Design of vertical slot fish ladder: review paper

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Abstract: Fish ladders are structures that are designed and constructed at water barriers, such as dams, to assist fish to migrate and complete their life cycle between different habitats without interruption or delay. The design of the fish ladders is considered a complicated process. It depends on two essential aspects; the biological and environmental nature of the fish. Consequently, hydraulic parameters such as velocity, turbulent kinetic energy, and flow patterns have to be designed to suit the fish's capabilities without affecting it. This study is dedicated to performing an overview of the design of one of the most common fish ladders, the vertical slot fish ladder. A brief on an empirical and numerical design method is presented first. Then, a review of the recent literature on the vertical slot fish ladder design is explored. From reviewing several works on the design of the vertical slot fish ladder, it was found that important design parameters, such as the velocity of the flow, the turbulence, the slope of the fish ladder channel, have already been investigated in previous studies. However, it was observed that other important parameters, such as the slot angle, have not been investigated or explored in the literature. It is predicted that this parameter has a vital influence on the velocity of the flow inside the fish ladder which controls all other design parameters.

Keywords: Vertical slot fish ladder, CFD simulations, flow velocity.

1. Introduction
Fish migration is one of the main and crucial aspects of their life that includes two primary cycles of downstream and upstream journeys [1]. Many aspects such as the species’ type, life stage, and the purpose of the migration define the journey’s type and its sequence. In rivers, fish migration must eventually contain a downstream and an upstream component [1]. Downstream migration is usually performed by fish at the early stages of fish life. On the other hand, the upstream migration is normally carried out by fully grown fish. For instance, through their life cycle, the pacific salmon, or as scientifically known Oncorhynchus, take on many migrations’ types [2]. The eggs of this specific type of fish hatch in fresh water so the newborn individuals will perform a migration towards the sea. This type of migration can be called a downstream migration. While during their spawning season, they perform an upstream migration towards the coastal rivers.

The common purposes of fish migration are reproduction, feeding, seek protection from other predators, or unsuitable environmental conditions. However, since the invention of barriers, dams, and other obstructions by humans along the rivers and around other water bodies, the migration of fish for the above-mentioned purposes have been affected severely. Structures created by humans in the rivers, such as dams, weirs, culverts, and others, have been used increasingly in recent years [3]. Man-made obstacles have made the fish migrate to be delayed for weeks [4]. Fish migration can be slowed down or even blocked if no suitable solution was presented, which is the fish ladders. Furthermore, fish populations in rivers are decreasing due to the construction of artificial barriers, such as dams and barriers [5].

Fish ladders are structures that are usually constructed over or around the barriers erected on water bodies, such as dams, waterfalls, and rapids. They are also known as fish passes, or fish ladders [6]. The earliest recorded use of fish ladders was in Europe approximately 300 years ago in France [7]. This was when the southern province of France made it obligatory to take passages that allow safe and suitable movement for fish into consideration in constructed dams and weirs. In general, a fish ladder is simply a
channel with a certain slope. This channel is divided into relatively small basins, weirs, vanes, or baffles. These wires are designed to include openings that allow fish to swim through them. A fish ladder must be designed to be suitable for fish passing through artificial obstacles to avoid high-velocity flow. Very high velocity might surpass the swimming capabilities of the fish at fish passes and obstructions [8]. The main objective of constructing such structures is to provide a convenient path for fish to travel and migrate along the rivers and other water bodies to not affect their natural migration journey. The design of such structures requires adaptive management and continued innovation [9]. In some exceptional cases, some of the well-known fish ladders might be considered to act as an alternative tool to measure the flow [10].

2. The Aim and Objectives of This Study
The present study aims to review the vertical fish ladder design and to show what is commonly being investigated in the recent literature and what needs to be more investigated to ensure a better understanding of its design.

