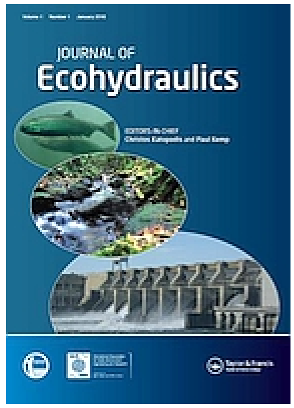
Computational fluid dynamics in fishway research - a systematic review on upstream fish passage solutions



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Journal:	*Journal of Ecohydraulics*
Manuscript ID	TJoE-2024-0005.R2
Manuscript Type:	Review Papers
Date Submitted by the Author:	21-May-2024
Complete List of Authors:	Tarena, Fabio; Politecnico di Torino Comoglio, Claudio; Politecnico di Torino, DIATI Nyqvist, Daniel; Politecnico di Torino Katopodis, Christos; Katopodis Ecohydraulics Ltd.
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Abstract:	Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to model the dynamic behavior of fluids, and it is increasingly applied in the study of fishways, allowing flexible, timesaving, and low-cost analysis of flow fields. Applications and methodologies, however, vary substantially between different scientific studies and no overview is currently available in the primary literature. Here we review published papers on CFD use in upstream fish passage solutions to identify and describe related spatial-temporal considerations, application fields, scopes and modeling procedures. Vertical slot was the most studied fishway type, followed by nature-like fishways and pool and weir fishways. Most often the CFD model was coupled with laboratory or field experiments, but only sometimes associated with actual fish behavior (observations or values from literature). Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently adopted set of equations, followed by Large Eddy Simulation (LES), but other promising approaches - scarcely applied so far - were also identified and suggested for future applications - e.g. Detached Eddy Simulation (DES). In general, the use of commercial software was prevalent compared to open-source, with Ansys (Fluent and CFX) and FLOW-3D being the most common softwares. The importance of model validation is highlighted, especially for merely numerical studies, together with the need for three-dimensional CFD to correctly represent the features of turbulent flows.

	Overall, ecohydraulic studies on the interaction between fish movements and hydrodynamics are needed to complement the CFD-analysis and improve the design of more efficient fish passage solutions.

Computational Fluid Dynamics in fishway research - a systematic review on upstream fish passage solutions

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RUNNING HEAD: Use of Computational Fluid Dynamics in fishway research

ABSTRACT

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to model the dynamic behavior of fluids, and it is increasingly applied in the study of fishways, allowing flexible, timesaving, and low-cost analysis of flow fields. Applications and methodologies, however, vary substantially between different scientific studies and no overview is currently available in the primary literature. Here we review published papers on CFD use in upstream fish passage solutions to identify and describe related spatial-temporal considerations, application fields, scopes and modeling procedures. Vertical slot was the most studied fishway type, followed by nature-like fishways and pool and weir fishways. Most often the CFD model was coupled with laboratory or field experiments, but only sometimes associated with actual fish behavior (observations or values from literature). Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently adopted set of equations, followed by Large Eddy Simulation (LES), but other promising approaches - scarcely applied so far - were also identified and suggested for future applications - e.g. Detached Eddy Simulation (DES). In general, the use of commercial software was prevalent compared to open-source, with Ansys (Fluent and CFX) and FLOW-3D being the most common softwares. The importance of model validation is highlighted, especially for merely numerical studies, together with the need for three-dimensional CFD to correctly represent the features of turbulent flows. Overall, ecohydraulic studies on the interaction between fish movements and hydrodynamics are needed to complement the CFD-analysis and improve the design of more efficient fish passage solutions.

Keywords: CFD, ecohydraulics, fish pass, hydrodynamic modeling, numerical simulation, turbulence

1. INTRODUCTION

Hydropower production is one of the most accessible and reliable sources of renewable energy in the world (Brown et al., 2011). Hydroelectric production, however, comes with a high cost for the ecology in rivers and beyond (Olden et al., 2015; Vezza et al., 2014; Wu et al., 2019). For mobile and migratory species, especially fish, dams and reservoirs constitute an anthropogenic barrier for their natural upstream and downstream movements (Lucas & Baras, 2001). Currently, river fragmentation and consequent alteration of natural flow regimes is considered as one of the main causes of decline in freshwater ecosystem complexity and biodiversity (Dudgeon et al., 2006; Sparks, 1995), with half of the rivers on Earth negatively affected by dams (Nilsson et al. 2005).

