UNIVERSITY OF GÄVLE

FACULTY OF ENGINEERING AND SUSTAINABLE DEVELOPMENT

DEPARTMENT OF BUILDING ENGINEERING, ENERGY SYSTEMS AND SUSTAINABILITY SCIENCE

Study of a vertical slot fish ladder

Evaluation of flow dynamics through a standardized bypass and the effect of predesigned roughness elements

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Preface

After finishing our bachelor studies in industrial engineering, both took the path of renewable energies as specialization. Therefore, the opportunity of working in a project which sought the resolution of an ecological problem involving hydropower dams has been really valuable for us, not only for the technical knowledge acquired but also for the experience as a whole.

The project was supervised partially by Vattenfall, an international energy company that works towards a fossil-free future. Although the project was originally proposed by Fiskvägsteknik AB, Vattenfall served as intermediary between this company and us. In particular, we would like to thank Bengt Hemström and Mats Billstein for the great opportunity and for all the help provided in the process. They have been important pillars in the progress of the report.

The other part responsible for the supervision was the University of Gävle. Taghi Karimipanah and Abolfazl Hayati have worked hard to provide us with enough resources for the competition of the tasks, including interesting papers and computer processors for the simulations, as well as helping us with all the administrative procedure needed for a master thesis. For all the effort made, we wanted to thank them thoroughly.

The support of our family and friends has also been important for the development of this project.

Finally, we would like to thank each other for the hard work put throughout these past months and the comradeship shown in the development of the thesis. From this experience we learnt to work and solve the problems found in the way as a team, helping one another should the situation require it.

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Abstract

Migrating freshwater fish population has been significantly declined, mostly by the obstruction of their migratory routes by hydropower dams. To diminish such impacts, fish ladders have been developed to facilitate the passage of migrating fish. However, fish ladders are associated with mortality and migratory failure, resulting in an ecological problem which has been a concern during years. The paper contained in the following pages focuses on studying the viability of an innovative modular design for a fish ladder developed by Fiskvägsteknik AB. The design is based in a vertical slot fishway (VSF) to which some roughness elements are attached to modify the flow. The aim of this bypass system is to restore the original biological continuity and diversity in the Swedish rivers, therefore solving a long-lasting ecological problem that hydroelectric production has caused over the years. Through a computational analysis, the flow has been evaluated as a function of the parameters that present an influence over its behaviour. First, a study of the changes in flow velocity influenced by four different slopes: 5 %, 10 %, 15 % and 20 %, has been performed with the objective to find an appropriate inclination according to the capabilities of the fish species considered. The lowest slopes have resulted to be the most appropriate ones, coinciding with low values of turbulent kinetic energy and lower flow velocities. The second step has been checking the effect of roughness elements on the bottom part of the structure tilted a 5%. The flow velocity has shown a considerable decrease, falling in the range of the fish swimming capabilities established. As for the streamlines of the flow, they were altered compared to the cases without the roughness elements.

Key words: vertical slot fishway, roughness element, pattern, slope, velocity, turbulence, Fluent

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1. Introduction

Energy generation in the contemporary world is evolving and adapting to comply with a more sustainable vision for the future. For this purpose, solutions to environmental and ecological issues are currently under development and analysis in different fields of power production. In particular, the paper contained in these pages focuses on solving a long-lasting problem presented by hydroelectric dams, because they suppose an obstacle for fish migration all over the world. The objective is evaluating the viability of a fishway modular design developed by Fiskvägsteknik AB in collaboration with Vattenfall. Fiskvägsteknik AB plans to design a full-scale model of the system, including new functional innovations, as the arrangement of different sizes of roughness elements on the bottom structure and the installation of control hatches in the slot between basins.

In order to understand what a fish ladder is and why it is necessary, it is important to first give a general overview of which sources are used for the global generation of energy and then analyse the impact they have on the environment and ecology in particular. This will serve as a starting point for the forthcoming contents that will be presented in the study.

The next part will provide a contextualization of the project by going through different researches in the field of eco-hydraulics. To begin with, a baseline will be established for the better understanding of the reasons needed to improve the passage systems analysed. The general characteristics and the main drawbacks that this type of passages present will be examined. The fish characteristics and information regarding their migration habits will be briefly described as well, to learn about the requirements that must be established for the design under development.

Afterwards, the objectives and methodology of the study will be described. The methods of the project will serve as a guide for the steps followed and the resources employed, like the simulation software. This step by step description of the process will show the work behind the results in a project like the one developed in these pages. The original model of the fish ladder will also be defined and dimensioned, together with the roughness elements.

After a theoretical introduction of the study, the analytical part will be presented through the results and discussion, in order to describe the outcome of the research. In the conclusions, apart from determining if the initially established objectives have been reached, the potential for a further development will be mentioned.

1.1. Background

Throughout the history of mankind, fossil fuels —consisting of coal, natural gas and crude oil— have been one of the world's primary energy source and they still represent more than 80 % of the total energy use in the present day [1]. The major applications of these fuels are concentrated in the transport sector, in the form of gasoline or diesel, and the industrial one, to generate electricity and manufacture chemical products.

The elevated consumption of coal, natural gas and oil in the contemporary world results in a strong dependency that is difficult to maintain in a long-term scenario, even worse with an increasingly large demand of energy. One of the problems that arise from the tendency to overexploit fuels with a fossil origin is related to the depletion of these resources, which will reach levels beyond the capacity of the reserves in several years. On the other hand, it is important to address the Global Warming issue that results from the pollutants released from the refining process and posterior use of this type of energy sources.

The main by-product released from the combustion of fossil fuels is carbon dioxide, causing an increase in its atmospheric concentration of a 30 % during the last five decades [1]. Carbon dioxide is considered a greenhouse gas, trapping solar energy absorbed by the earth as heat and causing an increment of the world temperature in recent years. Although carbon dioxide capture and storage (CCS) is a promising technique [2], it serves just as an immediate and, most surely, temporary solution due to the potential leakage it entails.

In order to reduce the carbon dioxide emissions and curb the Global Warming, some alternatives are currently under development, which can be classified into the nuclear perspective and the renewable one. The former is related to nuclear energy based on either fission or fusion processes, but the need for further progress, sustainable waste management and improved reliability are difficult obstacles to overcome. The latter, however, relies on the energy production from natural resources such as water flow, tides and waves, sunlight, wind and geothermal heat. Those renewable energies do not release greenhouse gases nor polluting emissions during generation, making them the cleanest and most viable solution to restrain environmental degradation.

Unlike solar and wind sources, which are available intermittently, water can be used continuously and be accumulated in reservoirs, complementing the availability of other resources. Moreover, water can be pumped upstream using extra electricity from overproduction periods to function as an energy storage system. Therefore, hydropower plants have an important role in stabilising the European power grid [3].

Nevertheless, there are several side effects concerning the renewable alternatives. Although it is clear that they are the best possible option as a sustainable and inexhaustible source, all the benefits regarding the environment and climate alteration do not prevail for the wildlife habitat where these power plants are built.

Hydropower plants use the water stored in reservoirs to reverse natural conditions, increasing water flow in winter and reducing it in summer. The short-term peaks of water released during operation are not strong enough to remove silt build up, but do have an impact on invertebrates, fishes and their habitats. Although the most important issue is that dams acts as a barrier for fish migration, which prevents them from going upstream or downstream depending on the season.

Innovative designs for turbines together with spillways are being developed to allow fish to cross the dams downstream while fishways are the proposed solution to overcome upstream fish migration. The main problem behind the implementation of these new technologies lies in the fact that a certain amount of water has to be discharged to maintain an appropriate flow [4]. As a result, the partial water spillage reduces the stored amount, reducing the water resources for electricity generation and other kind of applications.

The purpose of a dam is not just accumulating water for hydroelectric generation. Reservoirs are employed to store water for population supply, irrigation of crops and flooding control as well. Therefore, the incompatibility between human water needs and the necessity for migration of fish species will persist until an economic and efficient solution is found [4] to ensure appropriate conditions for the preservation of the aquatic ecosystems in rivers.

1.2. Context

Fish ladders are hydraulic structures with the purpose of providing a safe and effective passage for fish through an obstacle, typically a dam. Therefore, they present a certain slope and are typically divided by baffles into several pools, leading from the river above the barrier to the river below. The water flows from one pond to the next, either through slots or submerged orifices, allowing the fish to ascend and descend by jumping or swimming across the dam from pool to pool [5].

Through history, different types of fish ladders have been developed depending on the characteristics of the river and the target fish species of each site. Four general designs can be distinguished to facilitate fish passage: Denil fishways, pool and weir ones, vertical slot type and nature-like passages [6], [7].

- Denil fishways are characterized by single-plain baffles provided on the sides and floor as shown by Figure 1 and were developed as an experimental study to improve the design of steep ladders. The tests were conducted employing hydraulic modelling with various species to variations of a baseline design comprised of cup-shaped vanes and a 25 % slope, which proved to be viable (1908).

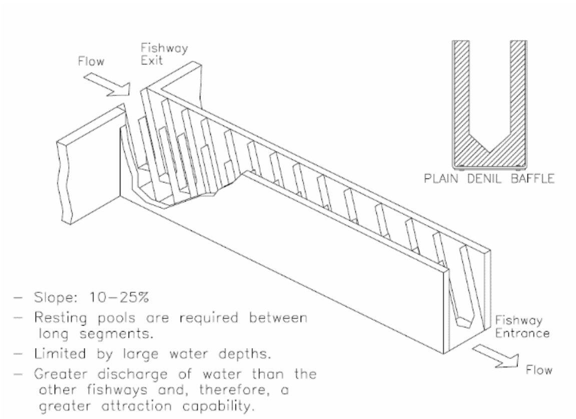

Figure 1. Sketch [8] *and image* [9] *of the Denil Fishway*

- Pool type of fish passages consist of a chain of ponds separated by weirs with a slope value between 5 and 12.5 %, as it can be seen in Figure 2. The inclination, discharge, weir height and spacing affect their performance. Further variations include surface or submerged openings, ramps and ripples, among others.

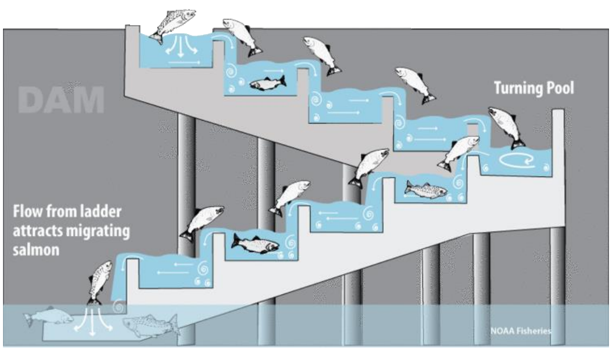

Figure 2. Sketch [10] *and image* [11] *of the Pool and weir fishway*

- Vertical slot fish ladders are characterized by the use of walls with narrow openings from top to bottom to connect one pool to the next and slopes between 5 and 10 %, as Figure 3 shows. The design allows to maintain steady hydraulic conditions through the system even with variable circumstances of the river water level.

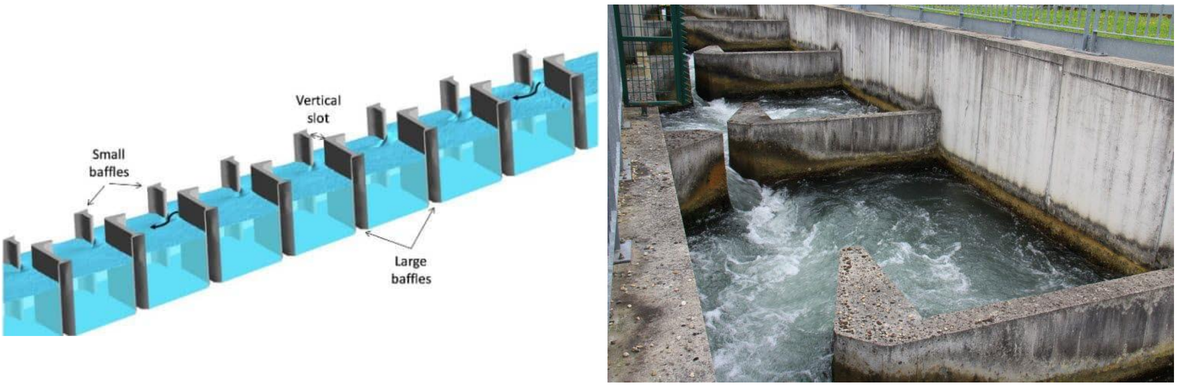

Figure 3. Sketch [12] *and image* [13] *of the vertical slot fishway*

- Nature-like fishways are the ones that simulate the natural habitat by estimating an equivalent width and slope, thus reducing the negative environmental impact. The main advantage of the design in question is the possibility to be implemented still when otherwise necessary data is limited. In Figure 4, an example of this type of fishway can be seen.

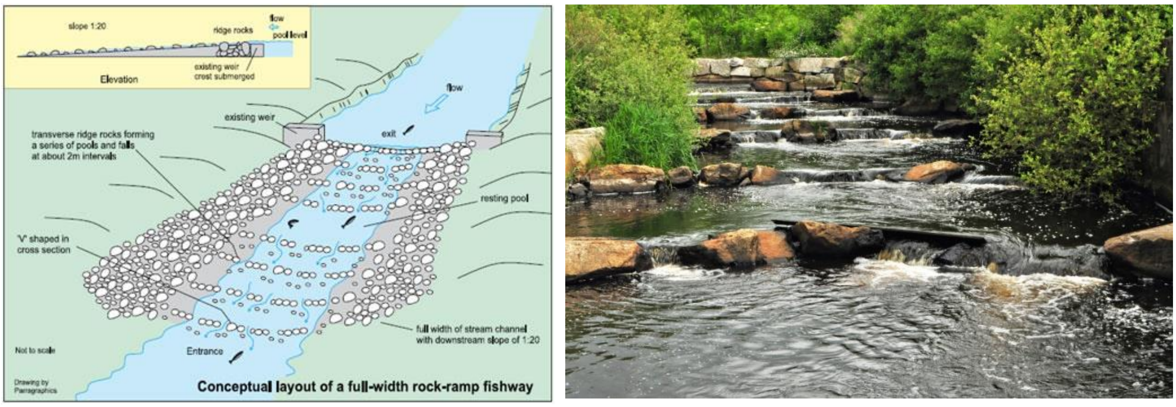

Figure 4. Sketch [14] *and image* [15] *of the nature-like fishway*

When taking the decision of installing a particular type of fish ladder, the hydraulic and ecological aspects of the area have to be taken into account to make the choice wisely. Moreover, the general characteristics of the different fish ladders mentioned before can be adapted to the environment where they are going to be installed to match the specific requirements.