3. A Brief Background on Vertical Slot Fish ladder
The vertical slot fish ladder (VSF) is among the most common types of fish ladders. The first version of the vertical slot fish ladder was built at Hell’s Gate Dam on the Fraser River in Canada [6]. This type typically consists of a rectangular channel divided into several small basins by baffles that are installed along the channel length at evenly spaced distances. These basins are generally known as pools [11]. The baffles have a vertical opening called slots that are designed to let the fish swim through passing upstream along the channel. The design of this type of fish ladder is aimed to create almost the same water velocities at the slots of the fish ladder. This makes it suitable for fish to burst their way through those slots upstream to proceed with their journey. Water flows downstream through the vertical slots from one pool to the next one below. During its flow, the water forms a jet at the slot. The mixing of the water inside the pools ensures that the high energy of the flow is being dissipated. This allows fish to ascend and pass the slots. The pool provides a resting area for the fish before proceeding to the next slot. Vertical slot fish ladder functions over a varied range of streamflow circumstances and permits a wide size range of fish [12]. Figure 1 shows a schematic drawing of a typical vertical slot fish ladder.

![Figure 1: Schematic drawing of a typical vertical slot fish ladder.](image-url)
Even in a specific fish type, there still other features that control the design due to the variety of fish features. For example, for one species of fish, the age, size, swimming ability controls many fish ladder design aspects such as the inclination of the channel, the discharge, the size of the opening in baffles, and the velocity of flow. The understanding of the swimming ability of the targeted fish determines the water velocities specification in the designed fish ladder [13].

4. Design of Vertical Slot Fish ladder

The design of a vertical slot fish ladder (VSF) structure is an elaborate and time-consuming process [5]. In general, two methods can be used to design such a structure. The first method is by using empirical equations. Based on previous observations and experimental works that have been carried out before, a vertical slot fish ladder can then be designed using a set of special empirical equations [14]. The second method to design a vertical slot fish ladder is by solving the flow equations to determine the flow field. In many cases of such a design method, the analytical solution is not possible and is given through an algebraic repetitive method with the aid of a computer system using Computational Fluid Dynamics (CFD) simulations.

4.1. Empirical Equations Method to Design Vertical Slot Fish ladder

In general, the methodology of fish ladder design using empirical equations can be represented in three main steps. The first step is to carry out a thorough investigation of the targeted fish by studying and recording their characteristics and behaviour. To achieve this goal, full cooperation with biology and the study of biological aspects of fish is highly required. The main features that are needed to be studied involve the average of dimensions and the burst speed of the fish which enables them to swim against the water flow direction (upstream). Typical values for all fish species can be found in previous literature. Once a detailed investigation is being done and all required data are being collected, it is crucial to determine the location of the fish ladder next.

Effective fish ladders allow the fish to find the entrance to the fish ladder easily and quickly. The attractiveness of a fish ladder is related to its position in the obstacle [15]. The width of the entrance remains small compared to the width of the total barrier. Moreover, its flow forms only a small portion of the whole flow in the river. The fish are actively guided by the flow at the barriers towards the entrance. For most water barrier types, the fish ladder can be placed on either side of the barrier. It might be considered as it is more efficient to construct a fish ladder on each side of the barrier for wide water bodies [15].

After selecting the optimum location of the fish ladder, geometrical and hydraulic parameters in the fish ladder design can be determined. As mentioned earlier, many aspects control the design of a fish ladder [16]. The most important aspect is the type of targeted fish. For a vertical slot fish ladder (VSF) geometrical and hydraulic design, factors such as the turbulence of the flow, slot width, and mean flow velocity at the slot are among the essential factors that affect and control the design. For example, the flow velocity in the slot should be suitable for fish to swim through. This can be managed by matching this speed to the burst speed of the targeted fish. Besides, maintaining a flow with a sub-critical condition is also assists in controlling the downstream flow [10].

4.2. The Design of Vertical Slot Fish ladder using Computational Fluid Dynamic (CFD) Simulation

Computational Fluid Dynamics (CFD) simulation is widely used as an approach to obtain the flow properties for a vertical slot fish ladder design [17]. It is the branch of Fluid Mechanics science that deals with analysing and solving engineering problems that consist of fluid flow cases using numerical analysis [18][19]. With the aid of computers, it has become more efficient, in terms of time-consuming and the accuracy of the results, to use computer software to solve complex problems using CFD simulation of fluid
flow-related problems. The FLUENT package is simply one of the ANSYS software codes that has a workbench platform [20], [21]. The main feature of this package is that it has specific cells that must be achieved to complete solving the next steps.

