards the Archimedes screw and the incisions. Highest discharge in front of the weir are observed on the right side of the weir cross-section, while the lowest discharge going towards the intake channel of all the combinations is observed. The channel displacement method with incision gate combinations favors hydraulic parameters most with all the incisions closed. In regard of the discharge distribution, there is no significant difference between the methods. When considering the velocity favoring migration it can be observed that the for all incisions closed the discontinuation towards the intake of the Kaplan turbine is the larges. Another factor favoring this combination is that the water depth is highest in front of the weir and therefor fish can pass more easy over the weir or more water can be used for electricity production. For the incision 1 outlays no major difference is observed between the 3 configurations. Therefore the most efficient setup is chosen on the migration possibility, as the complete incision reaches until the river bed, this method is investigated at the final comparison.

As final step the 3 best performing methods are compared at 3 different discharge scenarios. A complete comparison between the different methods is shown in table 4.6.

In regard of the hydraulic parameters favoring downstream migration the best performing method by far is the displacement of the channel. The channel that was constructed for shipping purposes and is in place today on the left river border leading towards the intake channel of the Kaplan turbine, is displaced on the right river border leading towards the Archimedes screw. This measure had the most positive effect on the discharge distribution on site, which is crucial for the guidance of smolts, as their large scale migration behavior is defined only by the main flow. Another positive aspect of this method is that no additional material has to be brought on site as the excavated material for the new formed channel can be used to refill the existing one. It shows that when the river bed is rebuild in a proper way it is possible to guide the main flow towards a desired direction. As this method is generally easy to execute when the water depth is not too high and because it can be done without drainage. Therefore it is favorable to test the influence of such a method when working on other similar projects.

In terms of overall performance the best option is to combine a new placement of a bar rack at the entrance of the intake channel from the Kaplan turbine combined with a deepening of the incision 1. This method has 2 major advantages, first if the bar rack is executed right, the fish cannot pass towards the Kaplan turbine. Second an incision next to a bar rack can be seen as a by-pass, in order to have a good by-pass efficiency the best option is to build it as deep as the river bed. With such a deep outlay it allows all the different fishes to migrate and even for very low discharge conditions the fish can still use it as a migration route. Another advantage is that the water level does not need to be superior to the weir crest in order that fish can pass past the weir, therefore more water can be used for energy production. The only limitation is the velocity directly in front of the rack which should not exceed $0,5[m/s]$ as this could hinder fish from swimming away from it. For projects where fish-unfriendly turbines are in use, the construction of a bar rack should be the first option investigated. Because even as stand alone measure it reduces the mortality rate of the site.

The best solution for the Mery site in terms of downstream migration optimization is to combine the positive aspects of the 2 methods. Therefore the channel displacement method should be complemented with a bar rack construction at the entrance of the intake channel of the Kaplan turbine. As the bar rack was not modeled itself, this solution is not simulated.

2 Prospects for improvement

To improve the analysis of the site some changes could be investigated such as:

- implementing the missing components (fish-way, by-pass, rack) into numerical model
- running the simulations for the case with both of the Kaplan turbines in use
- expressing the discharge used for energy production facilities (Kaplan turbine, Archimedes screw) as variable in function of the available water head
- using a larger model with a smaller grid
- 3D-simulation
- investigation of further parameters 2.3

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Appendix A

Appendix chapter 1

Appendix B

Appendix chapter 2

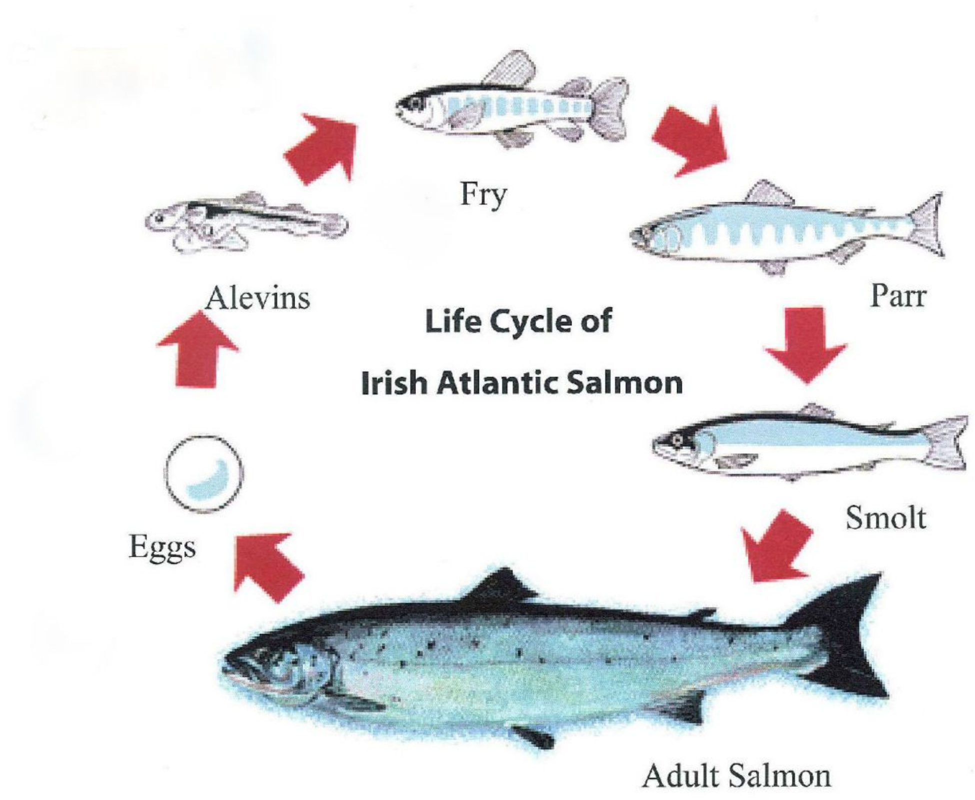

Figure B.1: Atlantic salmon life cycle - source: https://www.marine.ie/site-area/areas-activity/fisheries-ecosystems/salmon-life-cycle?language=en

Appendix C

Appendix chapter 3

Figure C.1: Mery Site - Slot fish-pass

Figure C.2: Mery Site - Archimedes screw

Figure C.3: Mery Site - Weir with 4 Incisions

Figure C.4: Mery Site - Kaplan turbines & Bypass

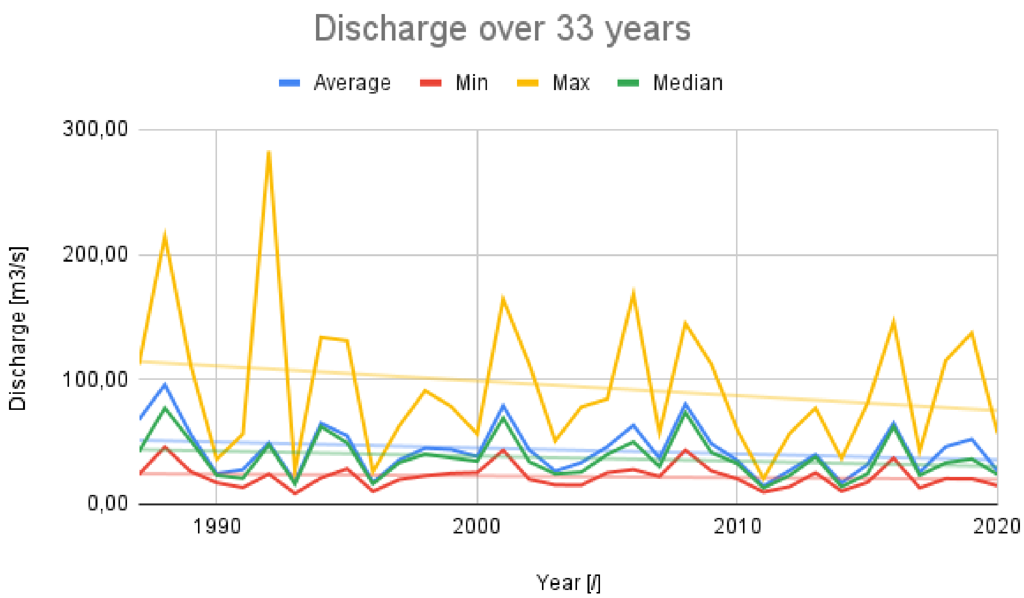

Figure C.5: Discharge Sauheid over 33 years - March to June

Cross-section	Point 1		Point 2		Bloc
	X	Y	X	Y	
Channel	44	405	57	414	1
Main riverbed section 1	210	129	291	171	1
Main riverbed section 2	168	193	251	248	1
Main riverbed section 3	152	221	138	20	1
Main riverbed section 4	87	347	257	193	1
Main riverbed section 5	244	258	235	97	1
Weir	5	4	4	4	3,6
Channel entrance	77	350	89	360	1
Weir end	88	333	21	97	1