Despite the benefits that a fish ladder would bring to the river ecosystem, the performance of these structures is not always successful. When it comes to the attraction efficiency between the different designs, defined as the proportion of individuals present downstream the passage capable to find the entrance of the fishway [16], it varies between a 48 % (nature-like) and a 77 % (pool-and-weir). As for the mean passage efficiency, that is, the number of fish that leaves the ladder relative to the number that entered, varies from 40 % (pool-and-weir) to 70 % (nature-like) [6]. The remaining fish, those that do not success leaving the fishway upstream, stay in previous stages of the passage. This is a result of too high water velocity, which can prevent some fish with weak swimming ability from passing through a fishway or too low water velocity, which may not provide sufficient stimulus to encourage fish movement upstream causing disorientation [17].

It must be pointed out, however, that the attraction and passage success of the fishway depend not only on the selected design but also on the hydraulic conditions established. For example, as indicated by [18] to achieve a sufficient efficiency of attracting fishes the water discharge through the passage should be between 5 - 10 % of the total river flow rate after the obstruction.

According to several studies [19] [20], some of the projects developed fail to achieve the set targets involving transport capacity of the passages, which shows a clear necessity of improvement. More specifically in [21] it is reported that the mean passage efficiencies through fish ways on the rivers of Susquehanna, Connecticut and Merrimack are less than a 3 % in recent years —between 2005 and 2010—. Therefore, only small fractions of the targeted fish species were able to complete the migration. Moreover, in multiple cases the fish ladders are adapted to be effective in the catchment and assistance of a certain species, generally salmonids [22]. Consequently, the possibility of diversity in river migration is diminished, even if a fish passage is installed.

Another problem shown by current fish ladders is related to the lack of multifunctionality in the design. In fact, although in general the passes are designed with the intention of fulfilling upstream and downstream movements, they do not typically succeed in both. As a consequence, the analysis of the fishways performed in different studies focuses just on one direction [23].

Taking into account that the major limitations of developing fish passage systems are related to the behaviour and the swimming abilities of the fishes, which differ widely among species, new technologies have been evolved to overcome the previous mistakes.

With the goal of providing a more efficient and adaptable fishway while preserving the main objective of reducing the impact that hydropower barriers have on migratory species, the Whooshh Fish Transport System (WFTS) was developed. This creative system consists in a flexible tube designed to move fish around dams using differential air pressure [6]. The constant irrigation causes it to be covered with mist on the inside, allowing the fish to breathe in a frictionless environment. It can be installed in river barrier sites where fish ladders are not possible due to accessibility or operating costs. As it is not limited by hydraulic conditions, its application is suitable for a wide range of fish species [24].

As an alternative to innovative designs like the one described before, there exists the possibility of evaluating the ones that have already been employed for so long. Most of the problems mentioned can be solved by the modification of the existing models and implementation of improvements. This way, the path is already marked, very much simplifying the whole process of analysis because the data can be adapted to the new cases easier, learning from previously made mistakes when performing the retrofitting.

In this paper, the object of study parts from the design of a vertical slot fishway (VSF), to which some roughness elements are attached with the purpose of creating various flows. The variability of the water velocity at different parts is attained through the modification of the size of the roughness elements and their distribution. The intention behind the idea is solving the problem of the different needs of the species that will be using the passage, because each type of fish requires specific hydraulic conditions, which will be analysed in the following section.

All in all, passage through hydropower dams is associated with mortality and failure for migrating fish, which has brought to develop different technologies more adaptable to the wide range of species of a certain site [25]. With the objective of improving the passage performance, a study of an innovative modular design of fish ladder will be conducted. Different hypotheses will be evaluated and verified in function of the increased understanding of fish behaviour as an important aspect of fish passage science.

1.3. Fish capabilities in Sweden

The earliest known attempts to build fish passages were made in the 17th century, but until the 20th century, none of these attempts was done following a scientific basis [26]. From then on, immense progress had been done in the science of hydraulics and as a consequence in the design of fishways.

Despite the long history of fish passages, most of them are designed for the classical commercial species as the Atlantic salmon and the brown trout, which have powerful swimming capabilities and good leaping skills, but do not work for most of the fish species [27]. As a result, the number of fish going upstream of the hydropower dam can be seen altered due to the passage being designed for a few species, those most suitable to the fish passage system site.

In order to study fishways that can be passed by most kind of aquatic organisms during their different life stages, a list of the most abundant migratory fish species in the Swedish rivers has been done in Table 1, where it is shown the swimming capabilities of each fish:

Table 1. Major migratory fish species in Sweden and their swimming capabilities [28].

FISH	*Swimming capability [m/s]*
1. Atlantic salmon	1.37
2. Arctic char	0.86
3. Brown trout	1.06
4. Arctic Grayling	0.67
5. European Perch	0.97
6. Pike	0.22
7. Roach	0.98

The swimming capability of the different fish species is the performance they have in terms of speed, time and distance. This performance also evaluates the influence of environmental factors such as water quality (contaminants) and temperature, among others, by measuring the difference in performance between the treatment and control group.

The swimming capability values from Table 1 are the critical swimming speeds measured by subjecting fish species to a progression of increasing velocity steps maintained for fixed time periods until the fish ceases to swim [28].

Regarding the migration season of each species, it cannot be easily determined due that it differs substantially depending on the type and age of the fish considered. These aquatic species change their habitat throughout their lifespan several times, in many occasions swimming large distances towards new environments to fulfil different stages of their life. The purposes of this migration mechanisms are various, which include feeding and growth, finding shelter from difficult environmental conditions or moving to their spawning areas [29].

In the case of the Atlantic salmon, it is born in freshwater, where it spends the first two or three years of life. Then, it migrates to the ocean to feed and grow, returning back to freshwater as an adult for the spawning period. It is for this fact that the most limiting velocities are going to be taken into account for the study, that is, the ones corresponding to the most restrictive characteristics.

2. Objectives and scope

The principal objective of the master's thesis in question involves the computational analysis of an innovative and flexible design of fish ladder developed by Fiskvägsteknik AB. The purpose includes acquiring a better understanding of its performance and demonstrating its viability in solving migratory impediments of freshwater fish species as a result of the human activity when building reservoirs. This means that the design has to be not only cost-effective, but also adaptable to different hydraulic conditions in order to ensure the efficient attraction and passage of a wide variety of species of fish.

Although the study through simulations is the main goal behind the development of the project, throughout the procedure and execution of the different steps followed several sub-objectives have to be considered. These secondary aims can be arranged according to the classification proposed below:

- Through the research of academic papers about fish ladder characteristics and applications, a technical but elemental knowledge in those areas will be acquired to comprehend the operation of these systems and their weak spots
- Establish a foundation on eco-hydraulics and fish species in Sweden through scientific literature, in order to learn about the physical characteristics and swimming capabilities of the migrating fish in the dam site.
- The performance of the analysis through simulation requires to get an insight into a Computational Fluid Dynamics (CFD) software. In the particular case of this research Ansys Fluent will be studied
- Flow dynamics will be verified through a standardized bypass, that is, taking into account just the general structure of the model unit
- The effect of the roughness elements on the flow will be analysed once they are distributed through the bottom of the fish ladder

The previously mentioned objectives are the ones involving the thesis project proposed. However, when it comes to the full study, it presents a larger range within a longer period of time. The further steps that have to be fulfilled to ensure a proper conclusion of the analysis of the mentioned fish ladder can be divided into the following points:

- The roughness elements will be arranged in different patterns to determine which one is the most suitable one regarding the conditions required for the fish
- The influence of control hatches in the manipulation of the flowrate will be analysed. These gates will be implemented in the slots between the basins

Apart from the simulation study through Ansys Fluent CFD program, once all the tests have been carried out and the data has been gathered, there is the possibility of performing an experimental validation of the results obtained. For this purpose, a large laboratory where to install the prototype and run the experiments is required.

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3. Methods

In this section the methodology followed for the completion of the project will be explained. Considering that the main objective of the study is to analyse if the new design proposed is viable and which is an appropriate distribution for the roughness elements that are employed, computational simulations are presented as an efficient and flexible way to obtain preliminary results for the posterior validation of the model.

The principal advantages of employing a simulation tool to evaluate the performance of the system include the possibility to understand the interrelationships between the established variables and easily modify the arrangement accordingly through a process that is not excessively time-consuming nor economically demanding. Therefore, it serves for the simplification of complex interactions by a hierarchical decomposition of the problem, which is known as a *top-down* technique.

In the project in question the *top-down* approach will help with the comprehension of the influence that the different variables have on the flow velocity. The considered parameters that will be subjected to modifications during the analysis are the slope of the given fish ladder and the distribution of the roughness elements. As for the design and dimension of the fish way and the roughness components, they are established at the beginning by the company behind the project, that is, Fiskvägsteknik AB.

3.1. Time plan

The thesis program will be conducted in the course of approximately ten weeks starting in March and establishing as target date the 25th of May. Since the project depends on a collaboration with a company, the first steps include the initiation of the contact with Vattenfall AB which works as intermediary between the corporation that proposed the project and the students involved. The project in question was presented in the job interview, and the general aspects contained within were explained.

After the first contact, a regular meeting schedule was established in order to update the company supervisors with the progress in the study and the research process began, with the purpose of acquiring a background in eco-hydraulics related to fish ladders. The foundation on the concepts associated with the topic of the task is utterly important for the proper development of the project, as it helps building up technical knowledge on the specific field mentioned.

The simulations will start once enough context is accumulated. This way it will be possible to gain deeper insight into a CFD program like Ansys Fluent, learning about how simulations work and which is the best way to plot the results to present the analysis in the clearest manner. At the same time, the report writing will commence, to compensate for the short time which is available to develop the thesis.

The regular meetings will help giving shape to the report step by step, and handling multiple tasks at once —that is, combining the simulation process with the thesis writing— through collaboration will enable a faster progression.

Towards the end of the period established for the thesis project, the report will be evaluated by the supervisors from both the company and the university involved. Consequently, different opinions coming from professionals in the area of the project will improve the quality of the report, correcting possible mistakes and suggesting improvements.

Finally, when the deadline is met and the project delivered, the paths of the university and the company will diverge. The former will focus on the coming presentation of the project to put an end to the project and the master, while the latter centres on further developing the project until more data is gathered from the simulations.

3.2. Software

Fish passages are structures designed with several geometric distributions and therefore, flow patterns can be modelled to show suitable characteristics for the site and the capabilities of different fish species [30]. To aid in the design of this vertical slot fishway through the study of the flow and the hydraulic conditions, a three-dimensional numerical model was used to simulate the flow for various geometric arrangements.

Using a three-dimensional numerical program allows the study and posterior result analysis of the hydraulic parameters, flow patterns through the passage, maximum velocities, velocity fields and turbulent kinetic energy in the pools [30]. In this study, the program used was Ansys Fluent.

Ansys Fluent software is a flow modelling program based on Computational Fluid Dynamics (CFD) which allows to perform challenging simulations involving different kind of liquid and gaseous flows.

- ### Characteristics and advantages

The use of CFD to investigate environmental problems and hydraulic habitats has become an effective and useful tool [30].

As it has been mentioned in Context, many failed fishways were built and did not fulfil the expected goals. In most cases, the fish are not able to migrate through the ladders due to a lack of relationship between hydraulic characteristics and the swimming skills of fish species. This absence of transmission of information and research leads to an inefficient design.

For this reason and in order to fulfil the hydraulic conditions and execute a proper design of the passage for fish to successfully migrate, a numerical model is the best option. Hence, there are many parameters to consider an appropriate design for the physical capacities of the fish, as well as to study the flow behaviour through the passage to prevent sudden pressure changes and analyse possible turbulences.

CFD programs allow accurate resolutions of complex geometrical surfaces by entering the design of the model in CAD and constructing a mesh. They also permit the design of mass flow rates as well as predict pressure drops —which can be fatal for the fish—, heat and mass transfer rates and fluid dynamic forces such as lift and drag.

Fluent solver in particular uses a finite-volume code that solves iteratively the conservation of mass and momentum over discretized volumes within the model domain until convergence is reached [31]. This discretization technique means that the system is divided into smaller and easier to solve parts, which are the elements of the mesh, in order to easily reach convergence and get a unique result for the whole structure.

CFD offers the advantage of enabling to test numerous geometries, predict their performance and consequently, optimise the design without the need to carry out the construction of a physical model, which would be a very time consuming option and not cost effective at all. Therefore, simulation hones the design of a physical prototype for further development and field validation [32].

The Fluent software solves the Reynolds averaged Navier-Stokes equations [32] with a coupled two equation k-ω turbulence closure model in this study.

Limitations

Some limitations that can be found with CFD programs include on the one hand that they work with solvers based in physical models, so the solutions cannot be more precise than these models, especially the turbulence one. On the other hand, the solving equations can lead to numerical errors due to not enough computational cells being used and the finite word size available on the program, resulting in round-off mistakes [33].

The accuracy of the results depends straightaway on the initial boundary conditions provided during the set-up of the model. Therefore, a mistake in this part can have severe consequences. Another critical aspect of using a CFD software is the knowledge of the designer about fluid dynamics, which is crucial for the understanding of the results.

CFD applied to fishways

An efficient fishway is not just about allowing the fish to pass through the pools or the slots, it also has to attract the migratory fish for them to enter and leave safely with minimal impact.

This performance is influenced by hydrodynamic variables such as velocity, water depth and turbulence fields in the pools. The goal of a fishway is not just to be used by targeted species, but attracting a wide variety of fish species and allowing them to go through. In consequence, knowing the swimming capabilities and the hydraulic preferences of the local fish species is essential [30].

The main characteristic of VSFs is the transition between pools. This transition consists of a narrow opening along the entire depth of the pool forming the vertical slot. Energy is dissipated through the slots, allowing the passage of fish without excessive effort.