When dam removal is not an option, other remedial strategies are necessary to restore river ecology (Katopodis & Williams, 2012; Silva et al., 2018). One of the most widespread solutions to restore longitudinal connectivity is represented by fishways, engineering solutions that create an ecological corridor to allow fish to pass barriers (Clay, 1995; Larinier, 2002). There are many types and shapes of these structures, but they can be generally divided into technical and nature-like fishways (Schmutz & Mielach, 2013). Technical fishways allow fish to overcome the drop created by the dam, through a sloping channel split into a sequence of compartments by dividing walls, creating less abrupt hydrodynamic conditions that are intended to be suitable for the movements of target species (Katopodis, 2005). Nature-like fishways, on the other hand, are low-slope bypass channels that mimic the natural conditions of a small water course connecting the original river upstream and downstream of the obstacle, or rock ramps mimicking river rapids. Fishway effectiveness depends on how well species abilities are matched with generated hydrodynamics within these structures as well as at fish entrances (Hershey, 2021; Katopodis, 2005). Typically, nature-like fishways, due to their more gentle and diversified flow fields, are usually easier for the fish to pass while limits in the available space often make their entrance more distant from the obstacle and therefore harder to find for upstream moving fish, compared to technical fishways (Hershey, 2021; Katopodis, 2005; Kelley et al., 2023).

The functionality of a fishway, is the result of a series of events involving fish swimming capability and behavior in encountered visual, acoustic and hydrodynamic conditions (Mawer et al., 2023; Silva et al., 2018; Williams et al., 2012). Hydrodynamics and, more specifically, velocity and turbulent conditions are considered the main drivers of fish passage performance (Goodwin et al., 2006; Katopodis, 2005; Tan et al., 2018). Indeed, special consideration has always been given to the description and analysis of the flow field inside a fishway (Katopodis, 1992). In the past, this was performed by taking measurements (typically of the velocity field) inside real facilities or by creating physical models in a laboratory environment (Katopodis, 1992; Leroy et al., 2018). With the recent technological advancements in computer science, the use of numerical models for fishway analysis has progressively become more accessible and reliable (Amaral et al., 2019; Stamou et al., 2018). In particular, the reduction in simulation times and increase in processing capacity has led to a widespread application of Computational Fluid Dynamics (CFD) to address fishway design issues (Barton et al., 2009; Duguay et al., 2017; Shahabi et al., 2023).

CFD is a numerical technique that solves the complex equations of fluid motion in various environmental contexts (Bates et al., 2005). The model consists of the definition and discretization of a computational geometry in elementary particles (meshless methods) or cells (meshed method), the application of boundary conditions at the inlet and outlet of the model, and the solution of the equations of motion within the discretized volume (Andersson, 2012). By using CFD-models, the flow can be described, and its hydrodynamic characteristics may be analyzed with only the known discharge, water levels and the geometry of the fishway (Andersson, 2012).

The application of CFD for fishways allows testing of different geometrical configurations and flow conditions with flexibility and at low cost (An et al., 2016; Bates et al., 2005). There is no widely recognized standard procedure to simulate the flow inside fishways with CFD. Each study makes particular modeling choices based on the expertise of the software user (Andersson, 2012; Leng & Chanson, 2020b), and a systematic overview of methods applied is lacking. In this context, the main objective of this paper is to elucidate the current state-of-the-art relative to the application of CFD related to fishways by identifying, analyzing and critically reviewing available primary literature. Specifically, we summarize spatial-temporal parameters, scope and application fields, modeling procedures and approximations related to the use of CFD in fishways. We limited the review to upstream migration solutions and internal flow field analysis, as numerical modeling applications for fishway entrance positioning (e.g. Andersson et al., 2016; Lindberg et al., 2013) and downstream passage (e.g. Feigenwinter et al., 2019; Zöschg et al., 2023) are still few, more site-specific, and not easily classifiable.

2. METHODS

A complete search of the available primary scientific literature on CFD and fishways was conducted on *Scopus* and *Web of Science* databases. The collection encompassed all the literature available in the two engines up until the end of 2023. The initial search and identification of papers were performed through the definition of a series of keywords, including general terms relating to numerical modeling, hydrodynamics and fishways: *CFD, computational fluid dynamics, fish ladder, fish pass, fish passage, fishway, hydrodynamic modeling, hydrodynamics, numerical simulation*. All the possible (meaningful) permutations of these words were explored, and the abstract of each paper was read to identify those that were suitable for this study. A paper was considered relevant only if dealing with a numerical model used to study the hydrodynamics within an upstream fish passage solution, and in that case the full manuscript was then read for further analysis. Papers unavailable online or not written in English were excluded from the study. When reading the selected full manuscripts, if referenced relevant papers that had not emerged in the search query were found, they were also included in the collection of papers.