Table C.1: Cross-section coordinates

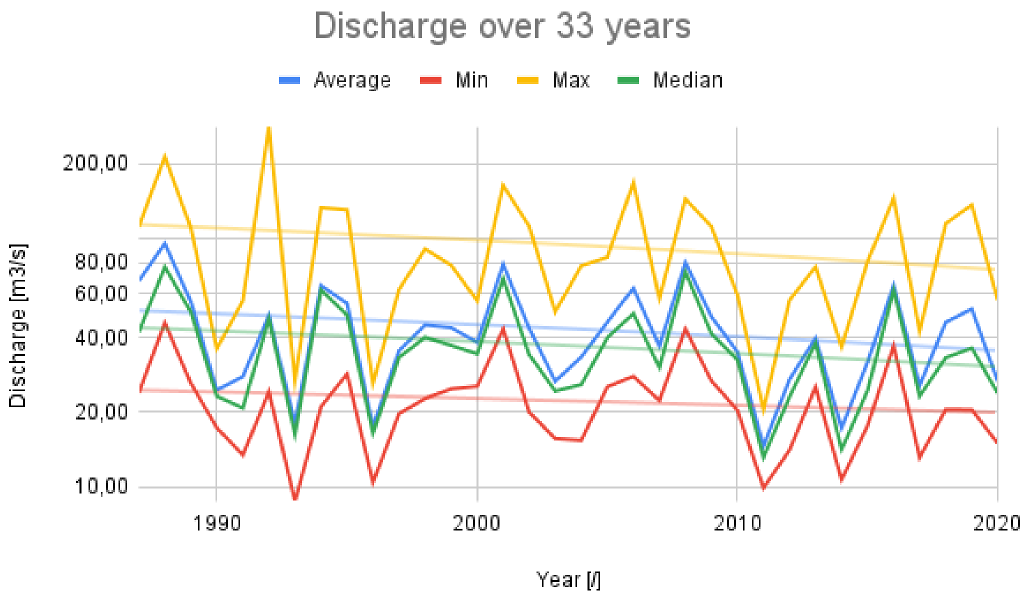

Figure C.6: Discharge Sauheid over 33 years - March to June - logarithmic

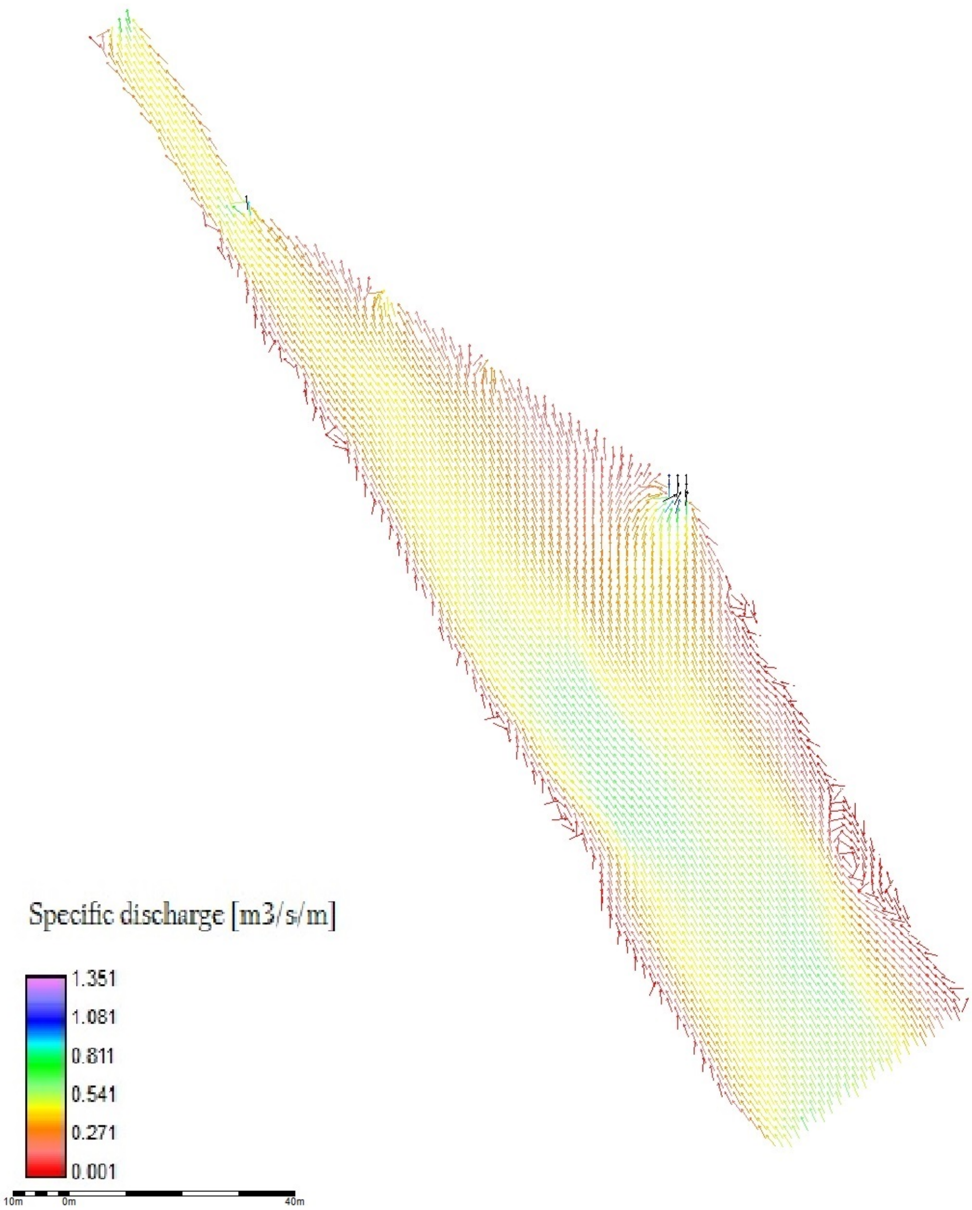

Figure C.7: Mery Site - Discharge vectors

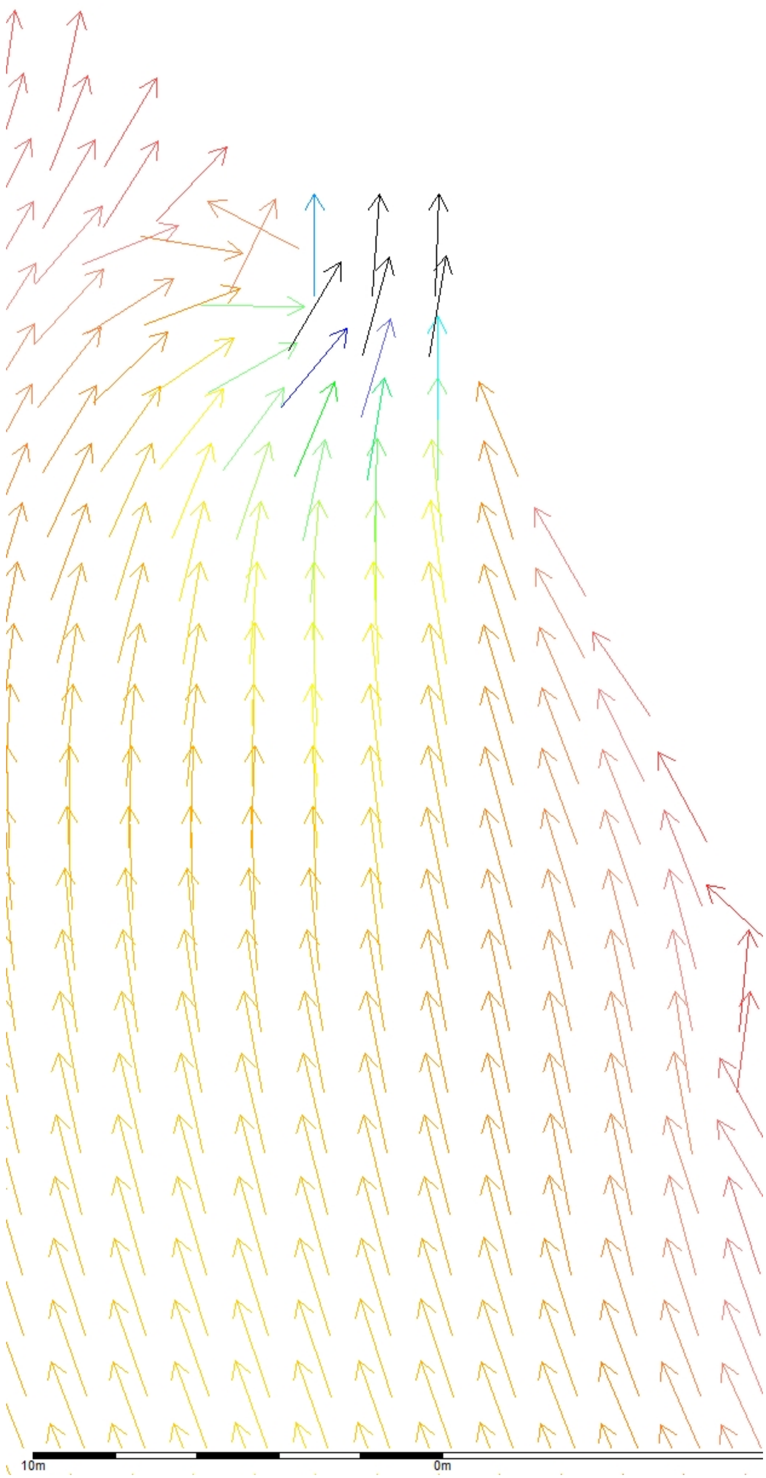

Figure C.8: Mery Site - Discharge vectors at the Archimedes screw

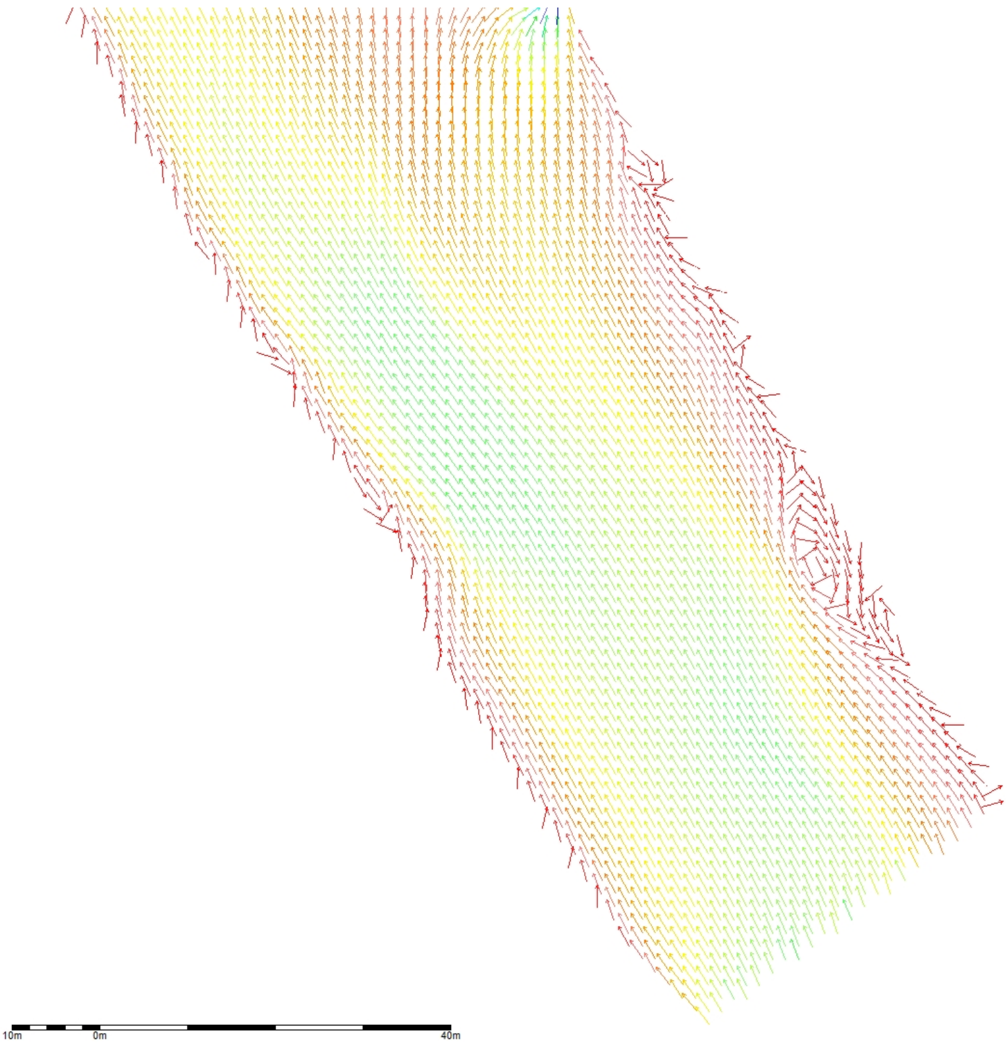

Figure C.9: Mery Site - Discharge vectors in main riverbed

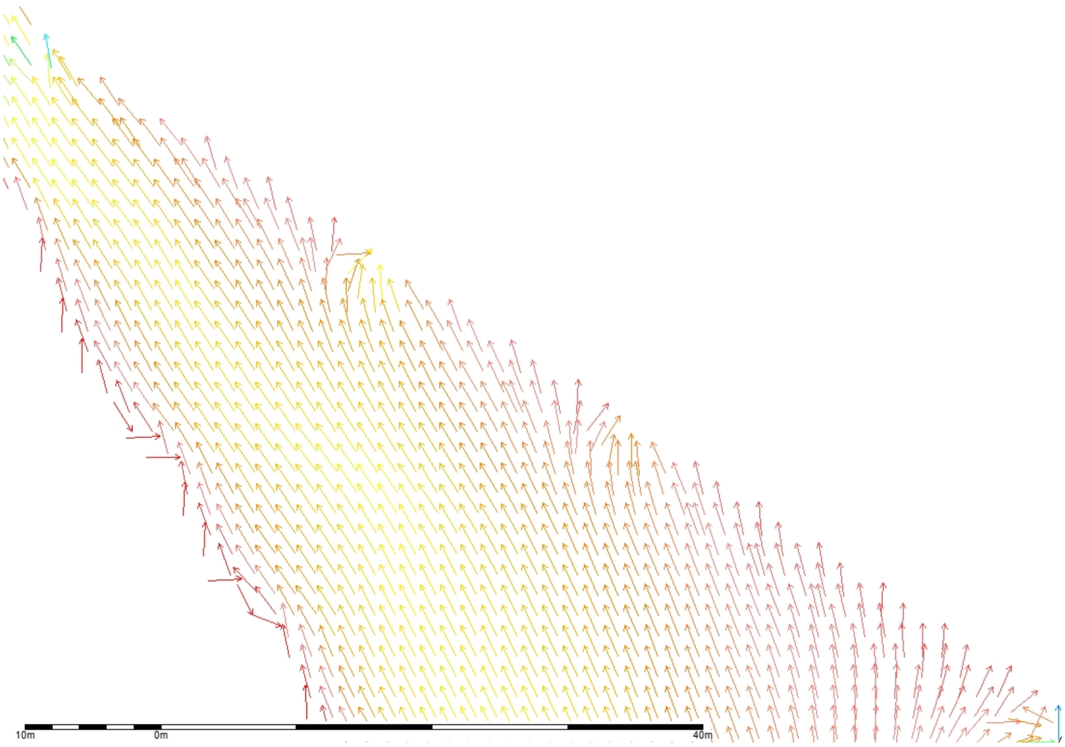

Figure C.10: Mery Site - Discharge vectors at the weir

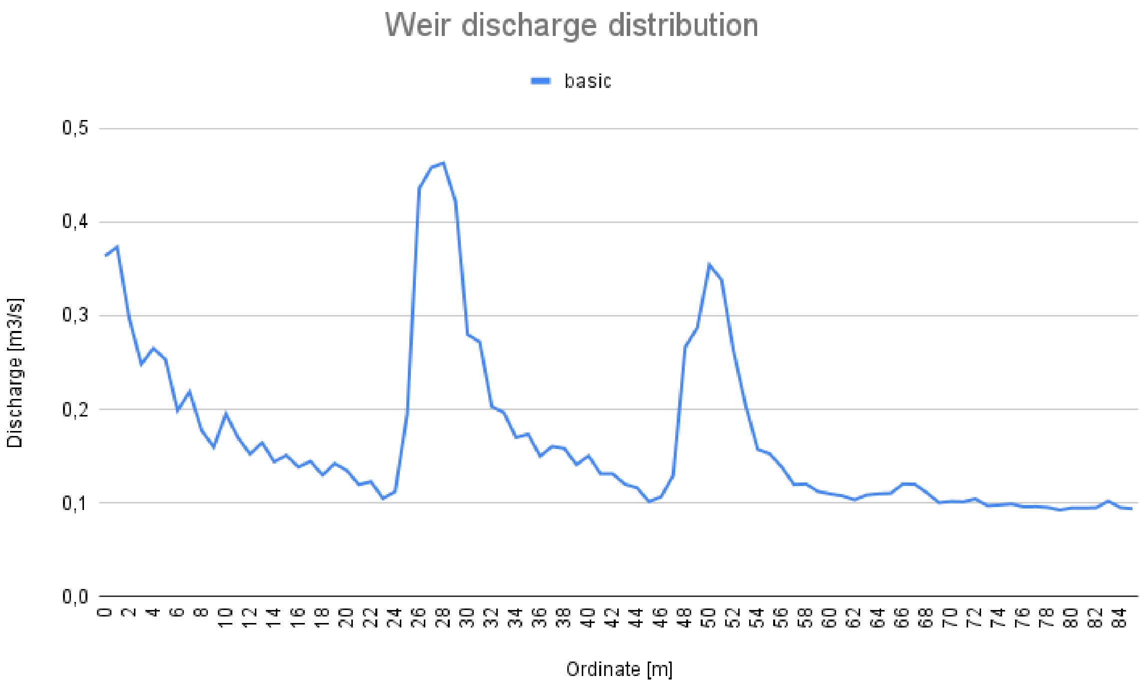

Figure C.11: Mery Site - Discharge distribution at weir cross section

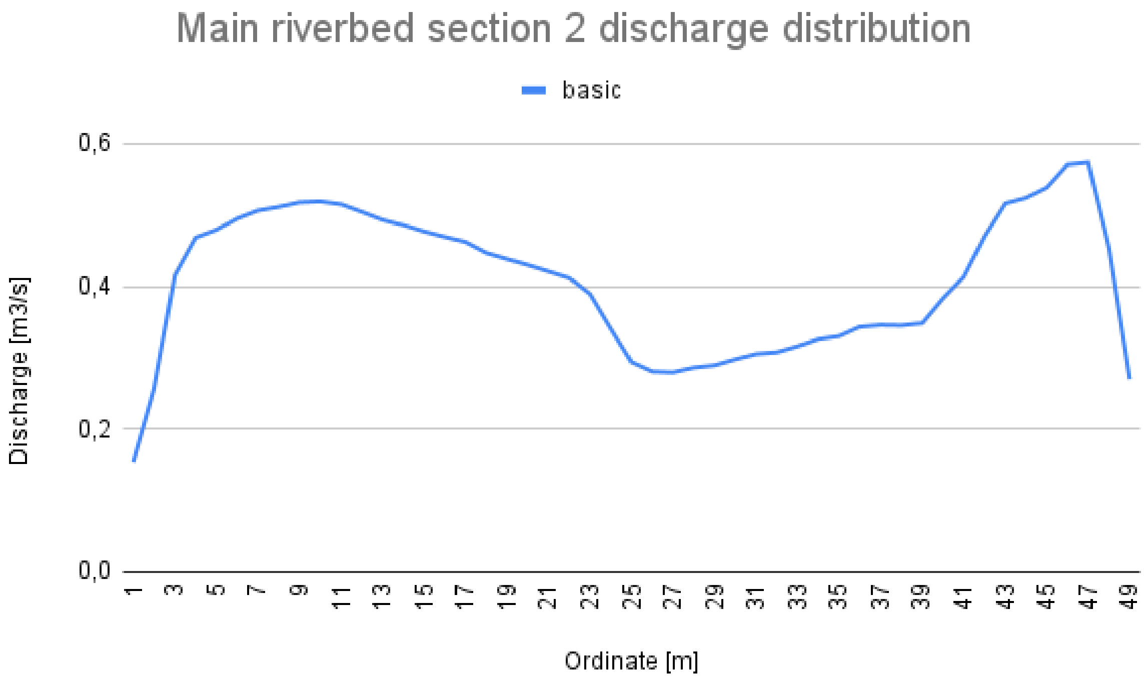

Figure C.12: Mery Site - Discharge distribution at cross section 2