The VSFs are considered favourable in eco hydraulic terms for three main reasons: (1) fish can select the water depth that suits them best in the transition between consecutive pools; (2) resting areas can be found in each basin where the velocities are lower than in the main stream, which can be suitable for fish passages where a large vertical gradient has to be overcome and a large number of pools are needed; (3) the maximum velocities are found in the main jet, which leads the fishes upstream direction and minimizes the disorientation risk of fish along the passage [30].

For these reasons, knowledge of swimming capabilities and hydraulic preferences of fish is required. A successful fish passage is related to the understanding on how species interact with the hydrodynamic flow conditions, identifying the flow characteristics that attract fish as well as the flow patterns that repel them. Although the swimming abilities and stream passage specifications depend on the age of the fish, the principal hydraulic requirements to consider when designing and analysing a fishway are [13]:

- The stream flow velocity within the fish passage should be less than the swimming capability of each fish species as well as less than the burst speed over short distances. The flow velocity will depend in part on the slope of the structure. Also, alcoves should be provided in case flow velocities exceed the swimming capabilities of the species and flow obstructions to produce velocity breaks.
- A minimum depth should also be maintained for when flow streams are low, in behalf of fish size, swimming abilities and behavioural responses.
- A maximum vertical height of the barriers according to the jumping heights of the target fish species allowing them to generate enough speed with the needed jump pool length and depth. However, in this case the height of the barriers is fixed by the previous design of the company Fiskvägsteknik AB.
- The turbulence fields should be studied due that turbulent parameters can significantly influence fish behaviour, causing fatigue or confusing them in their passage through the hydraulic structure.

Application of the k-ω turbulence model

Water movements generate forces such as shear force and drag, which makes fish prefer some areas and avoid others. When a fluid is flowing inside a straight channel, the flow velocity is not equal at all the points in the channel, being highest at the centre and dropping toward the channel wall. This velocity gradient is because of frictional forces generated between the adjacent layers of the flowing fluid and between the fluid and the walls of the channel [34].

In the following Figure 5, a wall shear stress is shown for different velocity gradients inside a boundary layer. In case of a channel, the gradient would have a parabolic shape, but the wall shear stress would present the same type of distribution.

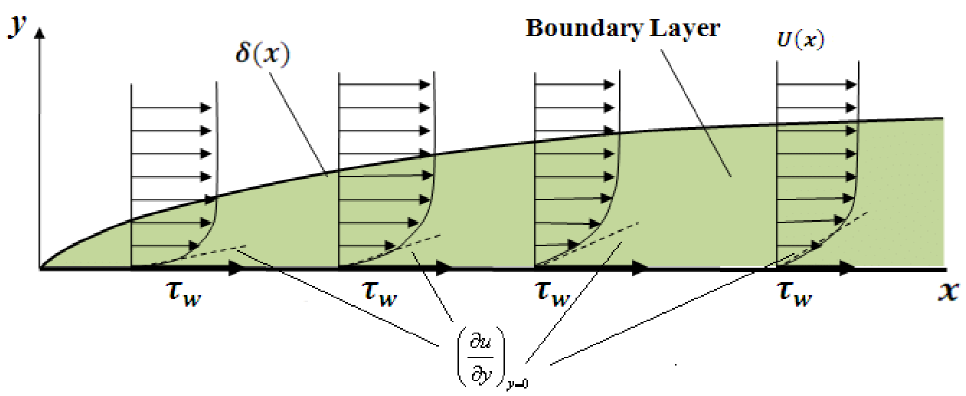

Figure 5. Wall shear stress for different velocity gradients

These frictional forces are defined as wall shear stress and are proportional to the velocity gradient near the channel wall, achieving significant values in near-wall areas in fish passages. Duarte et al. [35] conducted an interesting study where the response of diverse fish species to some hydraulic parameters was examined in a VSF. Low shear-stress areas were clearly preferred by the tested fish, provided by a low velocity gradient and therefore a more stable environment. Even if the mean velocities in the channel may be high, low shear stress ensured a less turbulent as well as less confusing environment.

Given that rotational flow patterns are common in vertical slot fishways, causing disorientation to the fish, ensuring a low wall shear stress values can help the fish to find and reach the exit of the fish ladder. Providing appropriate conditions for the fish will improve the attraction and passage efficiencies of the bypass system.

Therefore, the turbulence model chosen in Ansys Fluent is the Shear Stress Transport (SST) k-ω. This model is a two-equation eddy-viscosity model. It combines the suitability of the k-ω to simulate flow from the inner part through the viscous sub-layer up to the walls and the one of the k-ε model to predict the flow behaviour in regions away from the wall.

Some other favourable motives are that SST models present less sensitivity to the free stream, the flow outside the boundary layer, than other models and a limiter of the shear stress in the k-ω avoid accumulation of excessive turbulent kinetic energy near stagnation points or regions with strong acceleration.

3.3. Model

The model that will be analysed is based on a multi-basin vertical slot fish ladder, which includes several modifications. In particular, it consists of 5 pools connected in series through which the water will flow depending on the inclination.

Figure 6 represents one of the mentioned basins of which the ladder is composed. According to the flow streamlines depicted, the water enters from the right and crosses the pool creating recirculation zones on the corners. Some of those will work as resting areas for the fish to recover before resuming with the ascension of the fish ladder, also illustrated below.

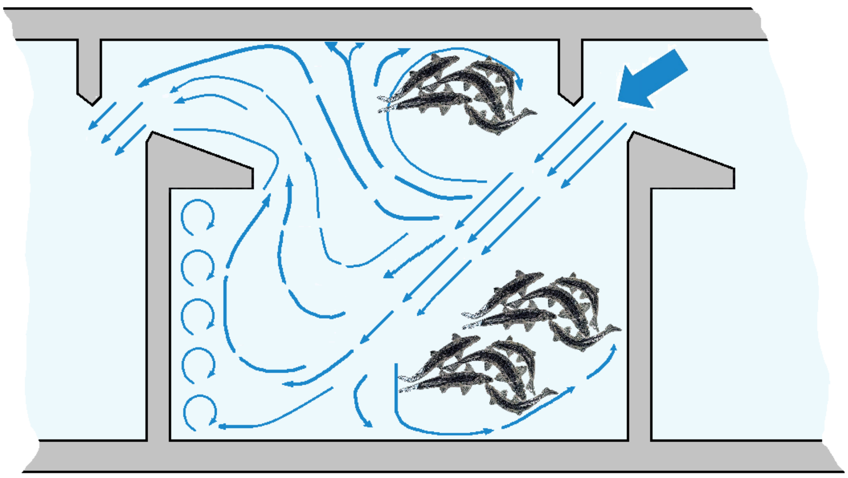

Figure 6. Outline of a basin

Regarding the geometry of the pools, the base model is defined by the dimensions gathered in Table 2, which are constant. When the different slopes are analysed, the bottom level at the inlet of the water will be higher, so the height of the pool as well as the water level will increase.

Table 2. Pool measures of the base model

Characteristics	*Value [m]*
Pool length	*3*
Pool width	*2.5*
Pool height	*1.9*
Water depth	*1.3*

In the following Figure 7, the specifications of the basins and the vertical slots is shown. In the side view, it can be seen that the walls are 600 mm above the water surface, to allow for water level variations along the basin.

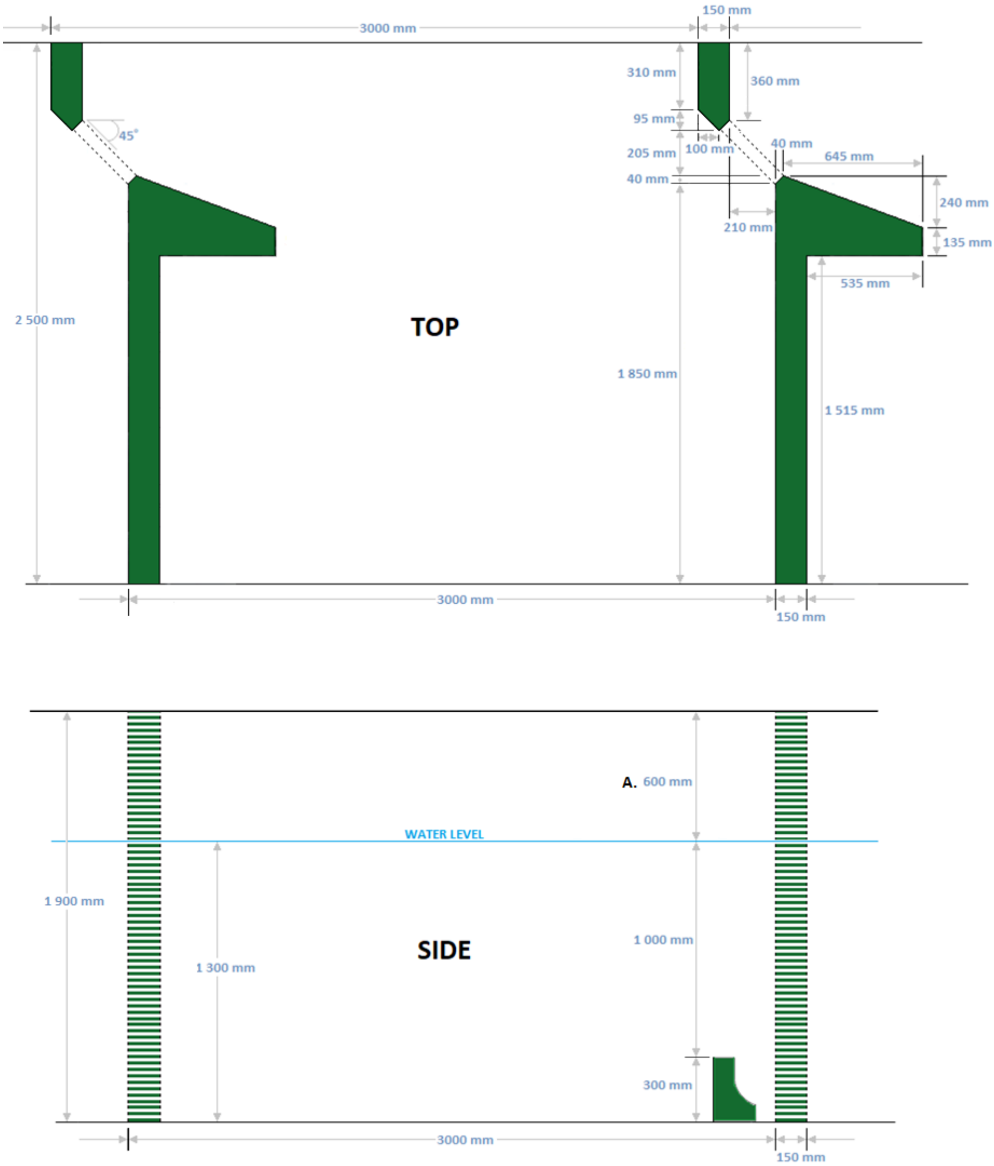

Figure 7. Top and side views of the basin

The floor of each basin will not be flat, which is the case for other designs of fishways. Instead, the floor will be fully covered by roughness elements, all of which will present the same principal shape but of varying size. When it comes to the shape, the components have a conic outline horizontally cut to resemble a cylinder, with a curved plus semi-spherical milling on one side, as shown in Figure 8 below:

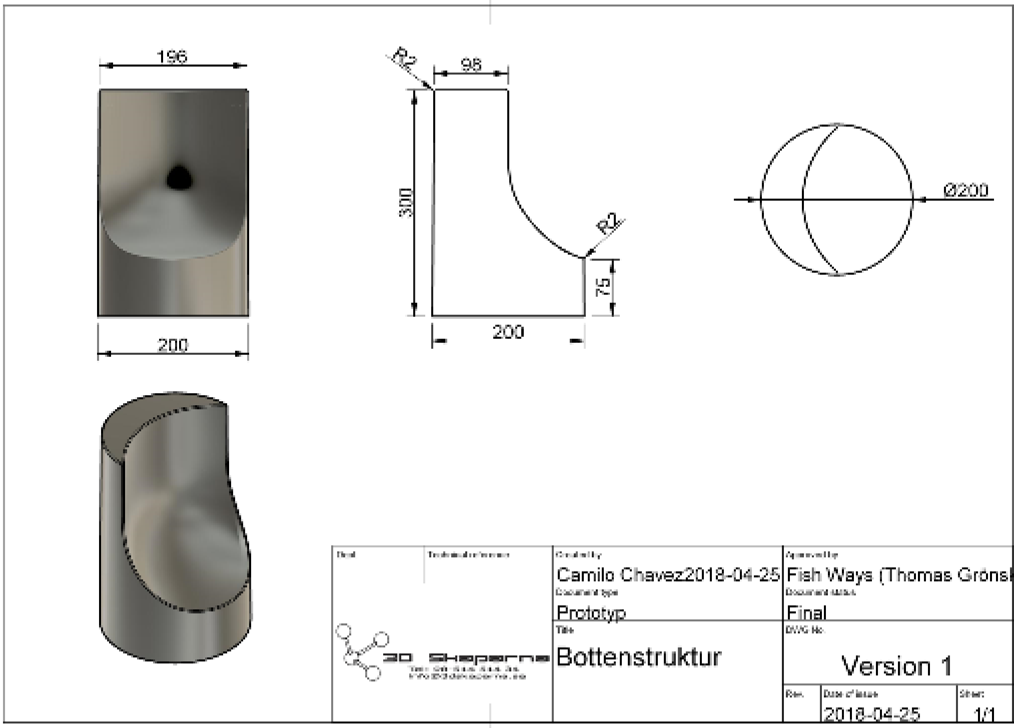

Figure 8. Geometry of the roughness elements

As for the size, four different ones will be employed. Three of them will be arranged on a certain pattern through the bottom of the pools —variations of the one depicted in Figure 9—, while the fourth sized roughness structure will be placed close to the vertical slots. The objective of using this kind of distribution in combination with the shape of the elements is to allow water to flow with different flow velocities at distinct depths, therefore adapting to the requirements of a wider number of fish species.