The analysis of the full manuscripts included an initial critical reading of the paper followed by the collection of selected information to fill a summary database. The database was devised to assess the different ways computational fluid dynamics was applied in analyzing the upstream fishway from different perspectives. The database included the following classification/analysis parameters:

- Year of publication of the paper
- Country (and continent) in which the study was carried out;
- Type of fishway studied and modeled (e.g. vertical slot, pool and weir, nature-like, etc.);
- Aim of the paper (the reason why a numerical model was used for the analysis of a fishway);
- Approach type (if the numerical model was coupled with physical experiments or applied

alone);
- Equations of flow, turbulence approximation, and type of software used;
- Assessment of passage suitability (if and how fish biology and ecology were included in the study).

The database was progressively completed and analyzed in *Microsoft Excel* and can be found in the *Supplementary Material*.

3. RESULTS AND DISCUSSION

3.1 OVERVIEW

The complete paper collection consisted of 137 scientific articles published over a period of 19 years (from 2004 to 2023). The number of papers per year shows a consistent increase in the last 7-8 years (Fig. 1). In general, the number of papers focusing on applying CFD for fishway flow analysis followed the recent advancements in computation resources and power (Stamou et al., 2018). Whereas, until 2015, this number was limited to a maximum of five papers per year, more than three quarters of the collection (78.8%) were papers published from 2016 to 2023.