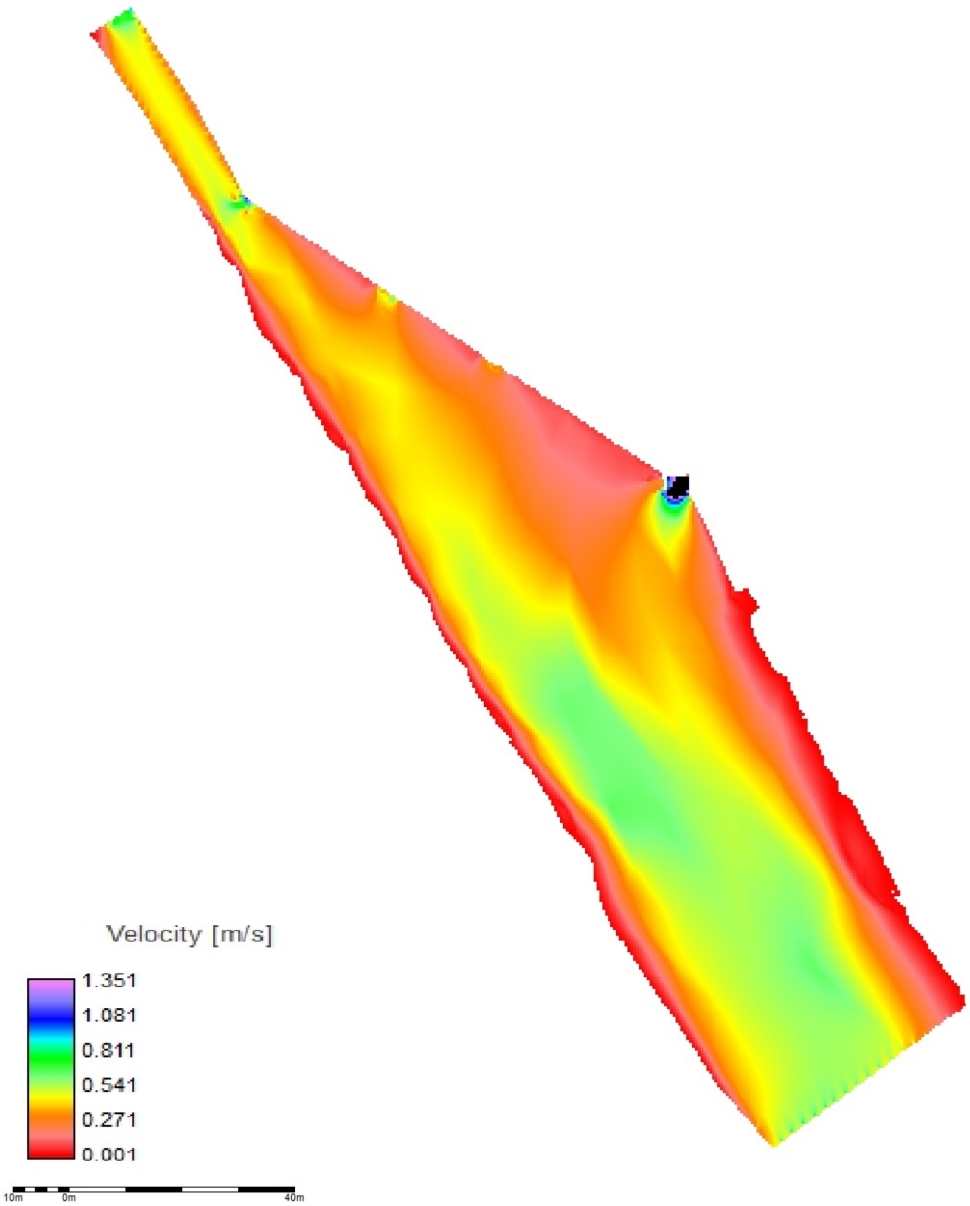

Figure C.13: Mery Site - Water velocity overall

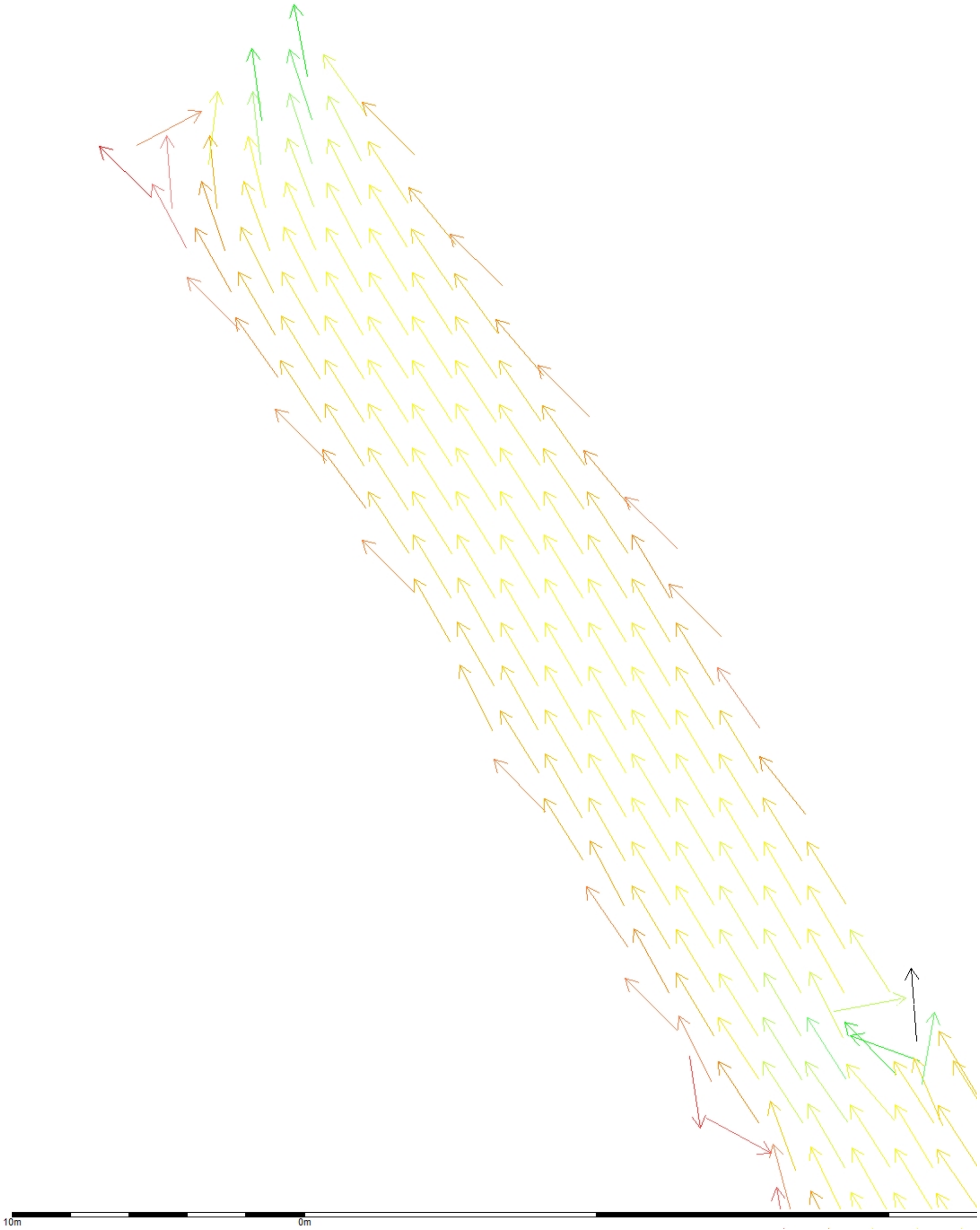

Figure C.14: Mery Site - Discharge vectors in the channel

Appendix D

Appendix chapter 4

cellule	0,25					
Cellule_geo	6,25					
		ancien	nouveau	**Excavation Volume**		
43	268,75	75,4393	74,5	252,436875	m3	
52	325	74,85	73,5	438,75	m3	
82	512,5	74,24956	72,5	896,6495	m3	
31	193,75	74,214	73,5	138,3375	m3	
2	12,5	73,9627	73,5	5,78375	m3	
7	43,75	73,559	73,5	2,58125	m3	
19	118,75	73,76	73,3	54,625	m3	
62	15,5	74,4779	72,5	30,65745	m3	
54	13,5	73,46	73,3	2,16	m3	
				1821,98	m3	
				Refill Volume		
112	700	73,06493	74	654,549	1167,43	
111	693,75	72,97	73,5	367,6875	799,74	