5. The Literature on Vertical Slot Fish Ladder Design

Many pieces of research have been done to improve and optimize this type of structure. The academic literature written on vertical fish ladders has exposed the emergence of several distinct aspects, especially in terms of analysing, designing, and optimizing the design of vertical slot fish ladders.

Rajaratnam et al. (1986) conducted an experimental study on the vertical slot fish ladders hydraulics. In their experimental study, seven designs, including some ordinary designs, were examined [22]. A state of theoretical uniform flow was introduced. For such an approach, a linear relationship between the relative flow depth and the rate of the dimensionless flow was obtained. They also analysed the non-uniform flow of the M1 and M2 types using the Bakhmeteff-Chow technique. Also, they studied the fish ladder submergence at the entrance by the tailwater. The results presented by this study were used to develop a theoretical indication of the uniform and non-uniform flow states. The rating curve was obtained, for each of the examined designs in terms of the dimensions both the relative depth and flow rate, by the utilization of the results gained from the experimental work and simple analysis. Both examined profiles, M1 and M2, were analysed using the Bakhmeteff-Chow technique.

Rajaratnam et al. (1992) carried out another experimental investigation on vertical slot fish ladders [23]. The investigation was, in fact, an extension of their previous study mentioned in [22]. The study dealt with the design of 18 vertical slot fish ladders. Additionally, the results for 11 more designs were added to this investigation. The study demonstrates, for all 18 investigated designs, the relationship between the dimensions discharge and the relative depth of flow of the pool ($y_0/b_0$), which is the ratio of the average depth of flow in the pool, $y_0$, measured at the centre and the slot width, $b_0$. According to the gained results by this experimental investigation, the study claims that the width and the length of respectively $8b_0$ and $10b_0$ that are commonly used in the pools are acceptable for designs. It also claims that the performance of the fish ladder is not very affected by some minor variations. As per the variations of flow, $Q$, concerning the relative depth of flow, $y_0/b_0$, according to the study’s assumption, it is probable to divide all the designs into three main groups. The first group assembled designs 3, 5, 6, and 7. The second group has 1, 2, 14, and 16-18 in its assembling. The third group contained the rest of the design. The recommended and practical designs suggested by this investigation were designed 6, 16, and 18 due to their simple design and construction and, in general, better performance.

S. Wu et al. (1999) studied the mean flow structure of a vertical slot fish ladder, at both the pools and slots, of a simple and effective design through a laboratory investigation [24]. Several discharges and a total of three slopes (5%, 10%, and 20%) were investigated in their experimental study matrix. According to this study, two distinctive flow patterns denoted as pattern 1 and pattern 2, as referred to by the study terms, can be observed. The first pattern, or pattern 1, occurs at a slope of 5%. This flow can be considered as a 2D curved jet from one slot to the other with two recirculation areas with a total volume of about 73% of the water volume in the pool. While for pattern 2, which occurs on the remained investigated slopes of 10% and 20%, the flow travels as a 3D flow with recirculation regions that are located between the short baffles as well as another with a horizontal axis close to the long baffles. The volume of these regions is about 38% of the water volume in the pool as measured by this study. As per the flow at the slot, it was considered to be a plane jet only. This assumption was a rough estimate due to the non-uniform velocity of the flow and the non-perpendicularity of the flow to the slot. Moreover, the deterioration of the maximum velocity values that are measured in the jet through the pool was higher than the one measured in a plane jet. The average kinetic energy head measured in the pool was about 12% of the head difference calculated from one pool to the next one, referred to as Δh in the study, while the maximum velocity at the slot is calculated using:
Rodríguez et al. (2005) performed a different approach in order to better understand the flow in fish ladders [25]. A well-organized analysis, in which the requirements and swimming abilities of a specific species were put into attention, was performed on two vertical-slot designs. The evaluated designs have empirical hydraulic properties characteristics that are obtained from a previous study. Since the best parameters of fish ladder design are governed by the interaction of biological and hydraulic variables, the methodology of this study was to assess three main criteria. These criteria are the minimum values of discharge that provide a minimum value for the appropriate depth for fish, the maximum sizes of the pools that guarantee low-enough velocities that fish can overcome, and the maximum sizes of the pool confirming low turbulence to be satisfactory to the fish. The mentioned design limitations were evaluated at two hydraulic parameters, namely two slopes (6% and 10%) and three water temperatures (10, 15, and 20 °C), and one biological parameter, which is different fish lengths. According to the study outcomes, the procedure resulted from its analysis was evidenced to be a powerful method that could assist in choosing the appropriate design of fish ladder facilities. Crucial aspects of fish ladders, such as the baffle configuration, the temperature, the pool’s size and slope, and the proper discharge, can be selected suitably using the proposed approach.