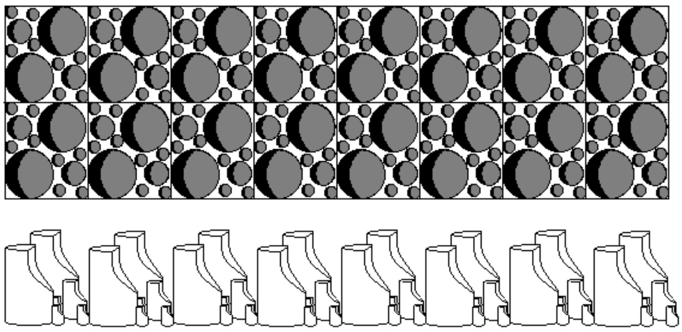

Figure 9. Pattern of the arrangement of the roughness elements according to the different sizes

The model will be presented in 3D because it is important to see the distribution of the flow on each basin on the horizontal plane for different heights, to be able to determine whether the velocities adjust to the most appropriate conditions.

3.4. Guideline of the simulation

In this study it has been worked remotely with the University of Gävle (HIG) programs. The software used is Ansys Fluent, with the version *2019 Fluent R3*.

Once the program is opened, 3D dimension and double precision are selected. The processing options has been chosen in parallel with 4 or more processes, if available, which makes the simulation faster. As shows in the following Figure 10, fluent is a code that parallelises very well.

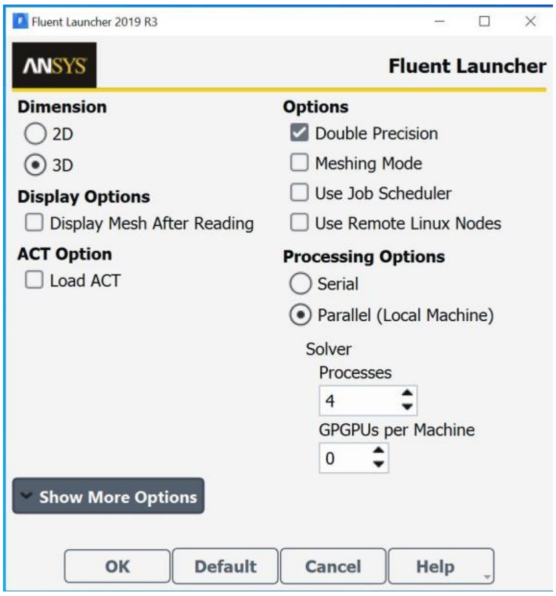

Figure 10. Opening options of the 2019 Fluent R3

This guideline has been done for the 5 % slope case as the reference one, but the same process can be applied to all the other cases, with the correspondent modifications that will be explained in Proceedings. The following steps have been followed and validated:

3.4.1. Setup

- #### Mesh

The starting point is to import the geometry previously done in a CAD program. This geometry has been given for the company Fiskvägsteknik AB and has the dimensions which are presented in Model.

To define the mesh, it is important to take into account to have a good and dense mesh in the regions where there is expected to be water, but extending the mesh a sufficient distance above the water surface to give some space to the water level for the fluctuations during the calculation.

As for the density of the mesh, it also should be finer close to the free surface. That mesh refinement has been done inside Fluent after getting the first solution, when the approximate location of the surface is known. The mesh refinement is conducted to test how big numerical errors are due to an insufficient number of cells and how this affects the results.

When it comes to the mesh size, for the case of the channel without bottom structures it is 1128534 cells, all of them being hexa cells. As for the basin with roughness elements, the mesh size ascends to 1635329 cells, which are mostly tetrahedral (93 %) because of the complicated geometry around the structures.

The meshes were checked for cell skewnees not being very high. This procedure was carried out both manually and automatically by the program itself when reading the file into Fluent.

- ## General

In the general settings (Figure 11), the solver parameters are chosen, although some of them are already set by default. The simulation has to be “pressure-based”, with an absolute velocity formulation and it will be run in transient, running steady will not work.

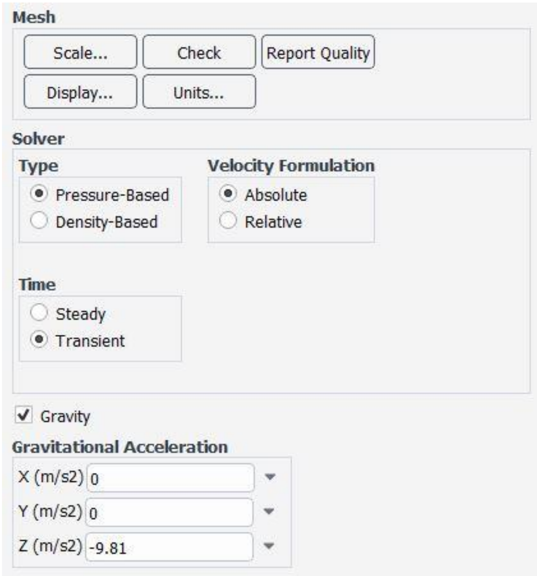

Figure 11. General solver parameters

- ## Models

Two types of models have to be defined: the multiphase and the viscous.

- ### Multiphase model

The model chosen to simulate the fish way is the “Volume of Fluid”, with two number of Eulerian Phases corresponding to water and air. The VOF (Volume of Fluid) sub-Models to activate is Open Channel Flow.

With the Open Channel Flow activated, the Volume Fraction Parameters selected is the implicit formulation by default, which implies that this is the most efficient choice [36]. The Options of the Interface Modelling is Sharp, activating also the Interfacial Anti-Diffusion.

The Volume Fraction Cutoff = 10^{-6} and the Implicit Body Force is applied. The following Figure 12 summarizes these parameters.

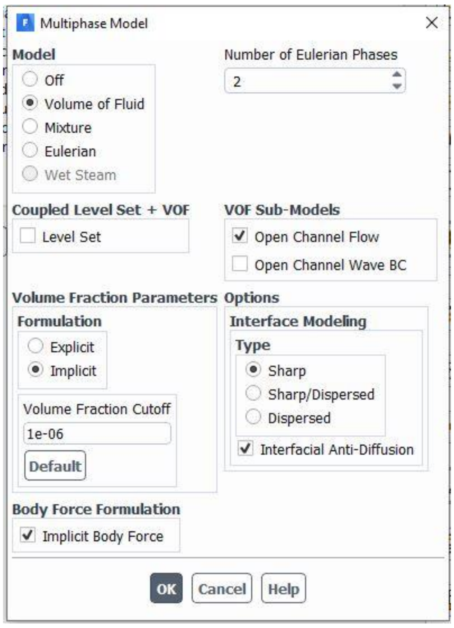

Figure 12. Settings of the Multiphase model

- Viscous model

The turbulence model chosen is the SST k-ω (omega) with a production limiter, as shown in Figure 13. There are several turbulence models available, the SST k-ω model is especially good when walls shear stresses are important, as it has been explained in Software.

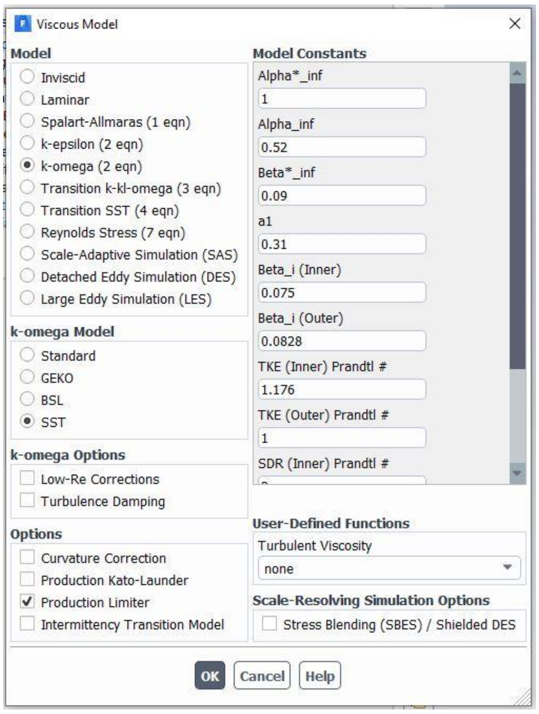

Figure 13. Settings of the Viscous model

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And with the following Model constants (Table 3):

Table 3. Values of the Viscous model constants

Model Constant	*Value*
Alpha*_inf	1
Alpha_inf	0.52
Beta*_inf	0.09
a1	0.31
Beta_i (Inner)	0.075
Beta_i (Outer)	0.0828
TKE (Inner) Prandtl	1.176
TKE (Outer) Prandtl	1
SDR (Inner) Prandtl	2
SDR (Outer) Prandtl	1.168
Production Limiter Clip Factor	10

- ### Material

The fluid materials set are water-liquid and air from the FLUENT database, with their values of density and dynamic viscosity. Assuming here that both phases are incompressible [36].

Once the materials have been established, it is important to define the phases. The primary phase to be set is the air. Choosing air as primary phase might be wise if you want to switch to compressible air later. And the secondary phase is the water-liquid, corresponding to the water.

In the phase interactions, there is the mass interaction and the surface tension, both of which are set to zero due that are normally not important.

- ### Cell Zone conditions

In the Cell zone conditions, 13 volumes are defined, including each one of the two phases. The reason to separate the fluid volume into several volumes is for the post processing, making it easy to determine the water volume in just one of the five basins, for example.

- ### Boundary conditions

Five different types of boundary conditions have been defined: the inlet, internal, outlet, symmetry and walls.

In the inlet boundary conditions, the water in the inlet has to be put below the water level, knowing this value, five inlet conditions have been set in inlet pressure and five in velocity inlet.

Pressure inlet boundary conditions are used when the inlet water level is known but the flow rate is not known, while the velocity inlet conditions are used when the water level is not fixed [37]. In this case the water level is known, which allows us to define the pressure inlet conditions where there is water.

The pressure conditions are suitable for both incompressible and compressible flow calculations, while the velocity ones are intended just for incompressible flows. In all determined conditions, the values of turbulent intensity and hydraulic diameter will be fixed.

The pressure inlet will be set with “Open Channel Flow” determining the constant water level, as it can be observed in the next Figure 14.

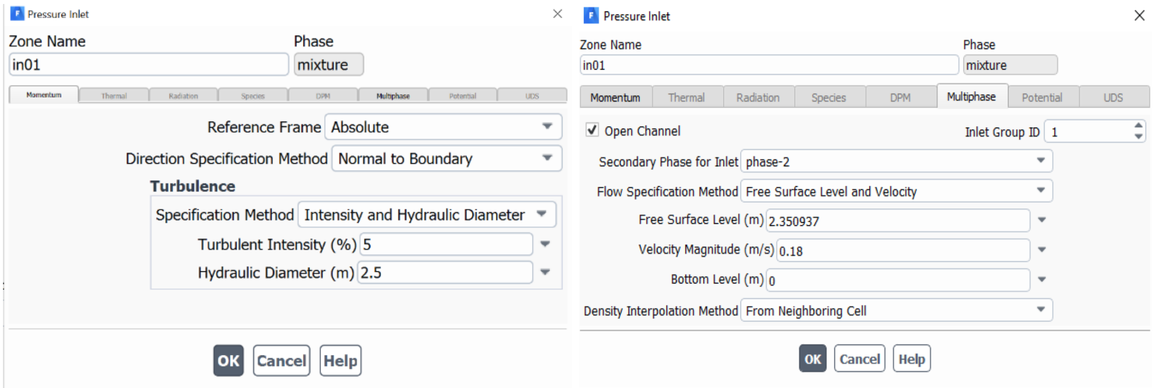


Figure 14. Momentum (left side) and multiphase (right side) scalar properties of the pressure inlet boundary conditions

In the velocity inlets, the velocity of air is prescribed. The air velocity at the upper inlet faces is set to approximately the same velocity as for the water phase, as it can be seen in Figure 15.

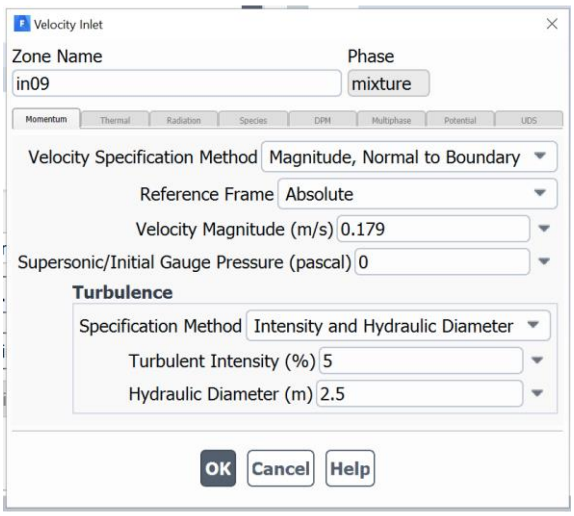


Figure 15. Scalar properties of the velocity inlet boundary conditions

The <u>internal boundary conditions</u> are set for post processing purposes only. Once the simulation is done, contour plots can be made on theses surface without having to make new surfaces inside Fluent. They are also useful to monitor parameters, as for example mass flow rate across these surfaces during the calculation.

For the <u>pressure outlet</u>, the static (gauge) pressure has been fixed to 0 at the outlet boundary and relevant values for backflow turbulence intensity and hydraulic diameter has been set according to Figure 16. The backflow volume fraction for phase 2 has been arranged to 0, meaning that only air will enter backwards, there will normally be lots of air going backwards over this boundary.

The “Free surface level” is the z coordinate at the water surface. The water depth is 1.3 m both at inlet and outlet, but as the channel is sloping, the water level is set at 1.3 m at the outlet and 2.35 m in the inlet, as the bottom level is higher at the inlet.

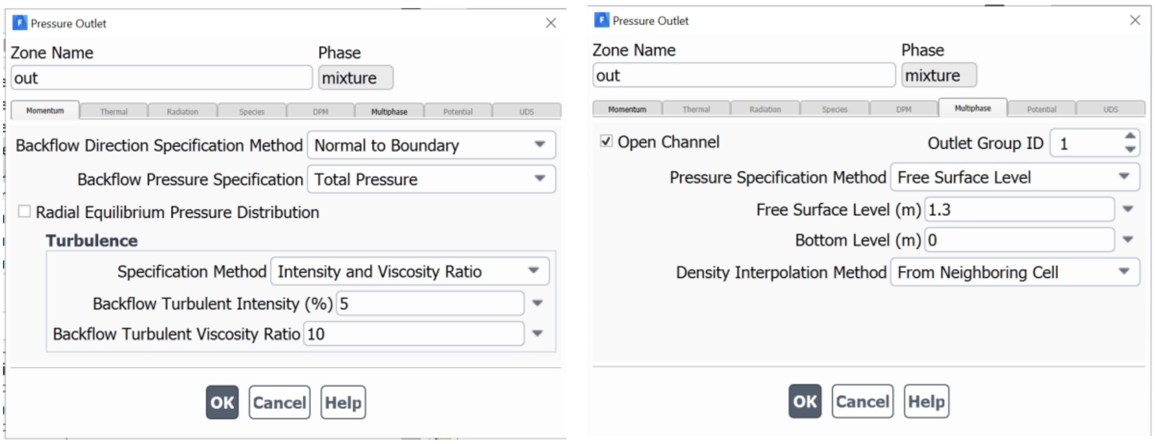


Figure 16. Momentum (left side) and multiphase (right side) scalar properties of the pressure outlet boundary conditions

In the symmetry boundary conditions, 13 surfaces have been defined in order to set a roof on the upper atmospheric boundary. The symmetry boundary condition is a “slip condition” for the air, what means that there is not shear stresses.