100	625	73,87315	74,4	329,28125	470,46	
3	18,75	74,30102	74,5	3,730875	466,73	
5	31,25	74,35	74,5	4,6875	462,05	
306	76,5	74	74	2,560455	459,48	
65	16,25	73,62135	74,4	12,6530625	446,83	
175	43,75	73,248	74	32,9	413,93	
40	10	74	74,5	5	408,93	
682	170,5	73,27918	74	122,89981	286,03	
3847	961,75	73,48087	74	499,2732775	-213,24	
1385	346,25	73,27829	72,7	200,2329125	-13,01	additional excavation

Table D.1: Refill and excavation volumes for Channel displacement method

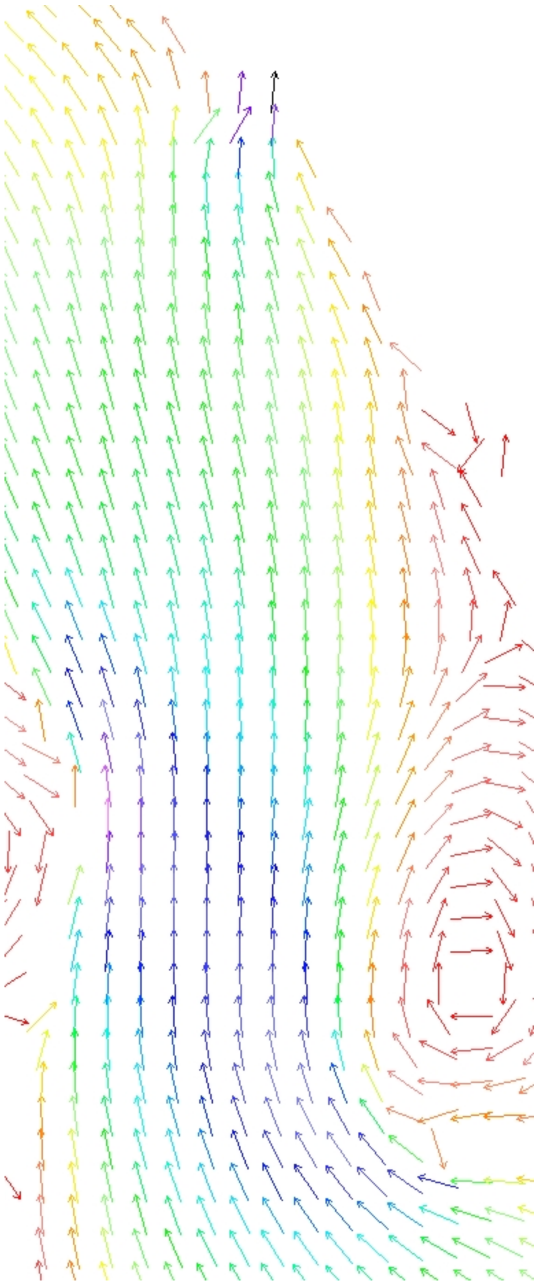

Figure D.1: Mery Site - 2 flow guides + incision 2 and 4 zoom at Archimedes screw intake area

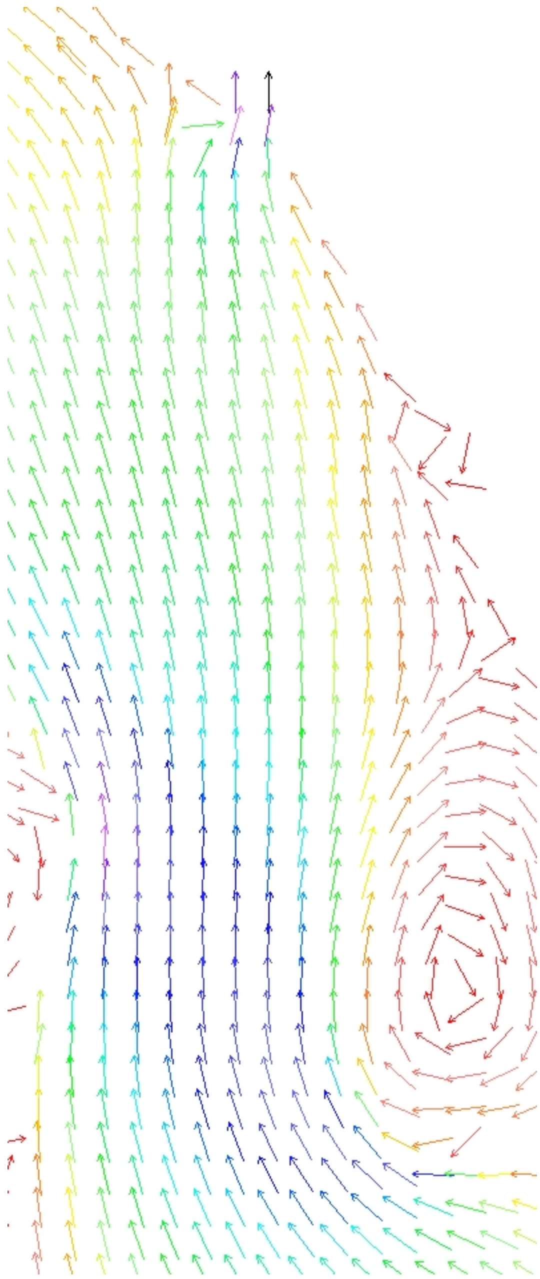

Figure D.2: Mery Site - 2 flow guides + deep incisions 2, 3 and 4 zoom at Archimedes screw intake area