For the shallow state system, a mathematical formulation of the optimal design problem for a vertical slot fish ladder, in which the state system is given by the shallow water equations to calculate the water velocity and height, vertical fish ladders optimum design was studied by Alvarez-Vázquez et al. (2007) using a mathematical formulation. The slot geometry and the objective function, which is related to the presence of repose regions for fish and suitable water velocity for fish to swim abilities, are the main parameters of the design [26]. Ten standard pools with a slope of 5% were the case of this study. Numerical results obtained by this study were used to determine the optimum geometry of the tested pools.

Some publications concentrated on the large recirculation zones’ effects. These effects cause certain species, especially small ones, to have difficulties in swimming in large pools of fish ladders. One of these studies that have undertaken the design of fish ladders through an experimental study was done by Tarrade et al. (2008) [27]. The study was mainly carried out to illustrate and characterize the turbulent flow for several configurations of vertical slot fish ladders. It was also aimed to determine how the fish ladder design might be modified to assist in easing the path of small species. The study matrix included three main variables, discharge (Q), pool width (B), and pool slope on inclination (I). The studied discharge values were 576, 736, and 864 litres/second. The slopes, chosen for this study work, were 5%, 10%, and 15%. Pool widths used were 1.7, 2, 2.3, and 2.7. It was shown by the results of this experimental study that, depending on the length to width (L/W) ratio of the pool, there are two topological models that the flow pattern always follows. Besides, the finding of the link between the mean kinetic energy of velocity fluctuations, which are measured inside pools, and the calculated volumetric dissipated power is another recognized observation driven by this study. Also, the study investigated the effect of the inclusion of vertical cylinders inside the pools and was displayed by laser tomography to further explore the range to which the dimensions of recirculation zones can be dimensioned.

Wang et al. (2010) conducted an experimental study of flow characteristics on a scale model of vertical slot fish ladders [28]. The slope variation range from this investigation was 5%-15%. Various novel results were obtained from this study, specifically the effect of shape factor (B/b), the ratio of the pool width (B) to the slot width (b), and slope on flow topology. However, only on the value of the shape ratio (L/b), the ratio of the pool length (L) to the slot width (b), was considered in this investigation. The study methodology was to combine both fish behaviours with the experimental hydraulic modelling in the proposed model of this study. Discharge coefficients ranged from 0.67 to 0.89 were considered. Two different patterns of flow were detected depending on two factors, namely fish ladder width (b) and the slope. The transition point
which separates the two flow patterns was calculated. Many other observations were perceived by this study such as the effect of slope on turbulent kinetic energy and low-velocity zone volume. Also, it was noticed that regions with low velocity were not resorted by fish consistently. The fish stayed most frequently in the region located just downstream from the slot. Another observation, found depending on specific fish behaviour, namely juvenile brown trout, was that the fish avoided regions in which flow velocity is high on the jet. However, regions at the slot itself were not avoided by fish due to the advantage of the non-stationarity of the jet. Such observation was driven according to an analysis that was done by the author in a scale model.