Regarding the wall conditions, many walls have been defined for the bottom surface and the two lateral walls. Although it could be defined with a single wall condition, having the bottom and lateral surfaces divided into several ones facilitates the post processing analysis and allows to plot on just parts of the walls. All of them include the two phases and follow the parameters of the Figure 17. Additionally, the roughness of all walls is set to zero.

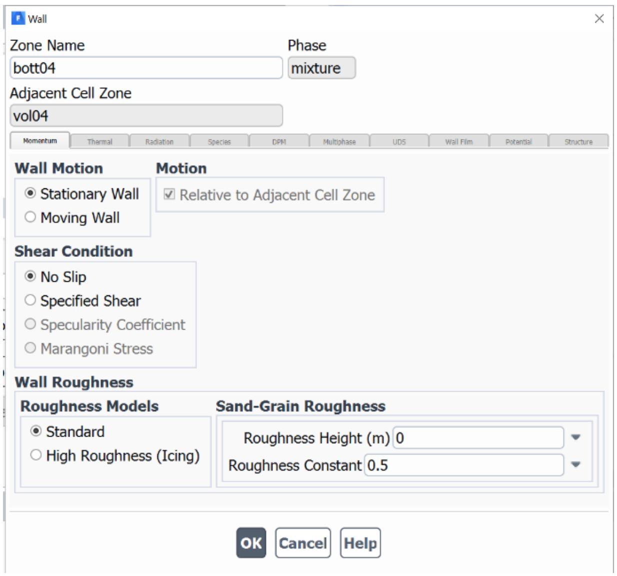


Figure 17. Specifications of the wall boundary conditions

- Reference values

It is also important to determine a Reference Pressure Location in the position where there will always be only the least dense phase, in this case the air, and where there will be small pressure variations in space and time, i.e. close to a pressure outlet. To set some reference values makes it easier for the Fluent solver to converge.

3.4.2. Numerical Solution

To run the simulation, first the method and some control parameters has to be defined:

- Methods

In the methods Fractional Step in the Pressure-Velocity Coupling Scheme has been defined, with the following parameters for the Spatial Discretization:

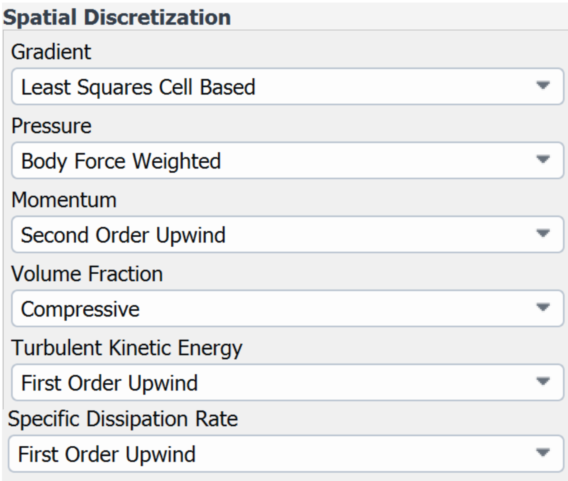


Figure 18. Spatial Discretization parameters

As the Volume fraction is compressive, an implicit solver is recommended to be used. If the solver was explicit, a Geo-Reconstruct should be set in the Volume fraction.

It is also important to select the Non-Iterative Time Advancement (NITA). NITA is faster than PISO, but is said to be less stable and cannot be used with meshes with skewed cells nor with a maximum Courant number bigger than 1.0.

- Controls

All relaxation factors should be set to 1. If you have problems with convergence in spite of using short time steps use even lower values, i.e. 0.7 for the relaxation factors for pressure, momentum and volume fraction.

- Monitors

During the solution process you can monitor the convergence dynamically by checking residuals, statistics, force values, surface integrals, and volume integrals [37]. The monitors created in this case are the residuals and some plots, as the mass flow rates in the inlet and outlet.

- ### Initialization

The initialization method has been set standard and Relative to Cell Zone as the Reference Frame. The phase 2 volume fraction has been initialized to 0, which means that the simulation starts with air everywhere. To speed up the simulation, water can be placed in the regions where it is thought there will be water in the final solution.

3.4.3. Run Calculation

To start running the simulation, the multiphase-specific method with a maximum Courant number of 1.0 has been used. But with a really small time-step of 10^{-5} s data sampling for time statistics is started when a quasi-steady flow has been reached. The sampled time of all the simulations will be of around 25 s. The calculation parameters are shown in Figure 19:

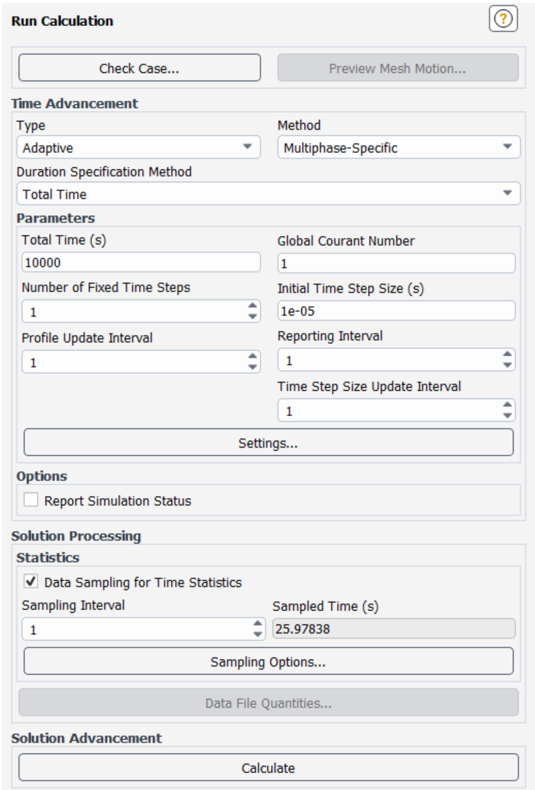


Figure 19. Run calculation parameters

3.4.4. Numerical Results

Under Graphics in Results, it is possible to plot Contours. For each case, the vertical coordinate at the water surface has been plotted to see the water level in each basin, as well as the velocity magnitude close to the bottom and at the surface. The turbulent kinetic energy has been also depicted to show the velocity fluctuations and the eddies in case of turbulent flow.

3.5. Proceedings

The analysis of this model will be done to increase the upstream performance, i.e. fishes travelling upstream, due that there are more technical parameters to consider than in the downstream passage, based on the requirements explained in the Software section.

According to the *top-down* technique, the model has to be decomposed into the variables of study with the objective of analysing the influence of each one independently. This way the approximation to the best possible solution will be developed in an easier and more precise manner.

The first step in the analysis is to study the changes in flow velocity influenced by different slopes. The objective is to find an appropriate inclination according to the specifications required to adapt the design for the species classified before.

With the purpose of having a general overview a total of four slopes will be analysed, classified into the gentle and steep ones. The former ranges from 5 to 10 % —or 1/20 to 1/10, respectively— whereas the latter between 15 and 20 %.

In order to change the slopes in the program, first it is necessary to know how they can be represented. When talking about slopes, the values are given in percentage implying a ratio between the height and the length of the system, the fish ladder in this case. Therefore, when the boundary conditions are determined, the length of the passage will be constant for each of the cases analysed, considering that neither the fish ladder design nor the number of basins can be changed. Instead, the modifications will be applied to the inlet height. The higher the inlet, the steeper the slope.

The analysis of the inclination of the fish passage system is important because the slope affects not only the flow velocity and turbulence, but also the applicability of the bypass model itself. The reason for this comes from the fact that the bigger the difference in water level between upstream and downstream of the dam, the steeper the fishway should be to fulfil its task properly. However, this will increase the flow velocity and turbulent kinetic energy, most surely above the swimming capabilities of the fish. Another possible solution would be to augment the length of the passage. The drawback to this alternative is the increment of the budget for the project and in some cases the unavailability of enough space.

According to the previously stated facts, the slope would limit the applications of the model design once its analysis is performed. Far from representing a disadvantage, it is crucial to know the restrictions of the project to be able to focus on what the project stands out as determined by its characteristics.

The second step of the project is to check the effect of the roughness elements on the flow direction and speed. The structures will be installed following the previously presented pattern, but all of them will not face the same side of the ladder, as depicted before. Instead, an intuitive arrangement for the direction of the elements will be followed, based on the results of the flow analysed in the first step —the one corresponding to the different slopes—. The initial pattern has been suggested by Vattenfall as an initial approximation of the best possible solution.

The reason behind this fact is that as some data will have been gathered by then, it could be useful to simplify the following steps and avoid starting from scratch. Even though the roughness elements alter the flow velocity and direction, the original representation contributes with meaningful data. Therefore, the initial design of the bottom with roughness elements will be the one depicted in Figure 20 below.

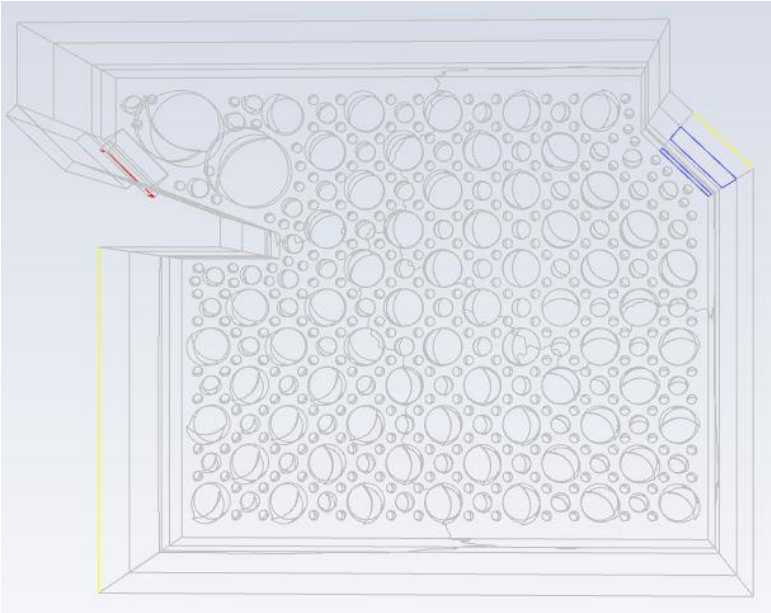


Figure 20. Blueprint of the pattern of roughness elements

When the roughness elements are installed at the bottom of the fishway, because of their variation in height and distribution together with their special shape, various velocity patterns will result. The intention for the specific pattern will therefore be to serve as a flexible solution adapted to different fish characteristics at the same time.

As mentioned, the applicability of different slopes depends on the available space and the height of the obstacle to overcome. This is the reason of analysing a wide variety of them, to verify if different conditions would adjust to the characteristics of the fishes determined. However, it is important to state in advance that the flow speeds resulting from the simulation of the fish ladder at different slopes will be higher before the roughness elements are taken into account. Therefore, even if initially a certain inclination does not comply with the original specifications, once the roughness analysis is performed the conditions can fall into the acceptable range established.

4. Results

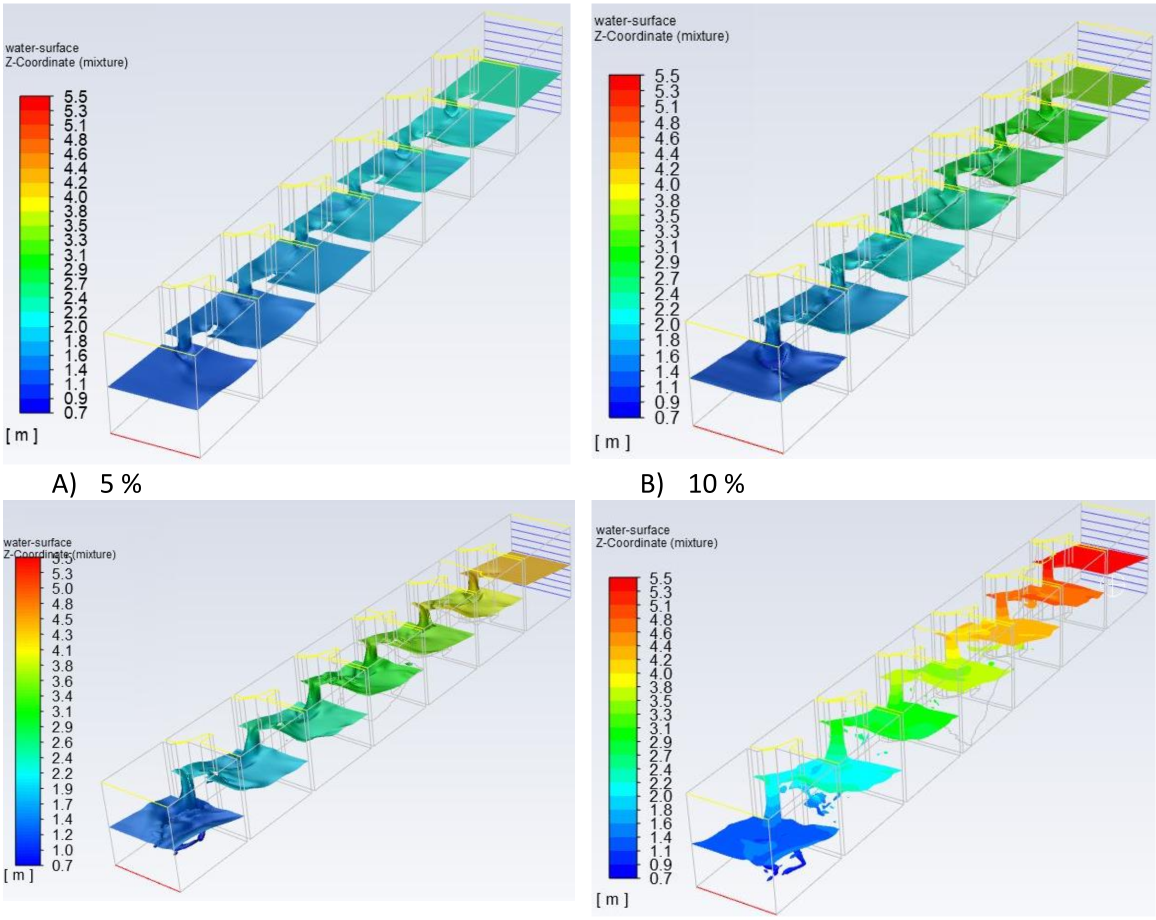
In this section, the results of the simulations will be presented before the analysis in the Discussion. Initially, some plots of the simulated slopes will be shown to visualize the changes to the speed, the water depth in the basins and the turbulence field as a result of the increasing tilt of the passage.