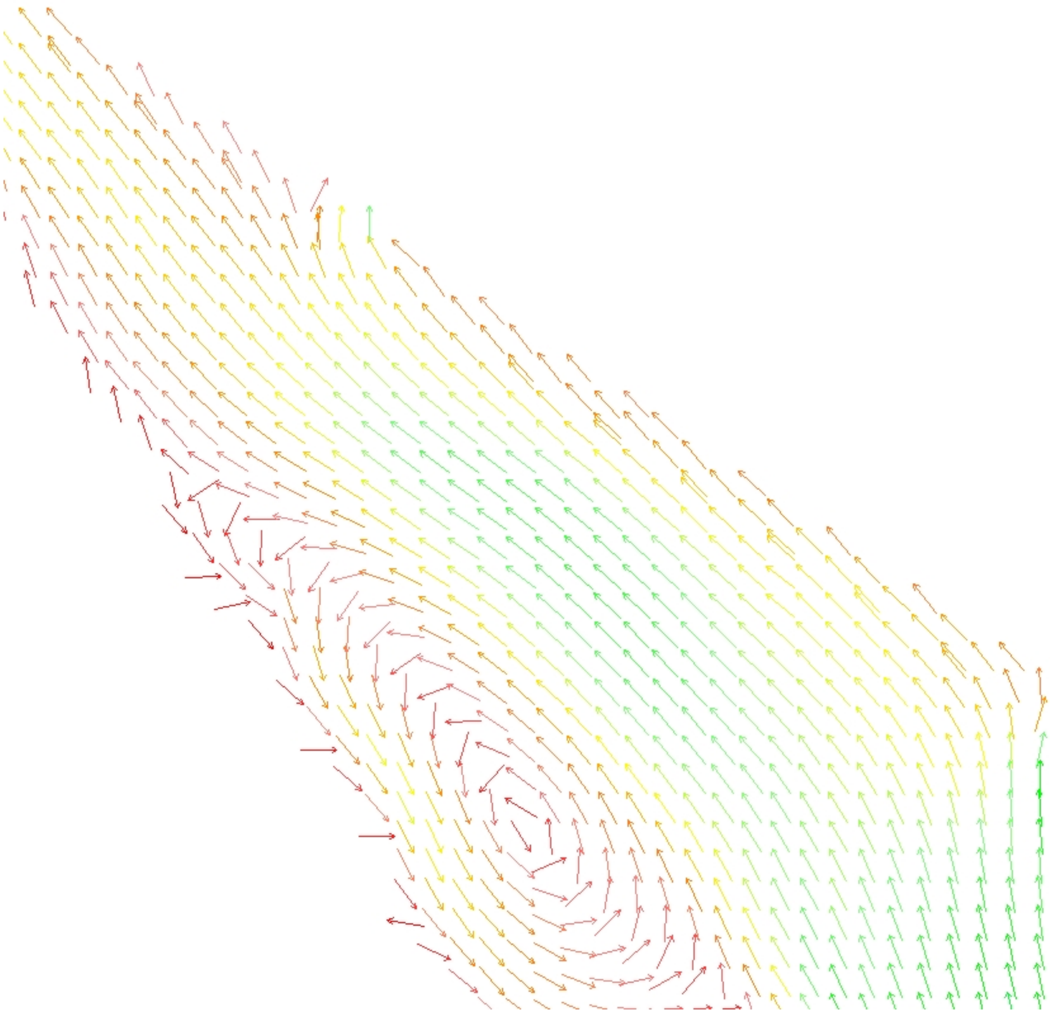

Figure D.3: Mery Site - 2 flow guides + incision 2 and 4 zoom at weir area

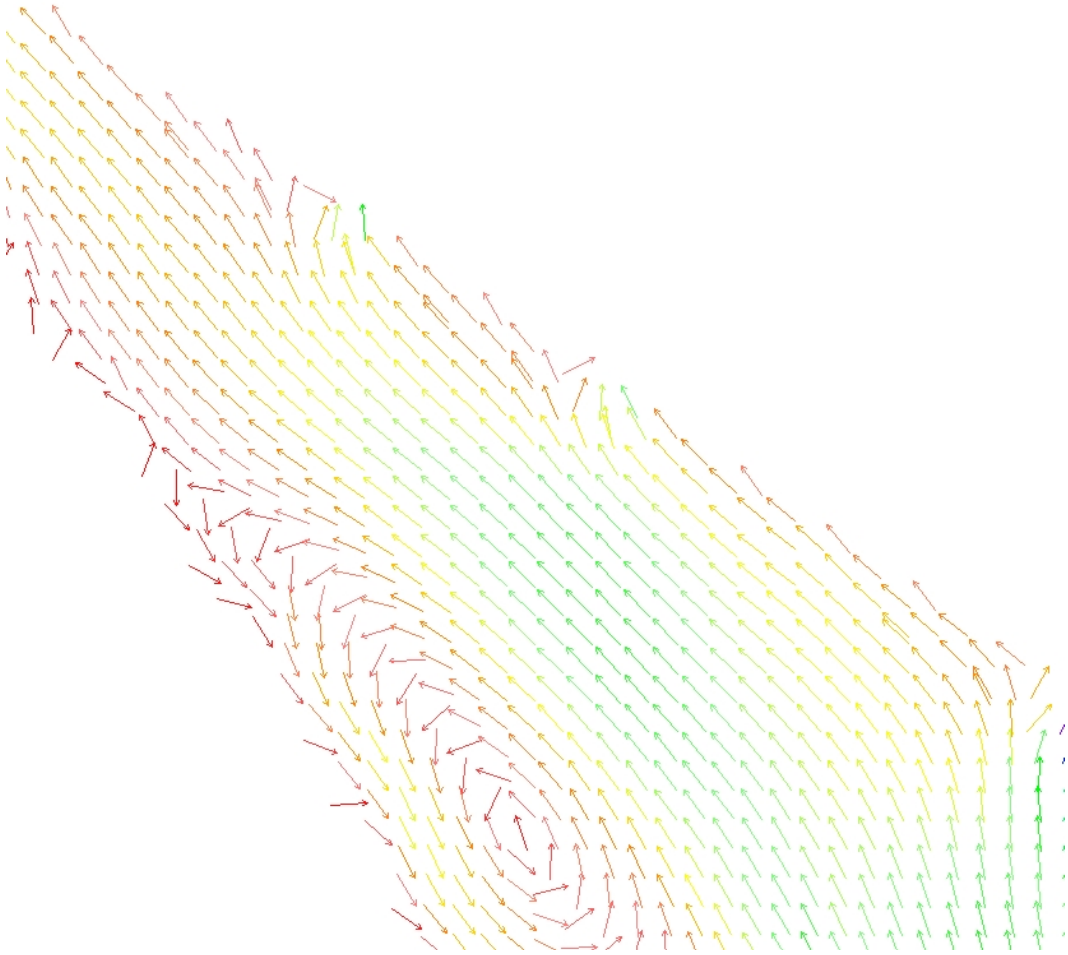

Figure D.4: Mery Site - 2 flow guides + deep incisions 2, 3 and 4 zoom at weir area