Regardless of the number of observations obtained by this investigation, more investigating, especially on flow velocity, energy dissipation, and even lower pool length to slot width ratios, are still required. Tarrade et al. (2011) carried out a detailed study on the hydrodynamic turbulent flows that are created in vertical slot fish ladders [29]. The study was mainly dedicated to inspect the kinematics of the turbulent flows for two values of pool width and to perform an analysis of the influence of the mean and fluctuation. A transparent experimental device was designed depending on an existing vertical slot fish ladder that was constructed in France. The influence of the variation of Reynolds number was considered, for this study, to be less than the Froude effect. 2D measurements, performed using Particle Image Velocimetry (PIV), were done to determine different kinematic parameters such as the velocity amplitude, the vorticity, and the turbulent kinematic energy. The Proper Orthogonal Decomposition (POD) analysis was applied to provide an unsteady and energetic analysis of the flow. The study indicates that the mean vorticity fields showed that, for various pool widths, the shear was very substantial inside the pool. This could be a significant obstacle that directly affects the migration of fish. The Spatio-temporal analysis was done to assess both the amplitude of the different motions on the unsteady flows and the beat frequency. For B/b=9 and 6.67, the POD analysis resulted in low frequencies at 0.12 and 0.08Hz respectively. These values were verified by Acoustic Doppler Velocimetry (ADV) measurements.

Marques et al. (2011) carried out a study in which a mathematical model of the fish passage decision structure is offered [30]. This approach was essentially intended to ease the complexity of decision-making for identifying the optimum design of fish transportation through dams. According to the study, the required modifications on a slope, pools’ number, and the head loss between adjacent pools (ΔH), can be made using the proposed optimization model to find optimum solutions under different circumstances, such as maximum energy dissipation, the minimum water depth, and maximum flow velocity and, slot width.

The results of the undertaken case study of this investigation reported a 52% reduction in the total cost, compared to a base situation similar to real operations.

However, it was declared by the author that the used model is still under development and more future improvements are required. These future improvements are expected to provide more alternatives for fish ladder design.

Vázquez et al. (2013) performed a study that deals with the preservation and enhancement of the migration of the natural fish stocks between fresh and saltwater [11]. This approach was essentially followed to enhance the vertical slot fish ladder shape design using applications of a mathematical model that simulated two main aspects of the fish ladder design, namely the height and velocity of the water, and an optimal control theory. In their approach, the authors articulated the study problem by employing an optimal control structure of partial differential equations. Then, the problem was approximated by using discrete optimization. The solution was done using two methods, the derivative-free method, and the gradient method. Two methodologies were proposed by the study to achieve the ideal shape design of vertical slot fish ladders. The first methodology is represented by the use of a direct search method, the Nelder-Mead method (NM-algorithm). The second methodology was achieved by using the Spectral Projected-Gradient algorithm, (SPG). Although it was concluded that both followed methodologies were reliable and operative,
which is can be seen by evaluating the cost reduction for the optimum design obtained by the first approach, difficulties, in terms of computation, presence especially when solving for more complicated models. Therefore, such approaches are limited to simple problems that deal with a few number variables.

Chorda et al. (2010) conducted a simulation on the mean velocity and turbulence level fields for the two-dimensional flow patterns that take place in vertical slot fish ladders [31]. Using Particle Image Velocimetry (PIV) and Acoustic Doppler Velocimetry (ADV), the obtained numerical results of this study were compared to velocity measurements that were examined at the Laboratoire d’Etudes Aerodynamiques of University of Poitiers, France.

The study approach is to solve Saint–Venant equations using TELEMAC-2D, a two-dimensional depth average free surface hydrodynamic model that uses the Saint Venant equation. Since the modelling of turbulence is considered as a vital aspect of fish ladder design characteristics due to the fact of considering a constant model for eddy viscosity results in improper mean flow patterns, the $k–1$ closure model legitimacy is validated through this study’s discussion. Moreover, the spatial distribution influences the fish ladder efficiency, which makes it important to be investigated. Therefore, the study had given great consideration to the calculated turbulent kinetic energy and the rate at which energy is being dissipated.

Despite the valuable solutions offered by this study, a limitation of this work still present. This limitation is represented by the difficulty of obtaining the local dissipation rate, which is considered as a variable in the fish ladders design study. This was referred to in this study as indicated that the local dissipation rate was, according to the study reporting, difficult to be obtained from measurement and calculation.