Then, it has been decided to simulate the roughness elements in the bottom part of the structure in just one basin tilted a 5 %, to pave the way for a subsequent analysis applying the roughness elements to the entire passage. In this case, as the flow field is more complex, velocity vectors are going to be presented apart from the water depth, speed and turbulence plots.

4.1. Flow dynamics through a standardized bypass

The results of evaluating different slopes for the described design of fish ladder will be presented below. The slopes selected in the study are 5, 10, 15 and 20 % and it will be focused on the water level of the basins, the mean velocity at the bottom and at the surface together with the turbulences in the kinetic energy at the bottom.

The water level presented in Figure 21 with the range of depth for each slope in meters. It can be seen that when increasing a 5 % the slope, the maximum value of the water depth increases 1 m.



A) 5 %

B) 10 %

C) 15 %

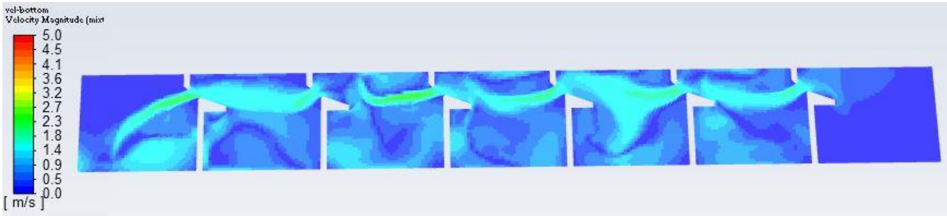
D) 20 %

Figure 21. Water level for each slope

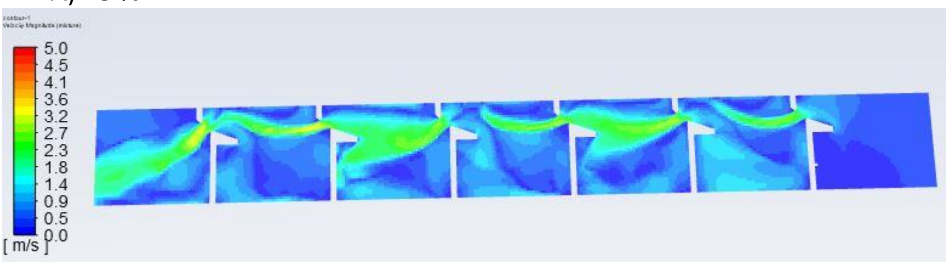
When the passage is tilted a 5 % the maximum water depth is 2.4 m, 3.4 m for a 10 % of slope, 4.5 m for the 15 % and 5.4 m for a 20 %. The contours have been prepared so that the range of values in the legend is the same for every case, making it clearer and easier to understand and compare.

The velocity magnitude at the bottom is one of the most significant parameters, because it is where the fish will rest before continuing their route upstream. It is important to mention that when plotting without nodal values —as in this case— it plots at a short distance from the bottom, where velocities are not zero. In Figure 22, it can be seen how the velocity increases with the slope. The maximum values of velocity increase with increasing slope resulting in 2.2, 3.2, 4 and 5 m/s for the respective slopes.

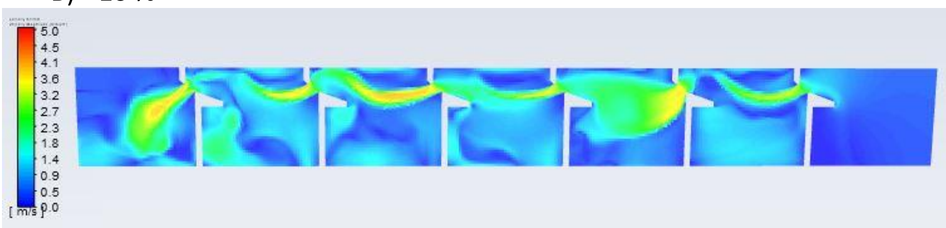
Therefore, in these simulations without roughness elements, it has been verified that the higher the tilt of the passage, the greater the velocity of the main jet. When this value exceeds the swimming capabilities of the fish, this main jet acts as an obstruction to them. One can also notice that the velocity pattern is quite different between basins, which might not be surprising considering the complicated nature of turbulence.



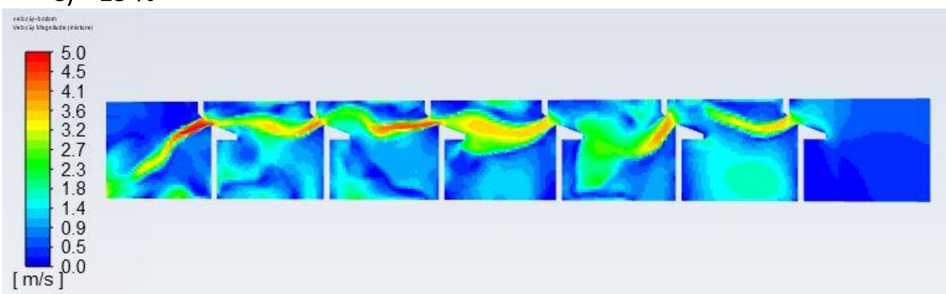
A) 5 %



B) 10 %



C) 15 %

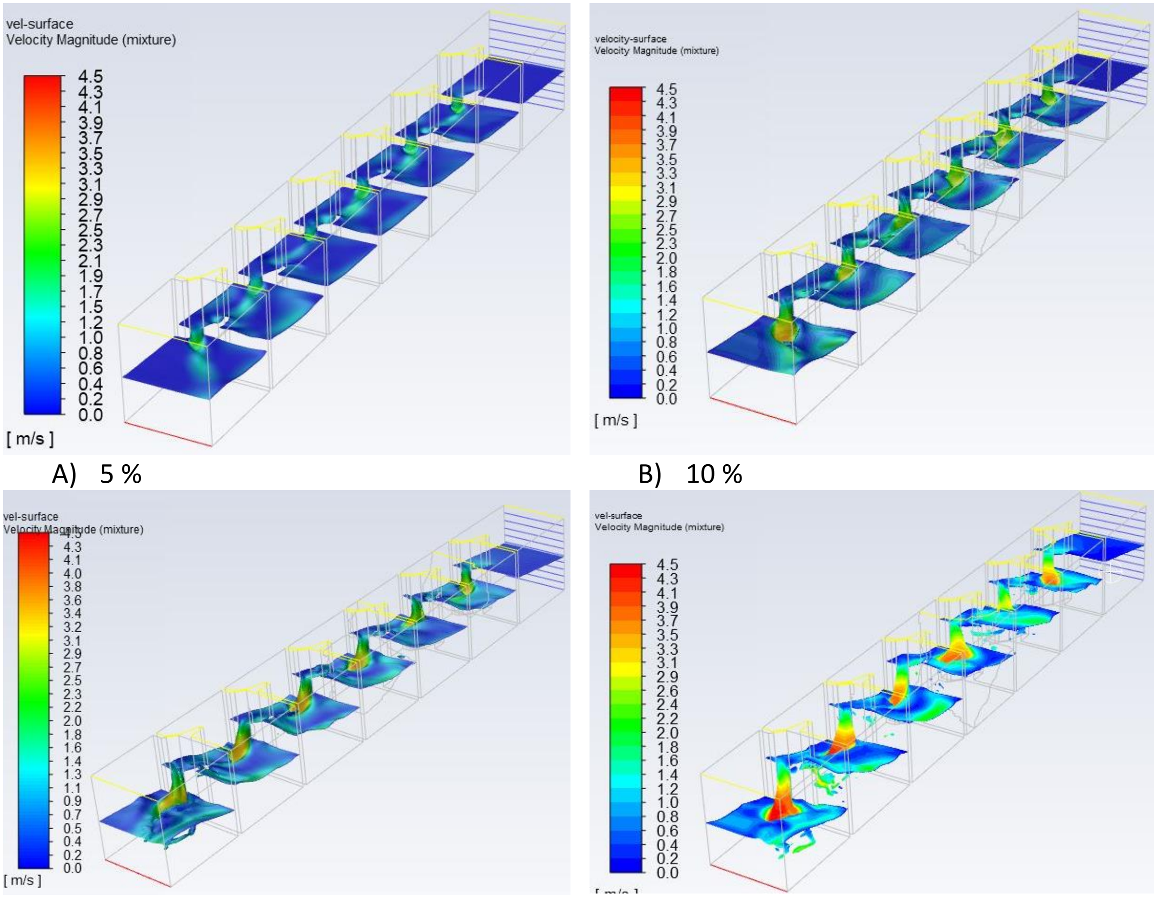


D) 20 %

Figure 22. Velocity magnitude at the bottom in m/s.

The plots of the velocity magnitudes at the surface are shown in Figure 23. This parameter is also important, as although there is a vertical slot which allows fish to select the depth that suits them the best, some fish are used to jump. Analysing the velocity at the surface not only gives information about the main jet, which helps identifying the upstream direction and minimizes the chances of disorientation, also about the suitable velocities and their value.

The values of the maximum velocity at the surface for the different slopes are 2.1 m/s for 5 %, 3.3 m/s for 10 %, 4 m/s for 15 % and 4.5 for 20 %. This maximum velocity is located in the water drop between basins and the increasing speed profile among slopes can be distinguished with the change of colour in the following plots.



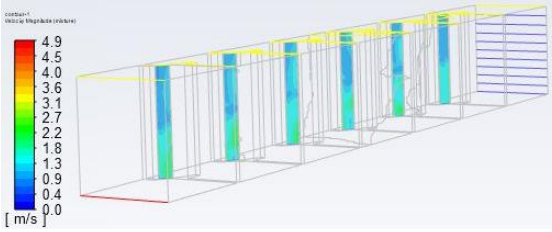
A) 5 % B) 10 %

C) 15 % D) 20 %

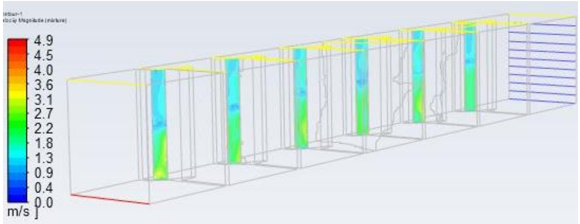
Figure 23. Velocity magnitudes at the surface in m/s.

The velocity at the slots determines if the fish can go upstream through the openings between pools depending on their swimming capabilities.

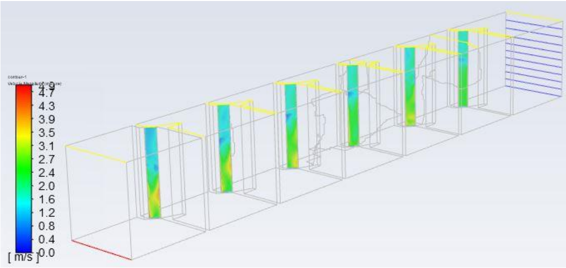
As it can be seen in Figure 24 the maximum velocity in the slots for a slope of a 5 % is 2.2 m/s, for 10 % 3.2 m/s, for 15% 4 m/s and for 20% 4.9 m/s. Knowing that the fish swimming capabilities range is from 0.22 m/s to 1.37 m/s a deeper analysis will be carried out in Discussion to comment on the limiting values of the slope.



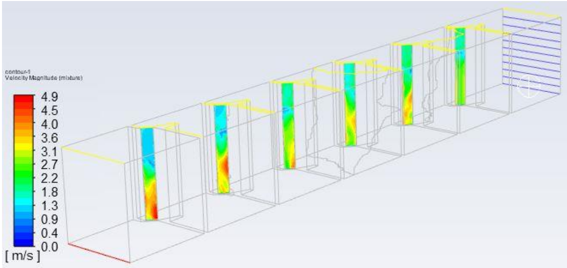
A) 5 %



B) 10 %



C) 15 %

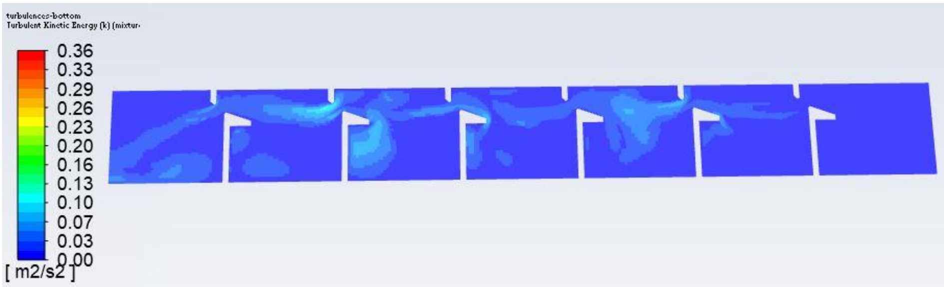


D) 20 %

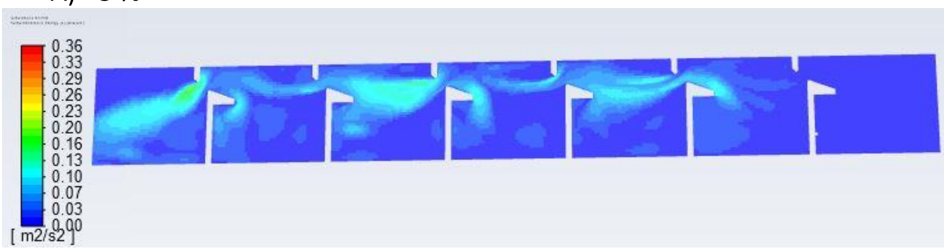
Figure 24. Mean velocity at the slots in m/s

Regarding the turbulences, it has been chosen to plot the turbulent kinetic energy because it is the one associated with eddies in a turbulent flow. In the case of having a lot of velocity fluctuations it will not be seen in the mean velocity, but in the turbulent kinetic energy instead. In the following Figure 25 the plots of the turbulent kinetic energy at the bottom of the passage can be seen for each slope.