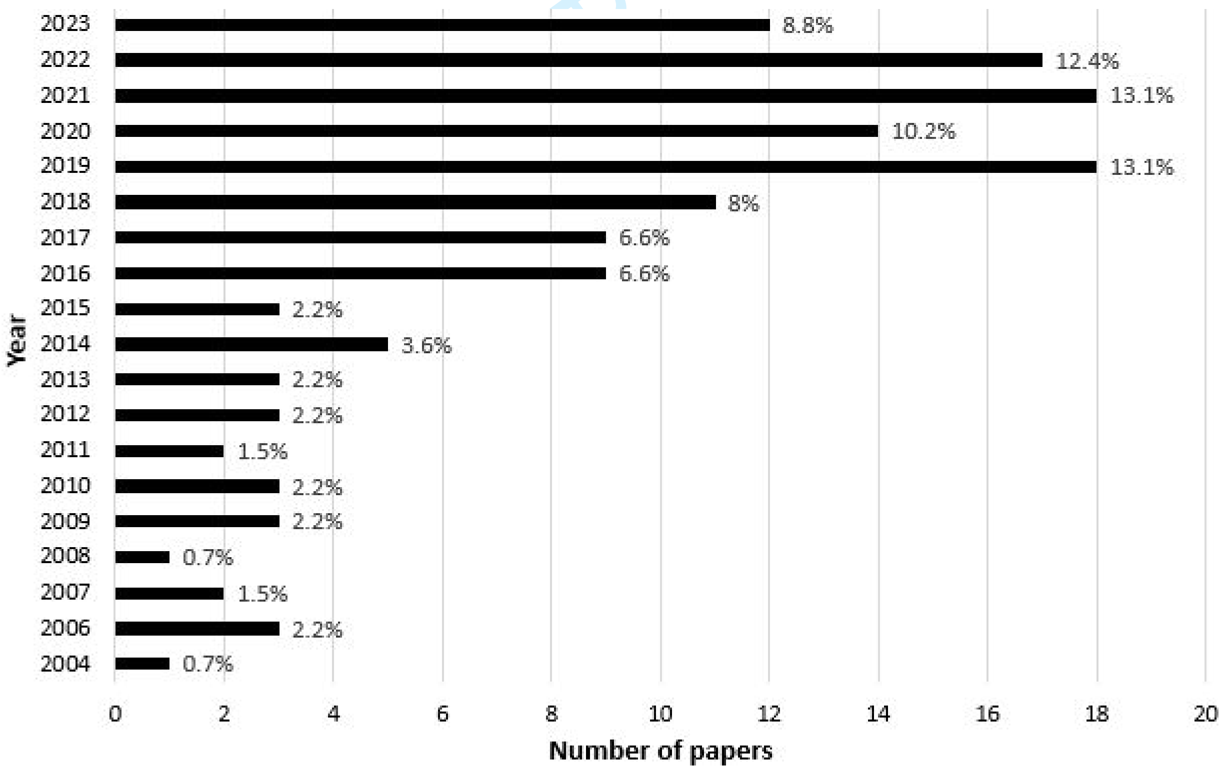

Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

CFD studies were conducted in five continents, encompassing research centers (first author affiliation) from 25 different countries (Fig. 2). The leading continents were Europe (41.6%) and Asia (35%). China was the country with the highest number of papers (25.5%), followed by Canada and Germany (8%). France, Spain and USA accounted for 6.6% of the collection, followed by Slovenia (5.8%) and Brazil (5.1%). Australia, Iran and Portugal contributed with 3.6% each, while Italy, Poland, Sri Lanka and UK with 2.2%. The rest of the countries (belonging to Europe and Asia), accounted for the remaining 8% of the final sample.

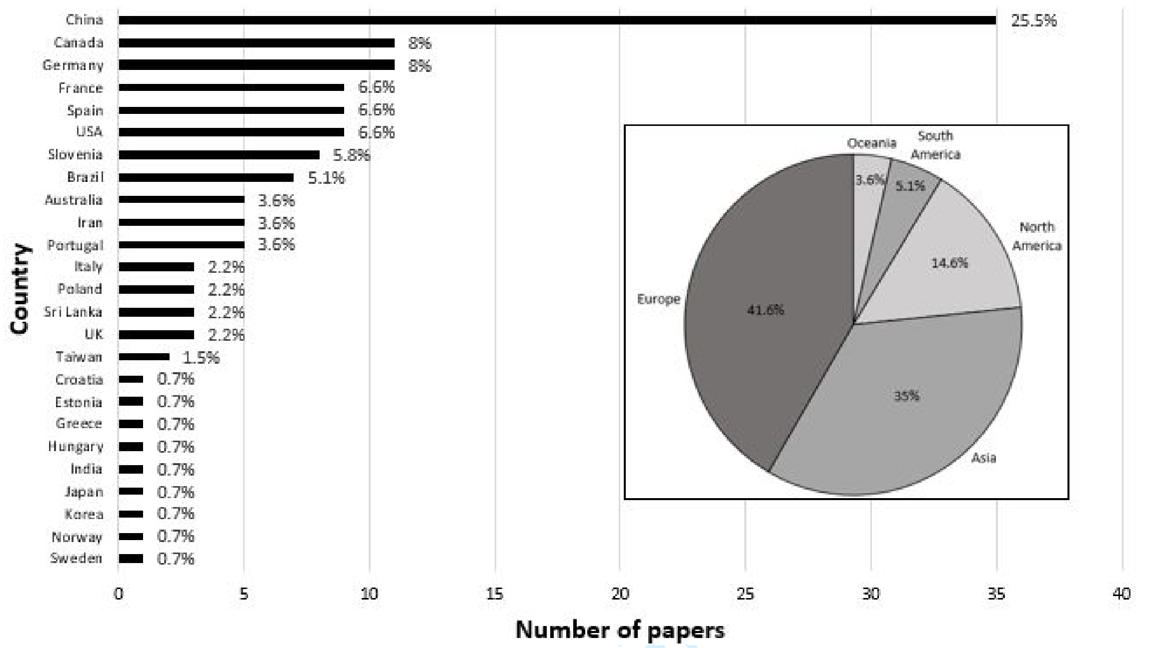

Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

3.2 TYPE OF FISHWAYS AND AIM OF THE CFD APPLICATION

As Fig. 3 indicates, technical fishways - e.g. *Vertical Slot* (VSF), *Pool and Weir* (PW) - represented the most studied types in the examined scientific literature (66.4%), while 17.1% focused on *Nature-Like* fishways (NLF) and 12.8% included various less studied fishway typologies (i.e. Denil steeppass, eel pass, flat W-weir, island fishway, locks in dam, pole fishway, small culvert), collected under the category *Other*. In 3.6% of the collection, the structure type was not specified (Fig. 3).