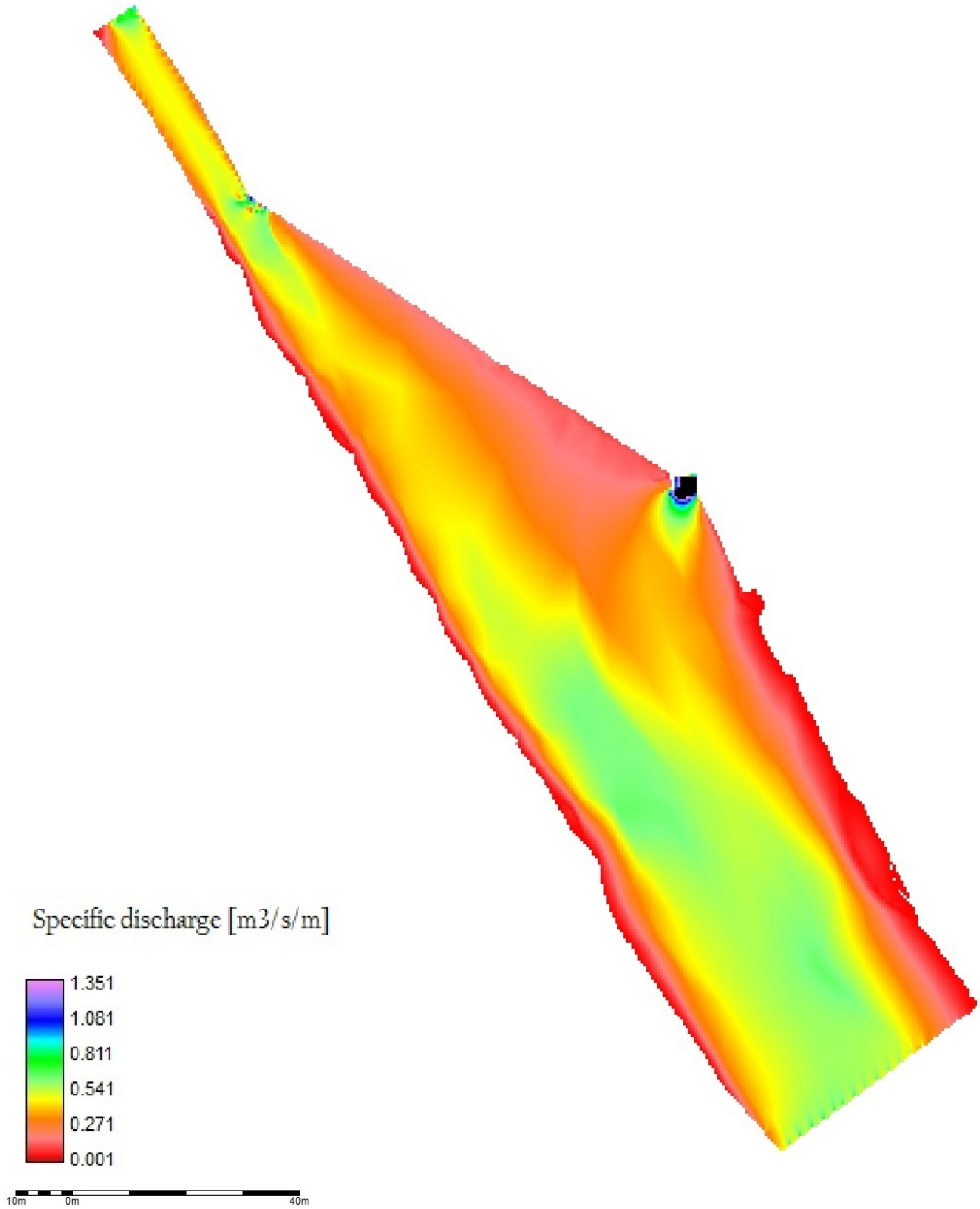

Figure D.5: Mery Site - Specific discharge - wide incision

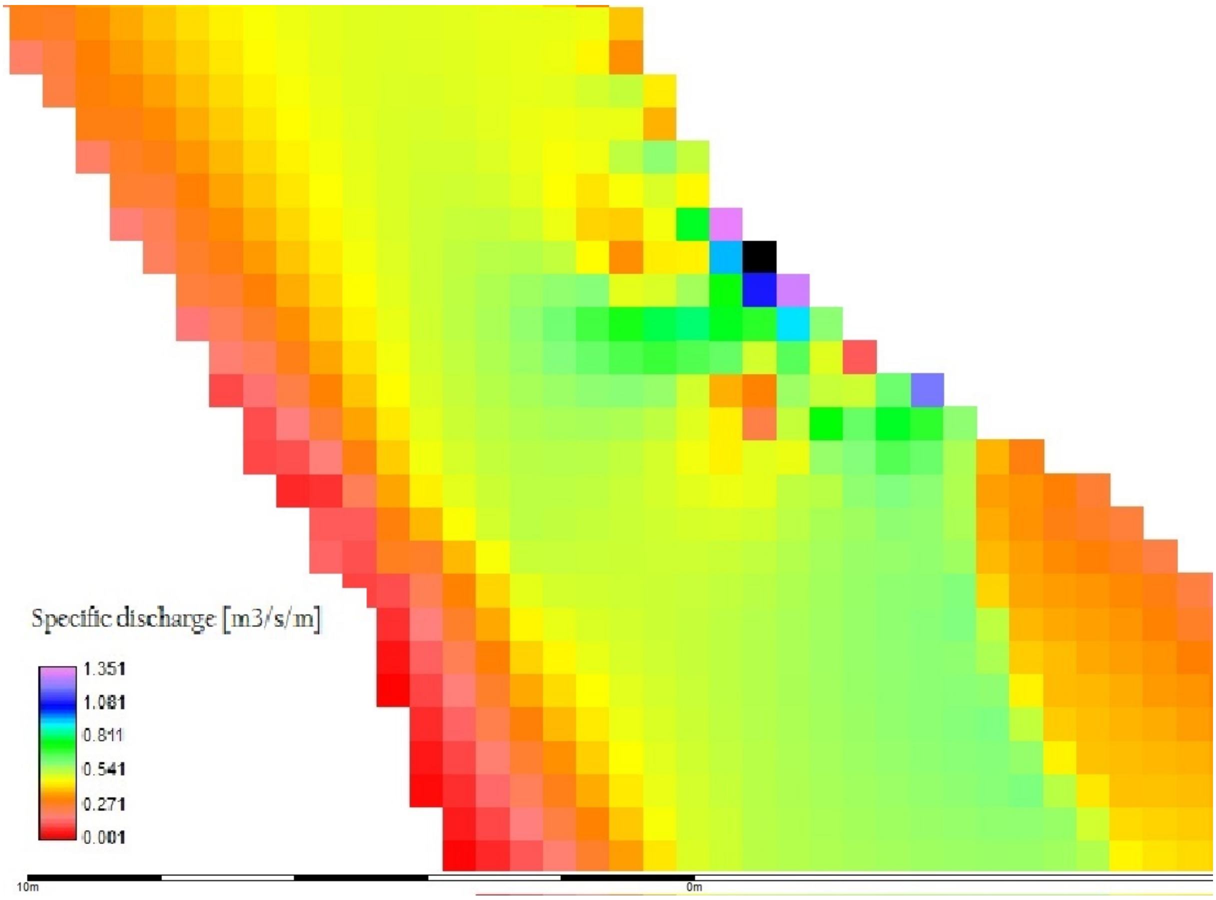

Figure D.6: Mery Site - Specific discharge - wide incision zoom

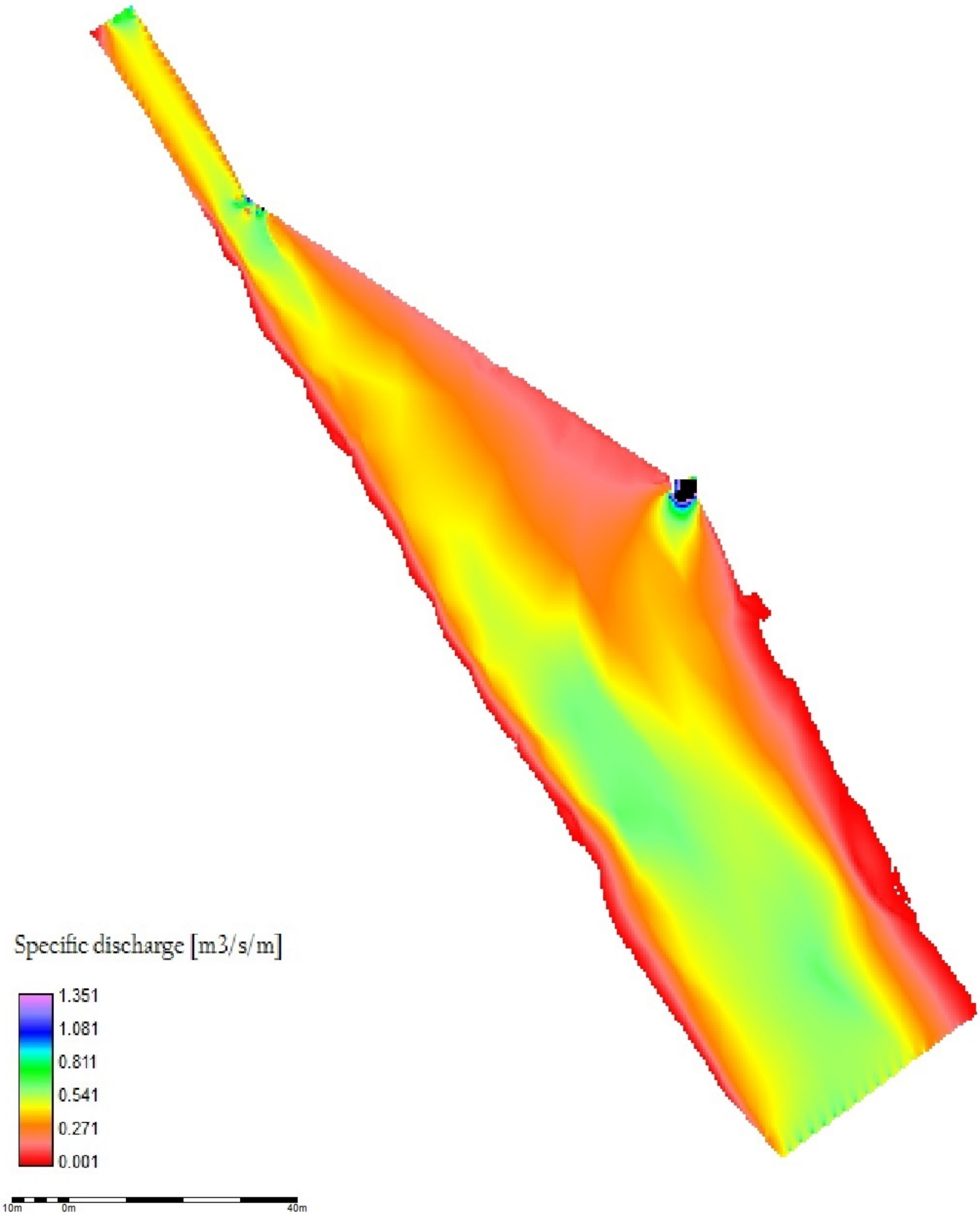

Figure D.7: Mery Site - Specific discharge - cubic incision

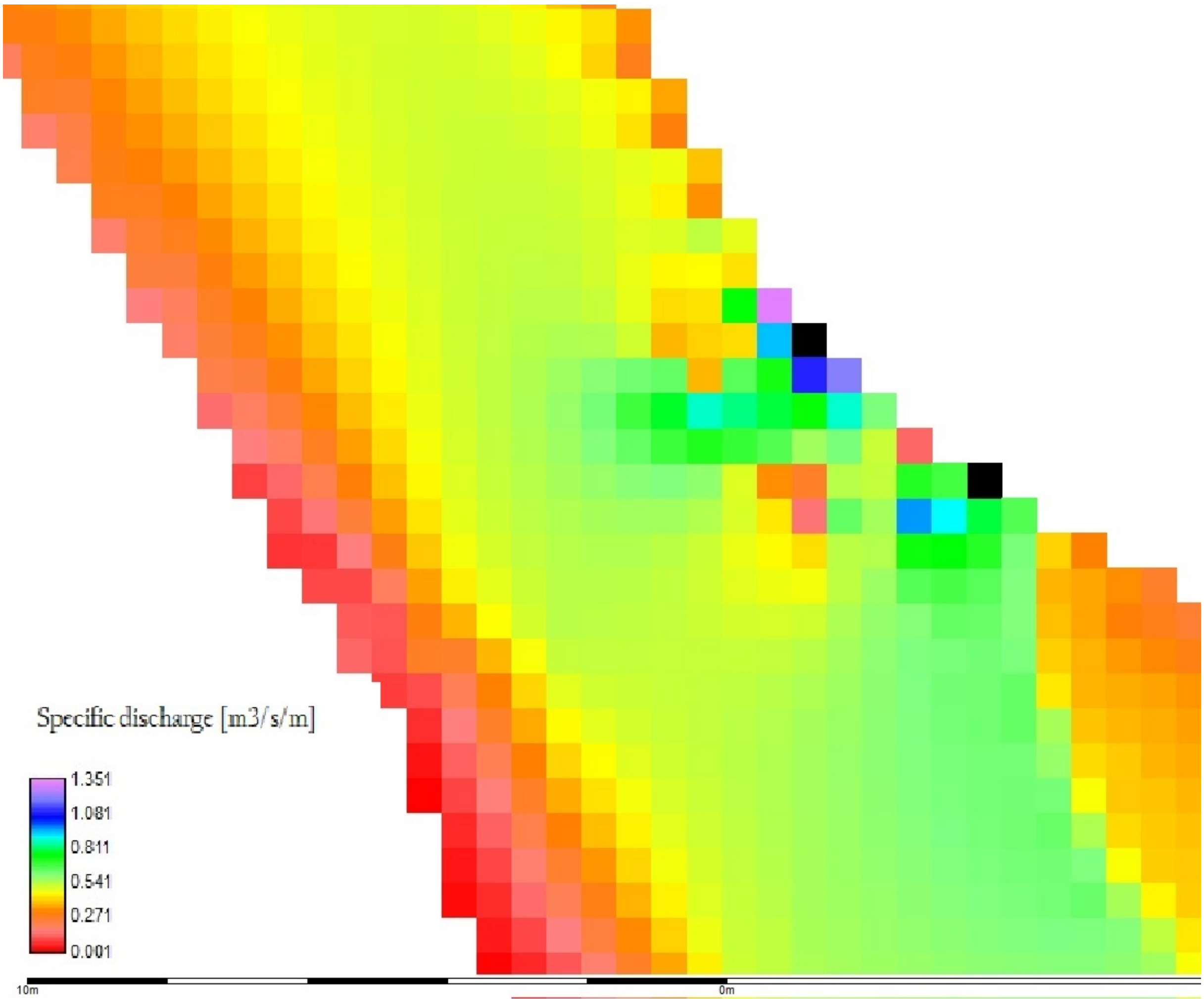

Figure D.8: Mery Site - Specific discharge - cubic incision zoom

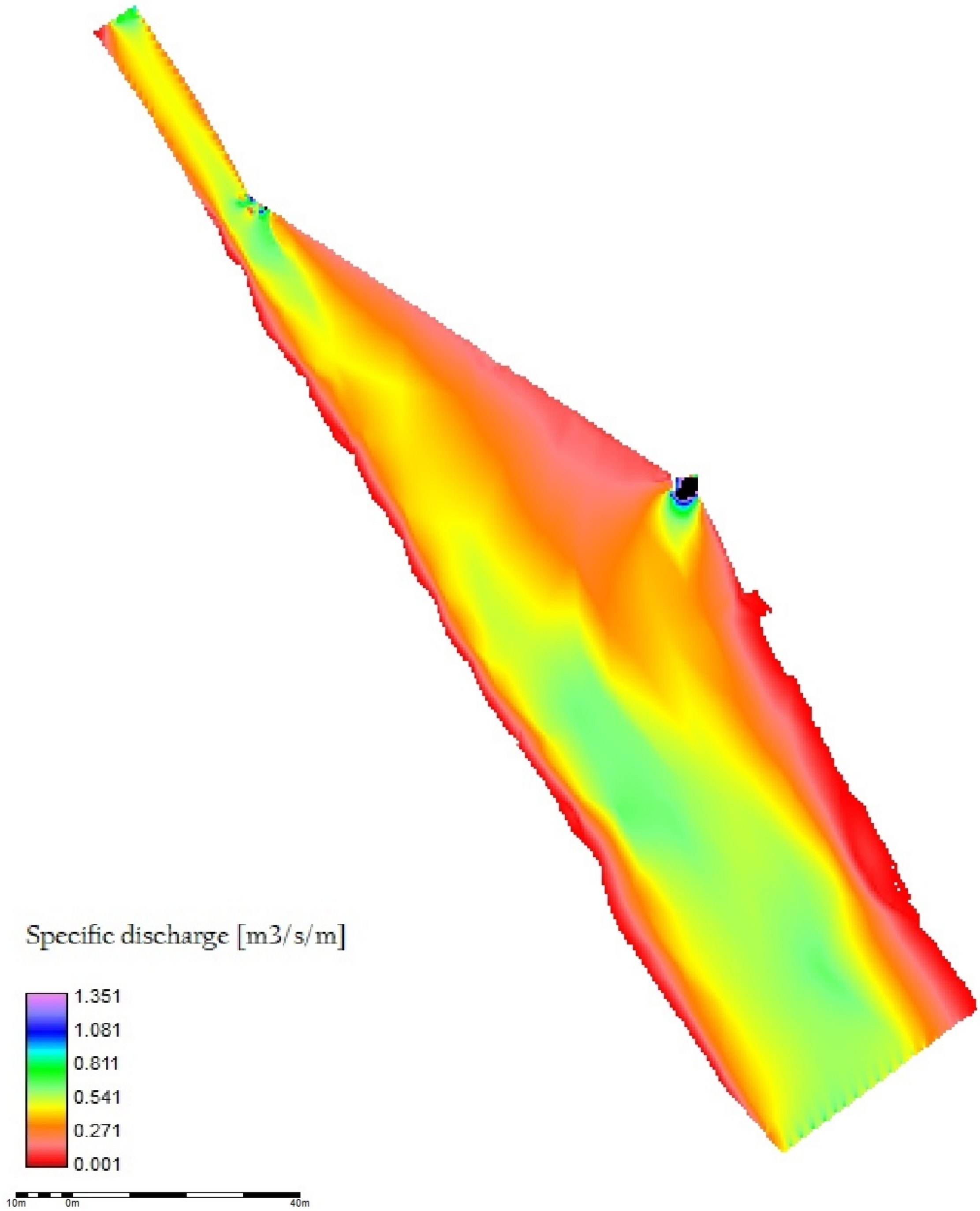