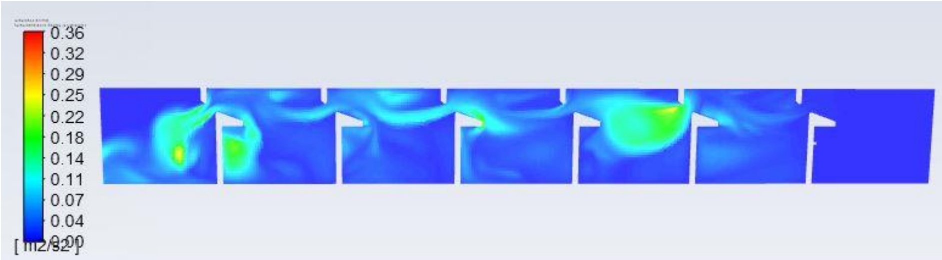
The maximum values of turbulences for each slope are 0.09 m^2/s^2 for a 5 % of tilt, 0.21 m^2/s^2 for a 10 %, a 0.26 m^2/s^2 for a 15 % and 0.36 m^2/s^2 for a 20 %.



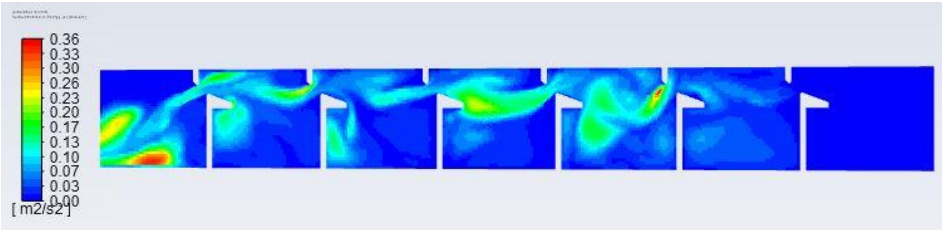
A) 5 %



B) 10 %



C) 15 %



D) 20 %

Figure 25. Plots of the turbulent kinetic energy at the bottom in m^2/s^2.

4.2. Effect of the roughness elements on one basin

A simulation with roughness elements has been conducted, but only with one basin with 5 % slope and with a gate between 0.25 m and 1 m. The plots that will be shown in this section include the water depth, the velocity at different heights of the basin and the turbulent kinetic energy. Here, the velocity magnitudes at the slots are not representative, as just a single basin has been simulated.

The water level goes from 1.3 to 1.4 m as can be seen in Figure 26. This range of values is reasonable taking into account that the inlet condition for the water level was set at 1.4, thus being the maximum value that the water level can reach. In this graphic it can be seen very clear how the inlet condition was set to 1.4 m, represented in red, and the outlet condition to 1.3 m, which is a blue line in the outlet surface. Moreover, there is an area in the far-left corner where the surface reaches 1.4 m again.

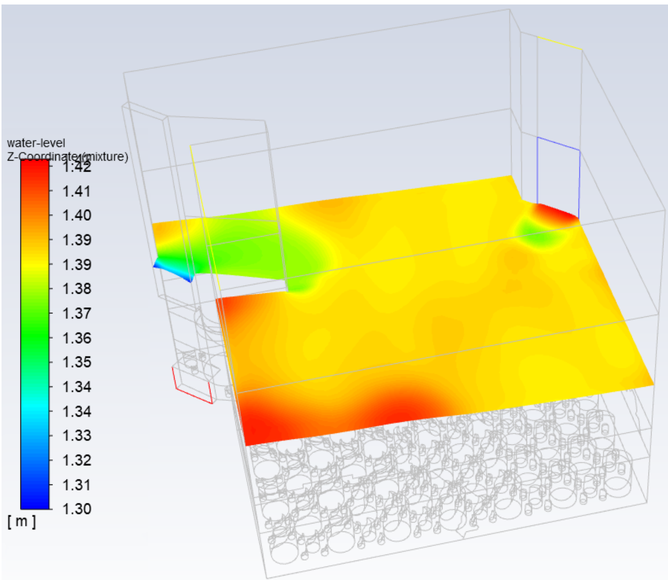
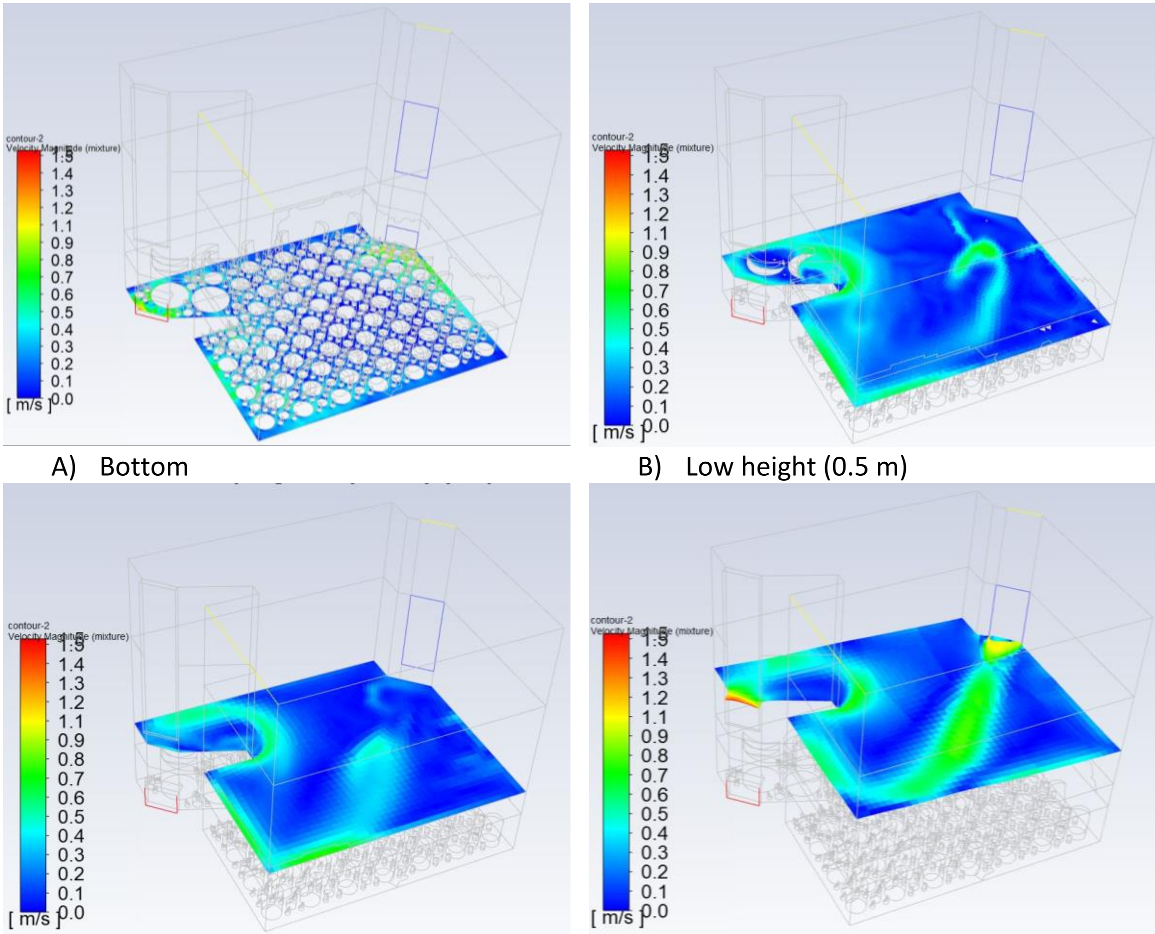


Figure 26. Water level in m.

The velocity magnitudes at the bottom, at a low and high height and at the surface can be observed in Figure 27. As it could be expected, the roughness elements provide some resting areas at the bottom part of the structure. The velocity at the bottom is plotted in the cells centre closest to the bottom, i.e. at a short distance above the bottom of the structure where the velocities are not zero. Just as explained before because nodes are deactivated when plotting. The maximum speed at a low height of 0.5 m is 0.7 m/s, increasing to 0.8 m/s for a high height of 0.8 m and reaching a maximum value of 1.5 m/s at the outlet part on the water surface.



A) Bottom

B) Low height (0.5 m)

C) High height (0.8 m)

D) Water surface

Figure 27. Velocity magnitude at different heights of the basin in m/s.

Although this simulation is for a single pool, some differences can already be noticed when comparing to the velocity magnitudes of the previous results, i.e. the ones corresponding to the fishway with different slopes without roughness elements. In this case, the velocity field is smoother. In particular, in the water surface the maximum value has been reduced a 28.57 % while the value at the bottom of the surface is almost reduced at a hundred percent. However, it is important to keep in mind that the influence of other basins is not taken into account in this case, which would alter the results to some extent.

In case the direction of the flow is not obvious, vector plots can be useful. In Figure 28, the velocity vectors have been plotted at the water surface of the basin, where the high velocities at the inlet at the right slot can be seen and how the flow moves through the pool up to the outlet at the left opening.

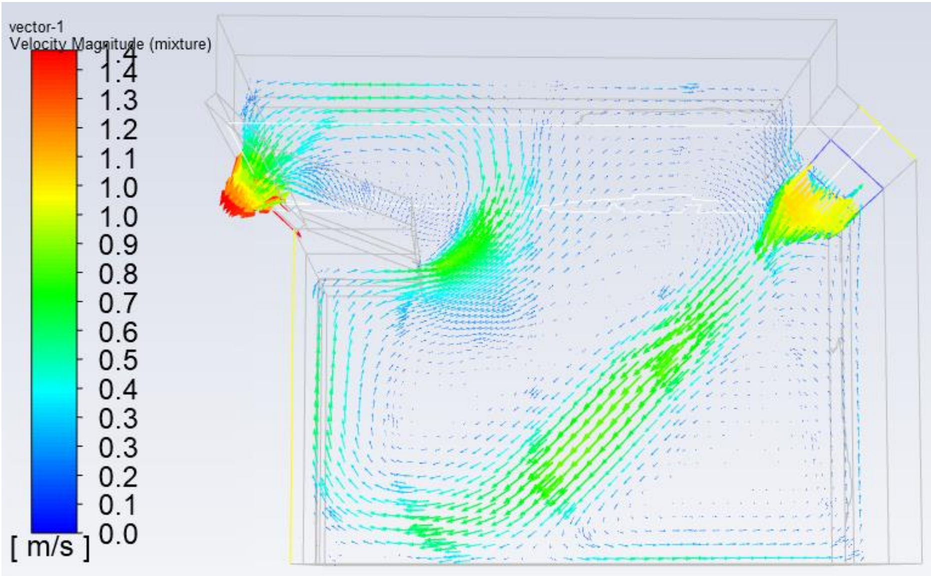
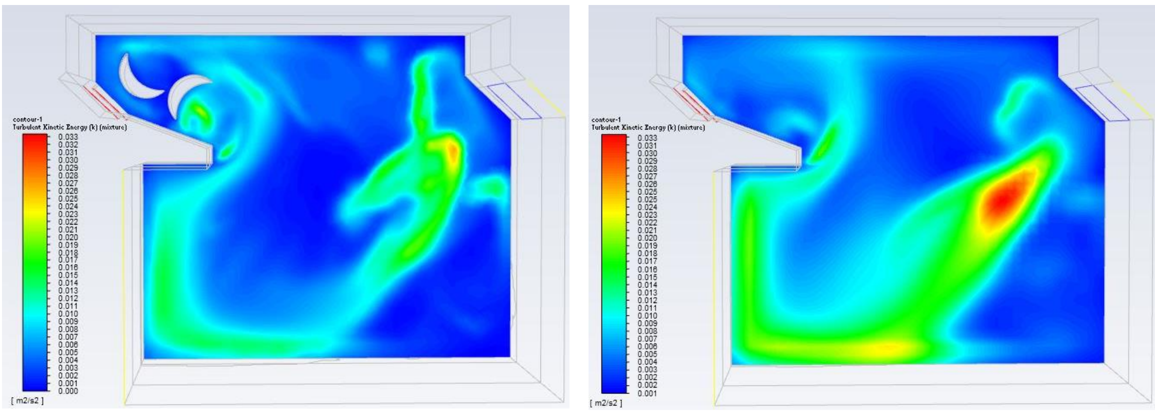


Figure 28. Velocity vectors at the water surface of the basin in m/s.

Finally, in Figure 29 the plots of the turbulent kinetic energy are presented. It is important to analyse this parameter due that it is the one that shows the velocity fluctuations. At 0.5 m high the maximum value of turbulent kinetic energy is 0.026 m^2/s^2 and at a height of 0.8 m it is 0.033 m^2/s^2.



A) Low height B) High height

Figure 29. Turbulent kinetic energy at different heights in m^2/s^2.

4.3. The y+ value

The non-dimensional distance between the walls and the first mesh node is known as y+ value. It represents how coarse or fine a mesh is for a particular flow pattern and it is based on local cell fluid velocity. It can be calculated as a ratio between turbulent and laminar influences in a cell.

The values obtained for the cases analysed before are gathered in the following Table 4:

Table 4: y+ values for the fish ladder with and without roughness elements

Roughness elements	Bottom		Surface	
	Min value	Max value	Min value	Max value
No (5%)	28.38	2131.47	0	2603.31
No (10%)	19.32	3157.74	0	3758.89
No (15%)	43.63	3530.48	0	4052.95
No (20%)	36.25	3828.09	0	4802.81
Yes (5%)	0.88	923.43	0	1392.34

5. Discussion

This section fulfils the purpose of performing an analysis of the previously presented results from different perspectives to gain a further insight into the outcomes of the project. It is divided into the same categories as the previous chapter, in order to follow the same order when going into detail about the results.