Sanagiotto et al. (2019) studied simulation of the vertical slot fish ladder by using ANSYS CFX with $k$-$\varepsilon$ turbulence model with the mesh grid was the element size = 90mm for a three-dimensional hydrodynamic model to simulate the flow [14]. Their study aimed to validate the numerical simulation with the experimental results. The results were analysed such as velocity, pressure, and turbulence. The results showed good agreement of validation of the numerical simulation and experimental results.

Li et al. (2018) introduced a numerical study using ANSYS FLUENT to investigate the flow patterns inside the fish ladder channel [32]. The approach adopted in their study was to vary the length ratio between the short baffle and the width of the pool (P/B). Different cases were examined. For instance, when the ratio P/B = 0.1 was used, it was found that the was near the wall with no curve formed between one slot and the other. This type of flow pattern was referred to as Flow Pattern One (FP1). On the other hand, when the ratio P/B = 0.25 was used, the main flow was in the centre of the pool. The flow in this case entered the centre of the pool as a curved jet. Then, it spread to the centre of the pool before reaching the next slot of the fish ladder. This type of flow was referred to as Flow Pattern Two (FB2). The third case studied was to use P/B = 0.5. The flow jet in this case showed a curved pattern along the opposite side of the wall. The flow pattern, in this case, was referred to as Flow Pattern Three (FB3).

AN et al. (2016) investigated the use of an L-shaped baffle in a fish ladder design and without an L-shaped baffle using ANSYS FLUENT [33]. Different channel slopes, namely 4.2 % and 2.6 %, were adopted in the studied model. The targeted results were the flow pattern, turbulence, and velocity. The results obtained from this study showed that, when using an L shaped baffle in the fish ladder with a slope of 2.6%, the maximum velocity of the flow decreased from 1.22 m/s to 0.85 m/s. Besides, the study results claim that the flow pattern between one slot and the next took the fish-friendly form ($\Omega$) which is suitable for fish to ease swimming through the pools.

6. Discussions
Although there is a great deal of literature on the optimization and improvement of the design of vertical slot fish ladders, most of the parameters of fish ladder design need to be explored. The focus of the literature is on the vital characteristics, which are the flow velocity within the fish ladder and the energy dissipation of water. Other parameters, such as the slope of the channel, the slot width, and the geometry of the baffle
were also investigated in previous studies. These studies on all essential and other parameters of vertical slot fish ladder design are all dedicated to one main goal, the optimization of the vertical slot fish ladder design.

Since optimizing the fish ladder design has been the target of many researchers, more study and investigation are required. An increase in our understanding of the range of flow velocity and energy dissipation through experimental investigations and simulation models is required especially for unexplored parameters.

One of these crucial parameters that have not been investigated in the literature is the slot angle. The slot angle controls the direction taken by water flow after leaving the slot. For instance, a relatively large slot angle value would lead to directing the flow into the centre of the pool. This could cause the velocity to be reduced. But it might cause to decrease in the rest areas’ presence of fish inside the pool. On the other hand, a small value for the slot angle could assist in creating resting areas for fish while causing the flow to transfer from one slot to the next one without colliding with the baffles which cause high velocity. These are some of the assumptions that can be made if varying the slot angle in vertical slot fish ladder design is to be investigated. Therefore, more investigations are required on vertical slot fish ladders. In such cases, the best action is to involve the use of simulation models to study a varied range of slot angle values and obtain the optimum value of the design. An experimental model can also be used for the sake of proving the reliability of the numerical model.

7. Conclusion

In areas where the presence of dams and other barriers in rivers is a fact, fish migration issues are significantly affected by those structures. Therefore, the accurately designed fish ladder plays an important role in dimensioning these issues and assist in allowing fish to meet their life cycle’s necessities, such as spawning and feeding. Nevertheless, the fish ladders are still restricted at the small section of the dam or weir gives less priority [7]. Thus, fish ladder design is rather limited by engineering, hydraulic and economic restrictions.