Figure D.9: Mery Site - Specific discharge - complete incision

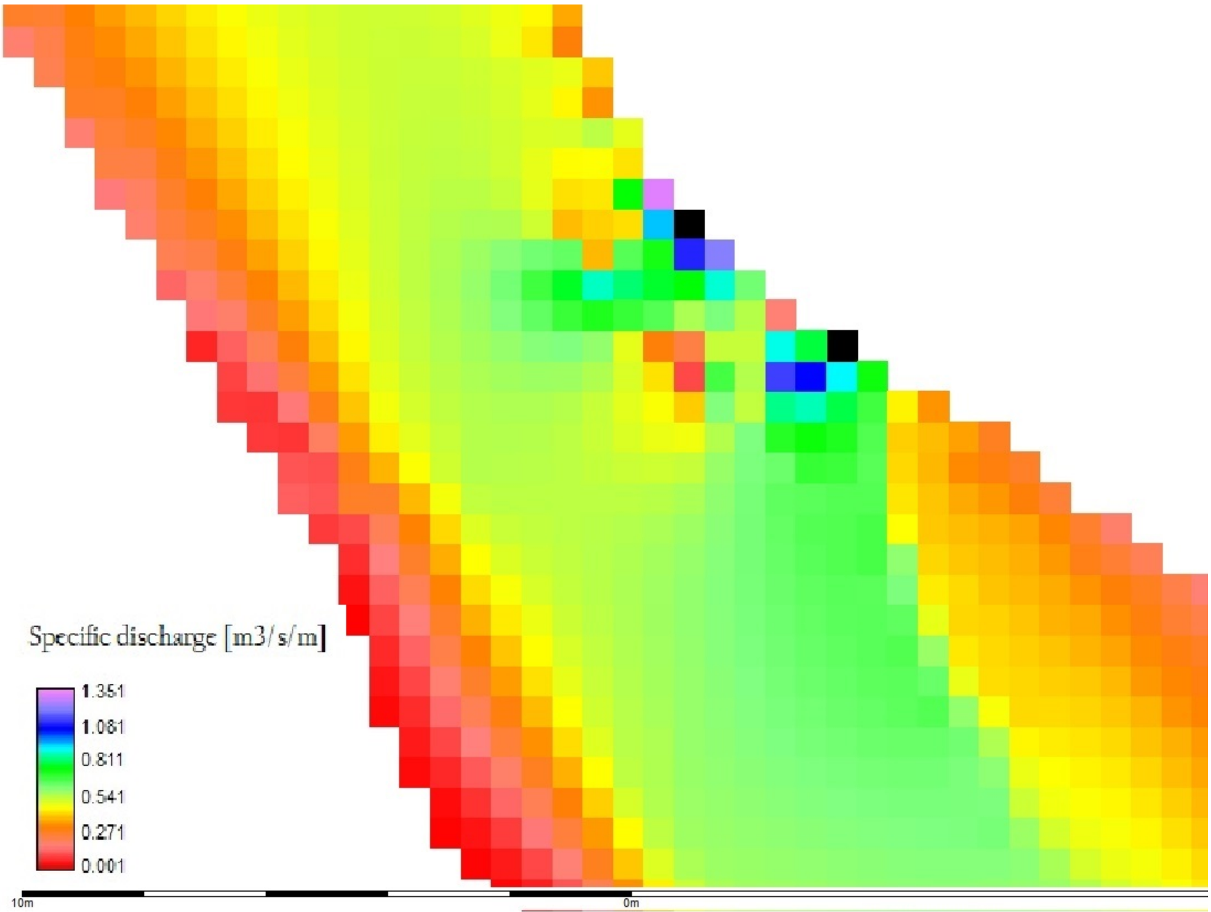

Figure D.10: Mery Site - Specific discharge - complete incision zoom

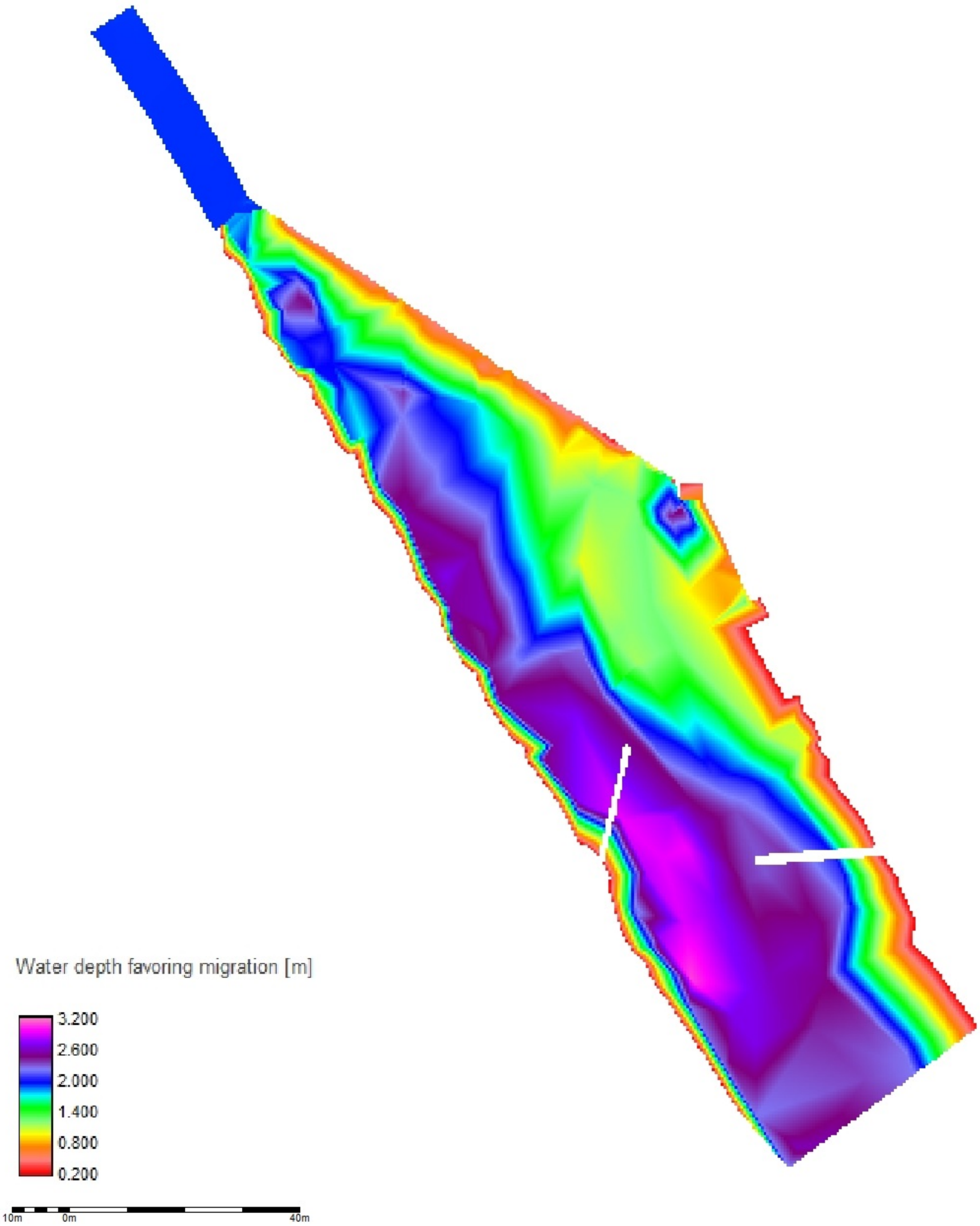

Figure D.11: Mery Site - 2 guiding walls water depth favoring migration scenario 2

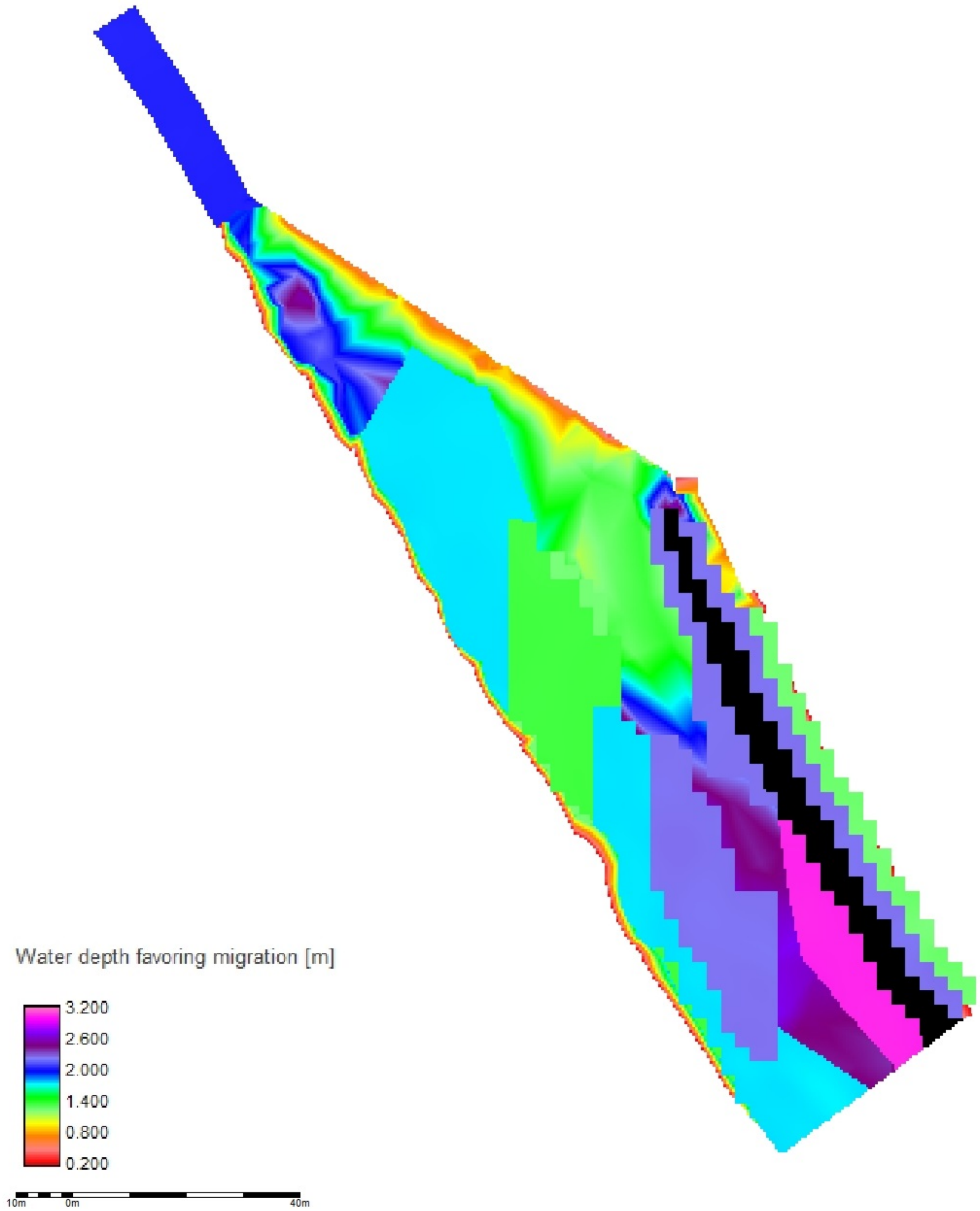

Figure D.12: Mery Site - channel displacement water depth favoring migration scenario 2