First the slope study will be conducted, comparing the different parameters like velocity or turbulence among each other to select the most appropriate one. The choice will depend on the mentioned criteria. Then, it will be proceeded to the analysis of the roughness elements, and it will be compared to the previous cases, the ones of the slope.

5.1. Flow dynamics through a standardized bypass

When it comes to the results obtained from the variation of the slope of the fishway, several outcomes can be derived. On the one hand, the most obvious accomplishment is the demonstration of the increase in velocity and turbulence with increasing slope. This implies that if the inclination is extremely steep then the fishes will not be able to cross from one basin to the next, resulting in a significant drop of passage efficiency of the system. Therefore, in order to comply with the characteristics of the fish considered, the slope has to be as gentle as possible.

The velocity in the openings which connect basins has been analysed because it represents a transition zone between consecutive pools of the passage. The openings allow the fish to go through the fishway and succeed in their route upstream. In the following chart of Figure 30, the maximum velocity at the slots for the simulated slopes has been drawn and the linear fitting curve associated to the obtained values can also be seen together with its coefficients.

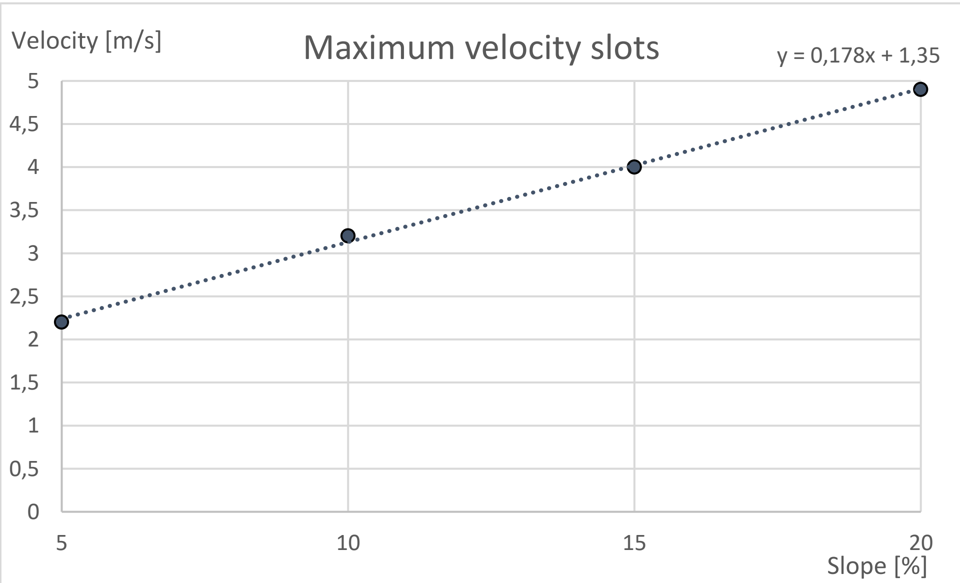


Figure 30. Chart of the maximum velocity at the slots for the different slopes

As it can be seen the tendency of the speed with the increasing slopes is almost a meter for every 5 % of slant. Taking into account that the maximum swimming capability is 1.36 m/s, corresponding to the Atlantic salmon, all the simulated slopes have a larger maximum velocity at the slots. However, the implementation of roughness elements reduces considerably the velocity and another important consideration is that the maximum velocity does just exist at a minor area of the slot, allowing the fish to select the most favourable speed to overcome.

Previously, it was mentioned that the typical slopes for vertical slot fishways lie within a range between 5 and 10 %. This is consistent with the results obtained, the lower the slope the better, agreeing with [30], where it is concluded that environments would be limited to structures with smaller slopes, so that the flow is more fish-friendly in terms of maximum velocities and turbulent flow patterns. Most of the fishes described will be able to cross because even if the maximum values could be too high in some points for those cases, areas with soft speeds can be found as well.

On the other hand, the path followed by the flow can be described as quite straight from the entrance to the exit, even if some spreading can be noticed. This occurs because there is no obstacle blocking or deviating the flow, and so the principal jet tries to follow the most direct trajectory towards the outlet.

With respect to the turbulence, on vertical-slot fishways, water travels from one pool to the next through a vertical narrow opening in the baffle, forming a water jet which causes central turbulence and thus energy dissipation, but at the same time leaves areas of much lower flow velocity on either side. The presence of low-velocity lateral areas allows the fishes to rest.

When analysing the turbulence results, it is noteworthy to mention that when the value of the slope increases the turbulent kinetic energy increase as well, as the Figure 31 shows with the corresponding fitting polynomic curve of third order. The gentlest increase of the maximum value reached can be seen between 10 and 15 % of inclination, where an inflexion point can be appreciated.

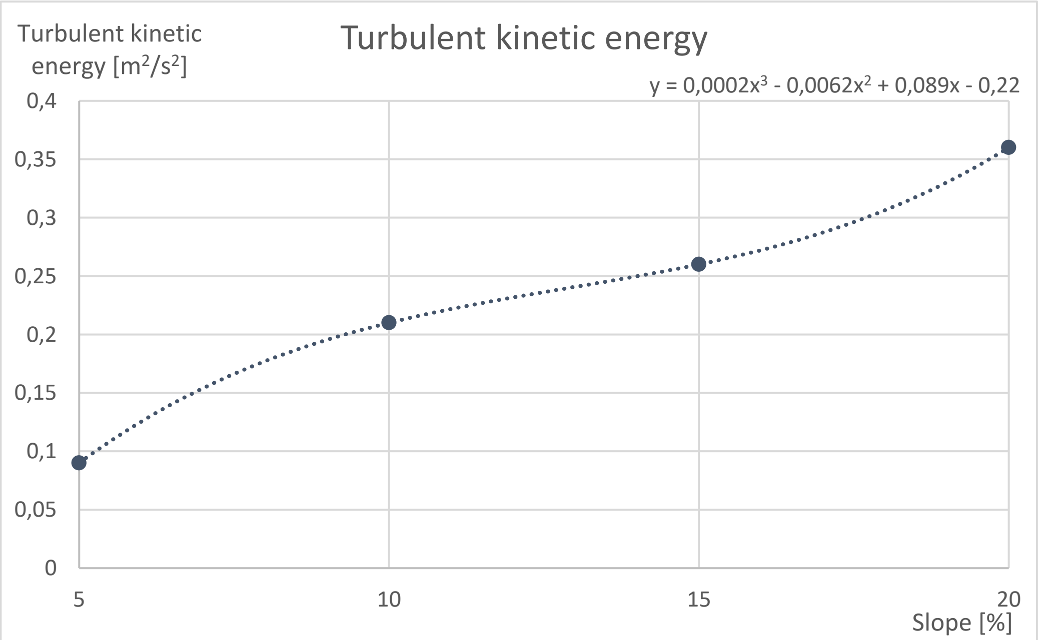


Figure 31. Chart of the maximum values of the turbulent kinetic energy at the bottom for the different slopes

Another important outcome related to the turbulence is that the highest slope, the one corresponding to the 20 %, presents the higher value of turbulent kinetic energy outside the fish ladder and not in the direct way of the main jet.

According to [38], excessive turbulence will make it difficult for the fishes, not only to orientate themselves correctly, but also a big amount of large air bubbles may hinder their respiration. It can be verified that for the conditions to be comfortable for the fish the turbulence value has to be low enough. Therefore, as the lowest values of turbulent kinetic energy coincide with the lowest slopes, once again it is demonstrated that the most appropriate range is between 5 and 10 %.

In the mentioned academic paper, apart from the parameters studied in this report, it analyses the effect of temperature on fish swimming capability. This parameter has not been considered in this thesis project, but it could be an important aspect to take into account to ensure that even under extreme temperatures the efficiency of the system is adequate.

5.2. Effect of the roughness elements on one basin

Once the roughness elements have been implemented, the principal outcome is the modification of the flow on the basin. The particular distribution and orientation of the bottom structures causes an alteration in the streamlines of the flow, resulting in a more open curve rather than the approximately more direct flow that was obtained without them. This occurs because, unlike in the previous situation, there are obstacles that redirect the principal jet, shaping it the way it shows in the plots of Figure 27 at different heights.

Apart from the change in path, with the roughness elements it has been demonstrated that the flow velocity is reduced considerably. Based on the results obtained it can be derived that for an inclination between 5 and 10 % the characteristics of the flow will fall in the range of the fish swimming capabilities established at the beginning. This fact concurs with the typical slope of the vertical slot fish ladders described in the Context.

On the other hand, it can be seen that the velocities vary at different heights, influenced by the roughness elements. As it could be expected from the beginning, the highest speeds are reached at the surface of the water level, because it is where the installed structures have less direct influence in slowing down the flow.

With depth the velocity decreases because the roughness elements gain relevance in stopping the flow. In the intermediate heights the flow is pretty constant, although a bit faster at 0.8 m. At the bottom, however, the flow is nearly stagnant, which will help the slowest fish to swim upwards without much flow opposition, towards the other side of the river. In [39], it is discussed the existence of these zones with low velocity is essential, where fish must be able to remain in a pool for short periods without excessive fatigue.

As it is emphasized in [30], the presence of cylindrical element within the pool is favourable in terms of reducing the maximum velocities and diminish the areas subjected to higher velocities, which may be considered as hydraulic barriers to the movement of fish. In the cited paper, it is calculated that the insertion of a taller cylinder (0.4m height) after flow-pass through the slot reduced the maximum velocity up to an 8 % and of a shorter cylinder (0.2 m height) up to a 6 %, both with 0.4 m of a diameter.

As previously explained, this was just a simplified version of the full fish ladder into just one basin to develop an initial analysis of the roughness elements. However, when combining the results from both cases studied, it can be derived that the maximum velocity in the vertical openings, which is determinant for the fish passage success, will be reduced considerably. For these particular cases, the reduction of flow speed when implementing the roughness elements is around a 30 %, therefore proving that with an appropriate distribution the velocity can be adapted to a more suitable value, within a reasonable range.

When it comes to the total flow, the reduction of velocity would consequently imply a reduction of the flowrate. Nevertheless, the implementation of bottom structures adds more hydraulic losses to the system due to the incremented roughness, which explains the lower water speeds when compared to the case without the elements. Therefore, the flow can be assumed to be nearly constant even with the new design. The implications this has are very important, because as mentioned before the attraction and passage strongly depend on the flowrate that is allowed through the fishway.

5.3. The y+ value

Depending on the y+ value, the cell can be turbulent if it is big or laminar when y+ is small. Therefore, it is important to determine the proper size of the cells near walls and impose some restrictions for the value to lay within an acceptable range. If y+ is excessively low, the wall functions will not apply properly to the cells, resulting in bad modelling assumptions. On the other hand, if it is higher than recommended, then other assumptions are invalidated. The restrictions will vary depending on the turbulence model employed.

Ideally, the viscous sub-layer should be solved all the way down to a value of y+ around 1 using Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES). The former is employed to resolve all the scales of the flows, from the largest eddy to the smallest one present in the flow, implying an excessive escalation of computational expense with increasing Reynolds number. The latter, however, computes just the largest scales while the small ones are modelled.

Nevertheless, in turbulence modelling CFD for large-scale industrial problems like the cases analysed, the previous ideal resolution would require a large number of cells, due to the high values of the Reynolds numbers. The use of a turbulence model such as SST k-omega together with some logarithmic wall-functions allows the grid close to walls to be much courser than it should avoiding computational problems. This results in higher values of y+ parameter, as they could be verified in the results presented before, as well as a significant reduction when the roughness elements at the bottom part of the structure are installed.

6. Conclusions

The design and implementation of fishways is crucial for the preservation and restoration of fish population and their natural habitat, because it provides them with a way to go upstream or downstream during the migration periods. In order to make sure that the systems are viable it is necessary to perform studies like the one contained in these pages, even more when the proposed design is an innovative model which seeks to improve efficiency and flexibility in operation.

By the computational study performed it has been established a foundation for the demonstration of the viability of the design submitted to analysis. Therefore, the main outcome is channelled towards its fulfilment. This implies that a further evaluation of the system is required to reach conclusive and meaningful results to verify its validity.

When it comes to the established secondary objectives, by the literature review presented in the introduction it can be concluded that technical knowledge has been acquired not only in the field of fish ladders but also in eco-hydraulics. This provides with a better understanding of the operation of those kind of systems as well as of swimming capabilities and migratory behaviour of relevant fish species that can be found in the Swedish river environments.

With respect to the software operation, the basic understanding was complimented with a deeper learning of the different functions of the Ansys Fluent CFD program. Firstly, to comprehend the set-up of the simulation, how to define the boundary conditions and perform the necessary changes to simulate each individual case. Moreover, the realisation of contours and vectors has been elemental for the analysis and understanding of fluid dynamics in the model of study. Achieving this knowledge has enabled to reach this goal, in which all the project is based.

The analysis of the standardized bypass provided a deeper insight into the flow field dynamics through a system like the one subjected to study with no roughness elements. This allowed to better determine the operation of a general design of fish ladder and understand the effects that the different parameters have over the flow. Apart from the shape and dimensions, which were fixed and could not be adapted to different conditions, the influence of slope was analysed.

Meaningful outcomes were obtained from the performed tests. After the evaluation of the resulting velocities and turbulences from the slope modification test, it can be concluded that the most appropriate inclination is between 5 and 10 %. Much more elevated slope is not recommended, because the considerable differences in fish swimming capabilities would consequently leave the slowest ones out of the range. These results serve as base for a further research project, implying that once the full ladder with roughness elements is analysed the proper slope can be better approximated.

On the other hand, the impact of each basin on the following one was verified, which comes as a result from the flow being continuous between the pools. Additionally, within each basin, the flow velocities were obtained to check the movement of the water and locate the spots where the fish can rest before resuming their ascension.

Finally, the roughness elements were added in order to verify their influence on the flow. It has been demonstrated, therefore, that not only they have an effect over the flow field but also that it would be possible to adapt the flow by arranging them in specific configurations because of their different sizes and peculiar shape. Moreover, the velocity of the water is reduced when compared to that of the no-elements case, implying that steeper slopes could fall into the acceptable range for the fish analysed.

In conclusion, evidence seems to suggest that there is still further research to be made for the proper understanding of the characteristics of this new design of fishway. However, the results obtained have proven that it satisfies the initial hypothesis, i.e. altering favourably the flow through the roughness elements implemented. Therefore, a strong foundation has been ensured for the coming future.

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