Regardless of the great work that has been dedicated to improving the fish ladder design, yet fish ladder science, as with many other engineering problems and practices, remains unsatisfactory and imperfect. Fish ladders are dominated by an engineering-focused approach. Consequently, nowadays, fish ladder science includes an extensive range of disciplines including fish behaviour, socioeconomics, and even complicated models of fish ladders prioritization options [9]. Most characteristics of fish ladder design need to be further investigated. Among these vital characteristics are the flow velocity within the fish ladder and the energy dissipation of water. Optimizing the fish ladder design has been the target of many researchers and, thus, more study is required. Since these characteristics have not been fully investigated in the literature, we must increase our understanding of the range of flow velocity mitigation and energy dissipation through experimental investigations and simulation models. An important parameter of the design of the vertical slot fish ladder that has not been explored in the previous studies is the slot angle. More experimental and numerical models that involve the variation of the slot angle need to be investigated to better understand the vertical slot fish ladder design and to improve its efficiency.

References

[1] Northcote T G, 1984 Mechanisms of fish migration in rivers,” in Mechanisms of migration in fishes, Springer, pp. 317–55.
[2] Cooke S J, Crossin G T and Hinch S G, 2011 FISH MIGRATIONS|Pacific Salmon Migration: Completing the Cycle, A P B T-E of F P Farrell, Ed. (San Diego: Academic Press)pp1945-2.
[3] Bravo-Córdoba F J, Sanz-Ronda F J, Ruiz-Legazpi J, Valbuena-Castro J and Makrakis S, 2018 Vertical slot versus submerged notch with bottom orifice: Looking for the best technical fishway
type for Mediterranean barbels, *Ecol. Eng.*, **122**, pp.120–5.

[4] Thorstad E B, Økland F, Aarestrup K and Heggberget T G 2008 Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts, *Rev. Fish Biol. Fish.*, **18**(4):345–71, doi: 10.1007/s11160-007-9076-4.

[5] Yagci O, 2010 Hydraulic aspects of pool-weir fishways as ecologically friendly water structure, *Ecol. Eng.*, **36**(1):36–46, doi: 10.1016/j.ecoleng.2009.09.007.

[6] Clay C H, 1994 *Design of fishways and other fish facilities.* CRC Press.,

[7] Mandal P, Tu Z, Yuan X, Gao Y, Huang Y and Peng H 2015 Importance of Design Factor in Improvement of Fishway Efficiency, *Am. J. Environ. Prot.*, **4**(6):344–53.

[8] Alabaster, J.S., 1970. River flow and upstream movement and catch of migratory salmonids. *Journal of Fish Biology*, 2(1):1-13.

[9] Silva A T, *et al.*, 2018. The future of fish passage science, engineering, and practice. *Fish and Fisheries*, **19**(2):340-62.

[10] Boiten W, 2002. Flow measurement structures. *Flow Measurement and Instrumentation*, **13**(5-6):203-7.

[11] Alvarez-Vázquez L J, Júdice J J, Martínez A, Rodriguez C, Vázquez-Méndez M E and Vilar M A, 2013 On the optimal design of river fishways. *Optimization and Engineering*, **14**(1):193-211, doi: 10.1007/s11081-011-9175-x.

[12] Stuart I G and Mallen-Cooper M 1999 An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/subtropical river. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, **15**(6):575-90. doi: 10.1002/(sici)1099-1646(199911/12)15:6<575::aid-rrr562>3.0.co;2-q.

[13] Mallen-Cooper M, 1994 Swimming ability of adult golden perch, Macquaria ambigua (Percichthyidae), and adult silver perch, Bidyanus bidyanus (Teraponidae), in an experimental vertical-slot fishway. *Marine and Freshwater Research*, **45**(2):191-8.

[14] Sanagiotto D G, Rossi J B, Lauffer L L and Bravo J M 2019 Three-dimensional numerical simulation of flow in vertical slot fishways: validation of the model and characterization of the flow, *RBRH*, **24**.

[15] Larinier M, 1992 Implantation des passes à poissons,” *Bull. Français la Pêche la Piscic.* pp 326–7, pp.30–44.

[16] O’Connor, J., Stuart, I. and Jones, M., 2017. *Guidelines for the design, approval and construction of fishways. Arthur Rylah Institute for Environmental Research* (No. 274). Technical Report Series.