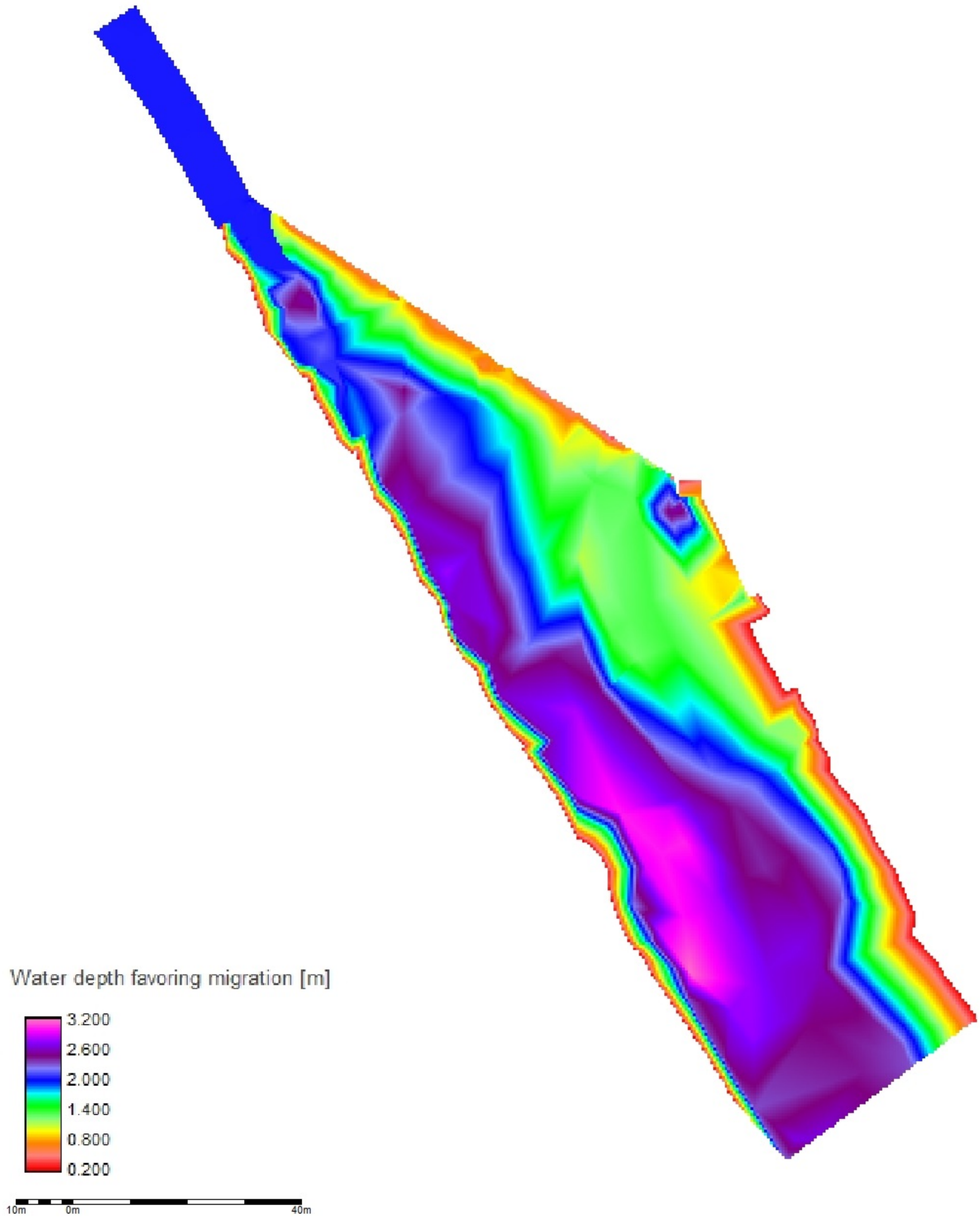

Figure D.13: Mery Site - incision water depth favoring migration scenario 2

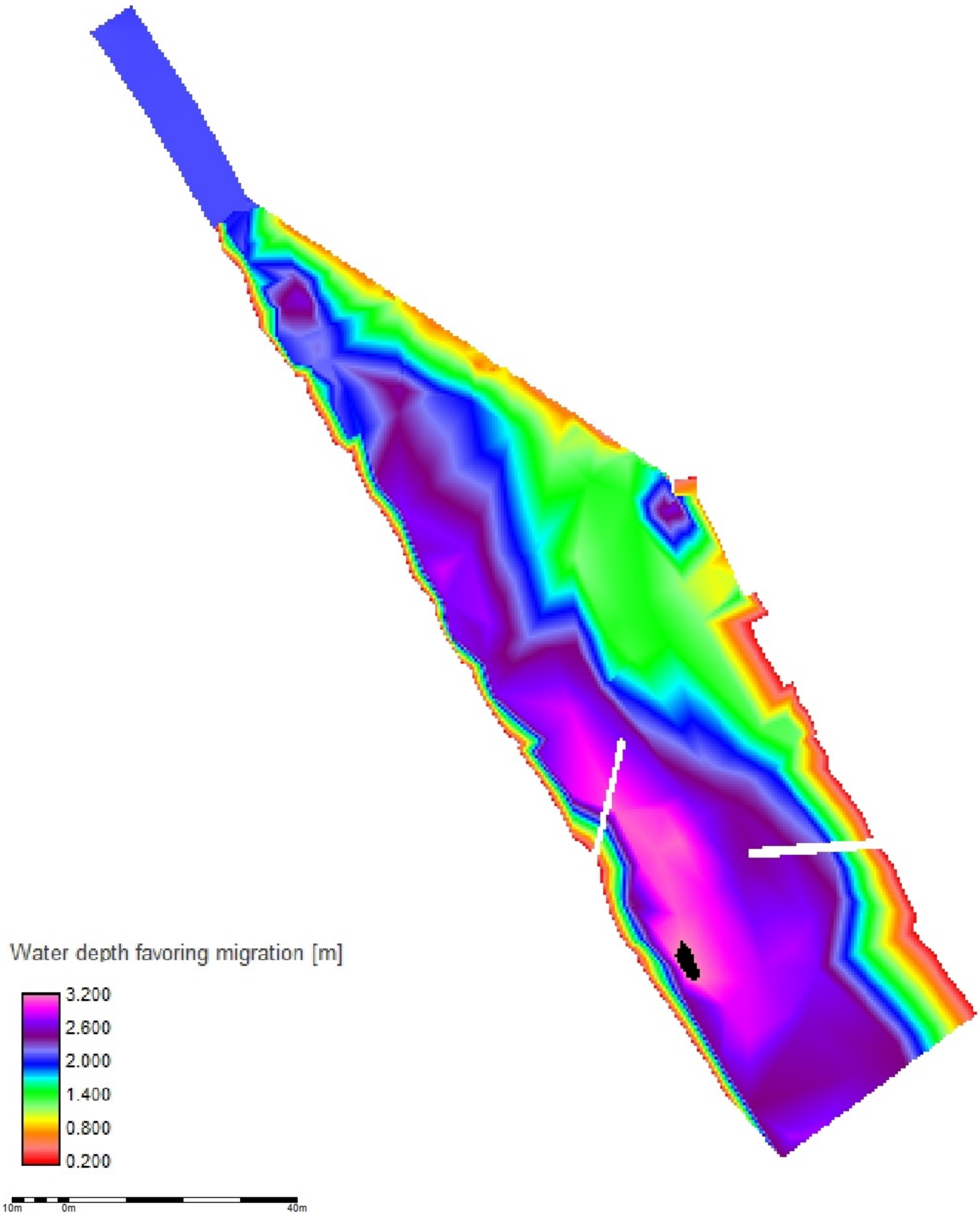

Figure D.14: Mery Site - 2 guiding walls water depth favoring migration scenario 3

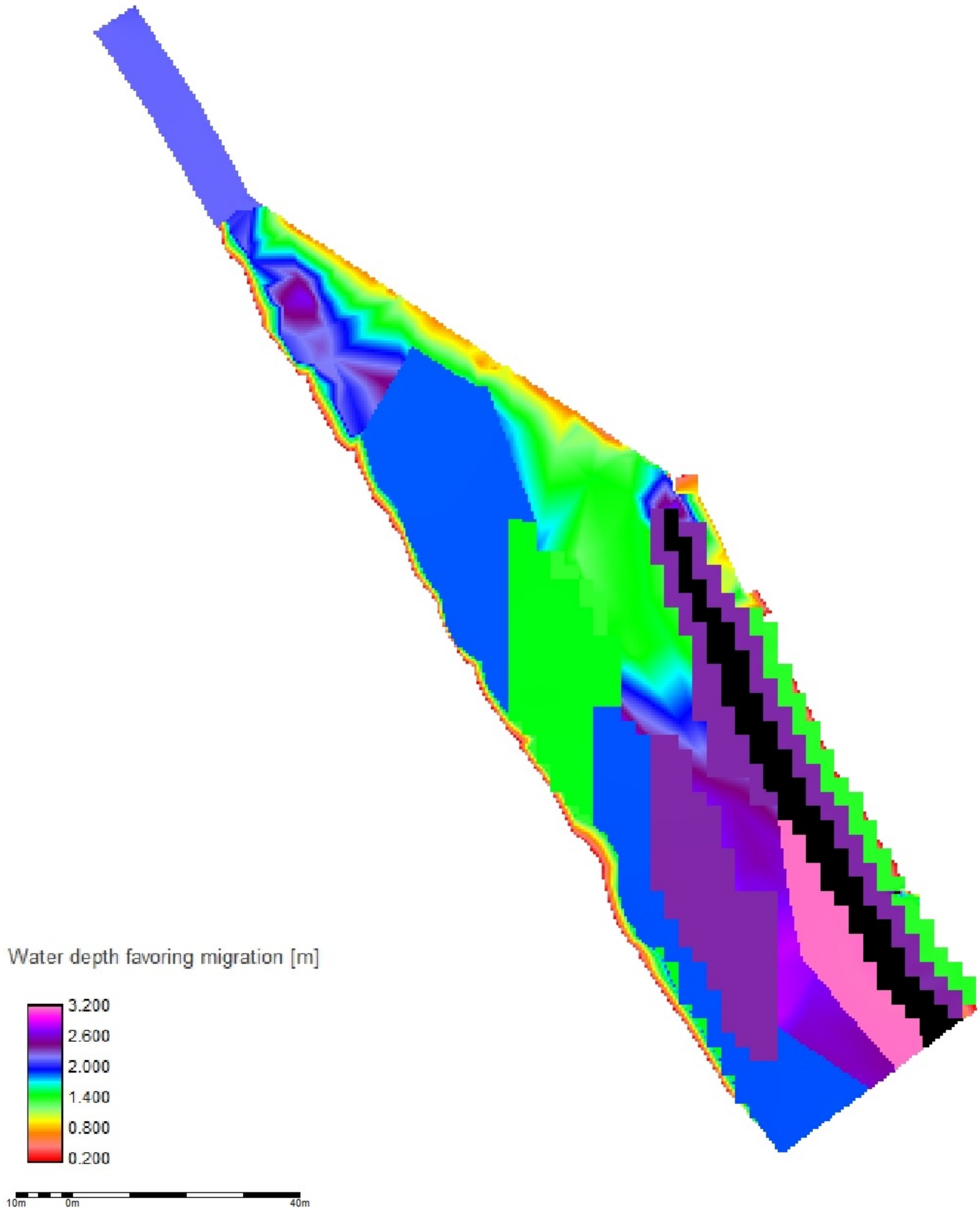

Figure D.15: Mery Site - channel displacement water depth favoring migration scenario 3

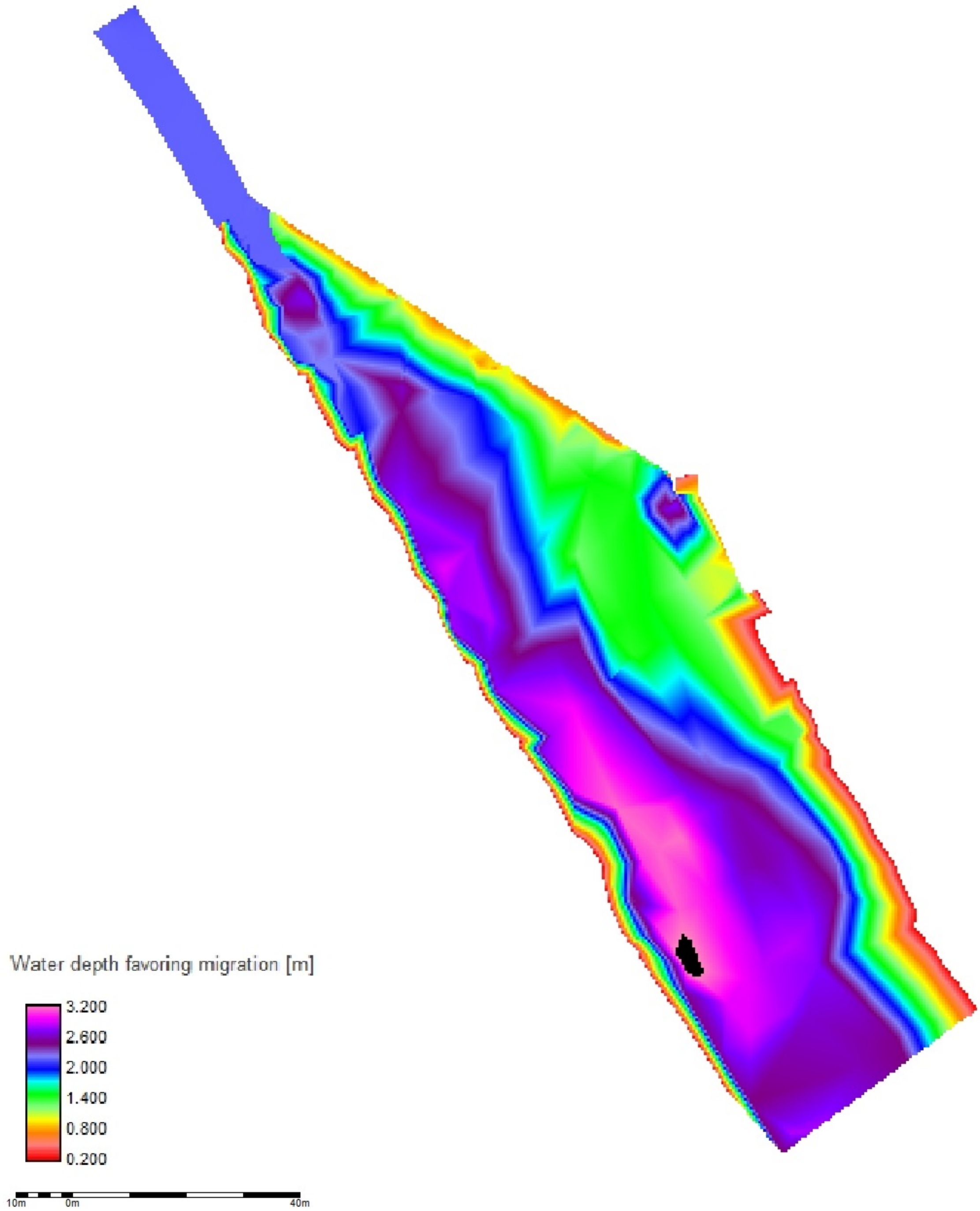

Figure D.16: Mery Site - incision water depth favoring migration scenario 3

Appendix E

Appendix chapter 5

Appendix F

Appendix chapter 6