The most studied fishway type was the VSF, that is considered the most effective technical measure to restore longitudinal connectivity in fragmented rivers, due to its adaptability to up- and downstream water level fluctuations, and its ability to allow fish passing through the slot at its preferred depth (Katopodis and Williams, 2012; Quaranta et al., 2017). Even though the flow pattern generated inside VSFs has been studied in both laboratory and in-situ experiments for several years (e.g. Calluaud et al., 2014; Liu et al., 2006; Rajaratnam et al., 1992; Wu et al., 1999), numerical modeling provides additional insights and a more thorough assessment of several geometry changes without the need for building physical models or experimenting with real fishways (An et al., 2016). Different types of VSF structures were studied numerically, testing the effects of different geometry additions and layout modifications. For example, Barton et al. (2009) studied the impact of a reduced slope on the flow within a VSF, Marriner et al. (2014, 2016) assessed the hydraulics of turning pools inside a larger VSF, and Romão et al. (2021) compared the efficiency of a Multi-Slot Fishway (MSF) with a standard VSF. Several studies focused on the numerical assessment of the flow in both standard and non-standard VSF layouts. Interestingly, more than one half of the entire paper collection (51.4%) was focused on VSFs (Fig. 3).

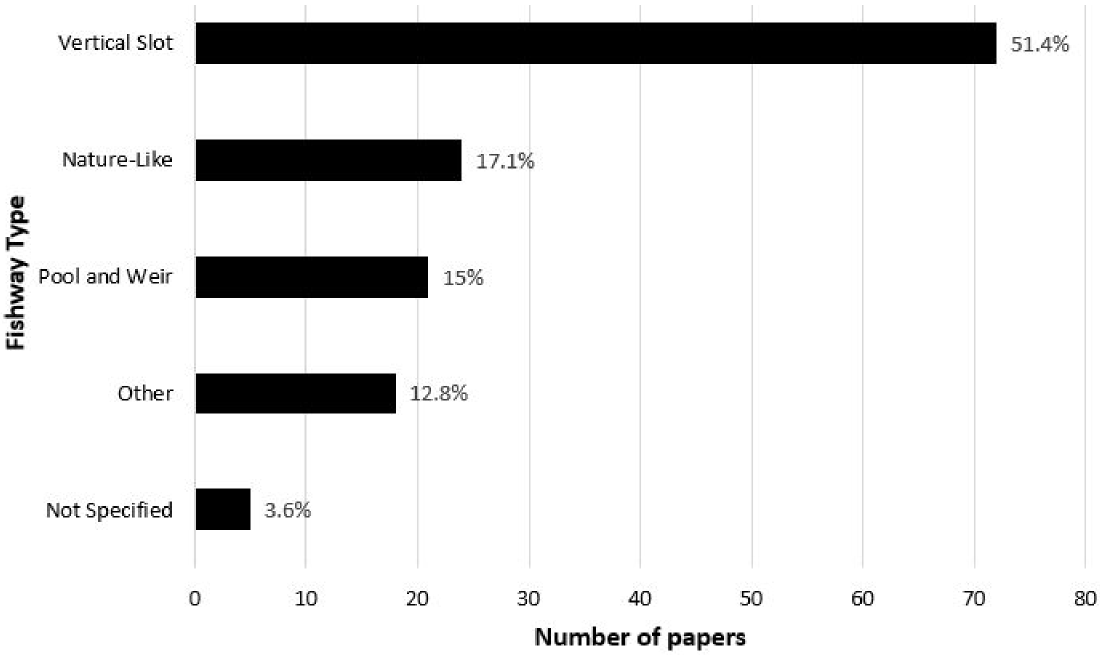

Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steeppass, eel pass, flat W-weir, island fishway, locks in dam, pole fishway, small culvert), while the category Not Specified includes papers where the fishway type was not made explicit. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one fishway structure contributed to the count for each fishway type dealt with.