[17] Khan L A, 2006 A three-dimensional computational fluid dynamics (CFD) model analysis of free surface hydrodynamics and fish passage energetics in a vertical-slot fishway. *North American Journal of Fisheries Management*, **26**(2):255-67

[18] Autodesk CFD | Computational Fluid Dynamics Simulation Software. [Online]. Available: https://www.autodesk.com/products/cfd/overview#internal-link-what-is-autodesk-cfd-. [Accessed: 01-Jan-2021].

[19] Computational fluid dynamics - Wikipedia.” [Online]. Available: https://en.wikipedia.org/wiki/Computational_fluid_dynamics. [Accessed: 01-Jan-2021].

[20] Launder B E and S D B 2013 MAN - ANSYS Fluent User’ s Guide Releasde 15.0,” *Knowl. Creat. Diffus. Util.*, **15317**(November):724–46.

[21] ANSYS Fluent.” [Online]. Available: https://www.ozeneric.com/products/fluid-dynamics/ansys-fluent/. [Accessed: 01-Jan-2021].

[22] Rajaratnam, N., Van der Vinne, G. and Katopodis, C., 1986. Hydraulics of vertical slot
fishways. *Journal of Hydraulic Engineering, 112*(10):909-27, doi: 10.1061/(ASCE)0733-9429(1986)112:10(909).

[23] Rajaratnam N, Katopodis C and Solanki S 1992 New designs for vertical slot fishways. *Canadian Journal of Civil Engineering, 19*(3):402-14. doi: 10.1139/92-049.

[24] Wu S, Rajaratnam N and Katopodis C 1999. Structure of flow in vertical slot fishway. *Journal of Hydraulic Engineering, 125*(4):351-60.

[25] Rodríguez T T, Agudo J P, Mosquera L P and González E P 2006. Evaluating vertical-slot fishway designs in terms of fish swimming capabilities. *Ecological engineering, 27*(1):37-48. doi: 10.1016/j.ecoleng.2005.09.015.

[26] Alvarez-Vázquez L J, Martínez A, Rodríguez C, Vázquez-Méndez M E and Vilar M A, 2007. Optimal shape design for fishways in rivers. *Mathematics and computers in simulation, 76*(1-3), pp.218-222. doi: 10.1016/j.matcom.2007.01.029.

[27] Tarrade L, Texier A, David L and Larinier M 2008. Topologies and measurements of turbulent flow in vertical slot fishways. *Hydrobiologia, 609*(1), pp.177-88. doi: 10.1007/s10750-008-9416-y.

[28] Wang R W, David L and Larinier M 2010. Contribution of experimental fluid mechanics to the design of vertical slot fish passes. *Knowledge and Management of Aquatic Ecosystems, 396*, p.02. doi: 10.1051/kmae/2010002.

[29] Tarrade, L., Pineau, G., Calluaud, D., Texier, A., David, L. and Larinier, M., 2011. Detailed experimental study of hydrodynamic turbulent flows generated in vertical slot fishways. *Environmental fluid mechanics, 11*(1):1-21. doi: 10.1007/s10652-010-9198-4.

[30] Marques, G.F., Fernandes, J.D.S., Santos, H. and La Sala, I., 2011. Modeling and Optimization of Fish Passage Structures. In *World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability* (pp 4232-45). doi: 10.1061/41173(414)440.

[31] Chorda J, Maubourguet M M, Roux H, Larinier M, Tarrade L and David L 2010 Two-dimensional free surface flow numerical model for vertical slot fishways. *Journal of Hydraulic Research, 48*(2):141-51. doi: 10.1080/00221681003703956.

[32] Li G, Sun S, Zhang C, Liu H and Zheng T 2019 Evaluation of flow patterns in vertical slot fishways with different slot positions based on a comparison passage experiment for juvenile grass carp. *Ecological Engineering, 133*, pp.148-59.

[33] An R, Li J, Liang R and Tuo Y 2016. Three-dimensional simulation and experimental study for optimising a vertical slot fishway. *Journal of hydro-environment research, 12*, pp.119-29.