NLF were the second most studied type, being the main focus of 17.1% of the scrutinized papers (Fig. 3). NLF is a category that included several types of structures and layouts, mainly focused on mimicking the natural conditions inside a river (Zhou et al., 2020). Two types of NLF were identified in the examined literature: bypass channels (29.2% of NLF), with the main aim to create an alternative route simulating hydrodynamics, slope and morphology of the original river, and rock ramps (70.8% of NLF) that form a continuous path connected with the river bed and various arrangements of different sized boulders. NLF aim to obtain improved passage efficiency for a large set of species through a variability of flow patterns closer to what fish encounter in nature, compared to the more artificial and repetitive flow fields occurring in technical fishways (Katopodis, 2005). The geometry of NLFs though is typically more difficult to model numerically, as they include structures with no side walls and paths with highly irregular flows through boulders of different dimensions and shapes. Additionally, experiments conducted with idealized bed roughness configurations, such as a regular pattern of nearly spherically-shape boulders (Golpira et al., 2022) or even single hemispheres (Shamloo et al., 2001), showed that flow regimes and hydrodynamic characteristics are highly variable with discharge and submergence levels. Therefore, overall numerical modeling of NLF is a more challenging procedure and the simulation is often performed over a simplified geometry. For example, for rock ramps, boulders were modelled with a spherical shape instead of an irregular shape closer to reality (e.g. Baki et al., 2016). Similarly, the natural roughness of a bypass channel bed was simulated through Manning's approximation, quantifying the uneven river bed granulometry with a single coefficient (e.g. Tran et al., 2016).

The third most studied fish pass type was the PW, comprising 15% of the paper collection (Fig. 3). Generally considered one of the most common technical fishway built, the PW geometry consists of a series of basins divided by cross-walls, over a sloping channel, that are connected through a weir and/or an orifice (Katopodis 1992; Santos et al., 2012). Various sub-types of fish passage structures were included within this category (i.e. Ice Harbor, Pool and Orifice, Fish-Bone) and several examples of numerical applications were found: from internal flow field analysis (e.g. Abdelaziz et al., 2013; Abeyratne et al., 2021; Shahabi et al., 2023), to testing of different layouts and geometries (e.g. Li S. et al., 2022; Zhong et al., 2021), and investigating the applicability and reliability of different modeling software (e.g. Chen & Tfwala, 2018).

Fishways types other than those in the previous three categories were also represented in the sample, including eel passes, flat W-weirs, island-type fishways, locks in dams, pole-type fishways, small culverts and Denil variants such as the Steeppass. Since the number of studies involving these kinds of structures was very small, they were grouped together in the category *Other*, and contributed to 12.8% of the papers collected (Fig. 3). Additionally, 3.6% described an application of numerical modeling for upstream fish passage purposes but without explicitly indicating the structure type - e.g. studies within a flume of different cylinder arrangements over a sloping flow channel (e.g. Chorda et al., 2019; Ducrocq et al., 2017). Since the methods and aims of these studies were overall similar to the other ones, they were included in the collection under the category *Not Specified* (Fig. 3).

The aim of each of the 137 papers (i.e. why CFD has been applied to study the internal hydrodynamics of fishways) was analyzed and subsequently classified into 7 different categories:

1. Application to theoretical fish passage geometries (experimental setups, inferences from other studies) or to non-specified existing structures, studying the relationship between modifications of the geometric layout and consequent changes in the flow field (32.8%): to assess the impact of fishway geometry changes on hydrodynamics and describe the internal hydraulic topology (e.g. Heimerl et al., 2008; Kim et al., 2012; Miranda et al., 2021).
2. Relationship between internal flow field and fish swimming ability (28.5%): to evaluate suitability of flow structure and flow parameters with respect to target fish species swimming abilities (e.g. Khan, 2006; Li M. et al., 2022; Mao et al., 2012).
3. Application to real structures (18.3%): to study the efficiency of an existing fishway (e.g. Bombač et al., 2015), to improve the geometrical design of an existing one (e.g. Bung, 2018) or to support the design phase of a new one (e.g. Song et al., 2019).
4. Suitability of different flow equations for internal fishway flow representation (7.3%): to compare different equation systems and evaluate the best option (e.g. Stamou et al., 2018) or to assess the suitability of the hydraulic model under determined hydrodynamic conditions (e.g. Barton et al., 2009).
5. Comparison of different fish passage structures (5.1%): to evaluate which was the best option for a specific location or fish reference zone (e.g. Klein & Oertel, 2015; Quaresma et

al., 2018).

6. Choice of the appropriate turbulence closure model (5.8%): application of different turbulence approximation equations with respect to the same structure and evaluation of the best option (e.g. Cea et al., 2007; Santos et al., 2022).
7. Software performance comparisons (2.2%): application of different computational software (commercial and open source) to simulate the flow inside the same fishway and evaluate the most suitable choice (e.g. Duguay et al., 2017; Fuentes-Pérez et al., 2022).

3.3 MODELING APPROACHES

The different ways numerical modeling was used to study fishways were classified, considering if the numerical model was applied alone or coupled with another type of experiment or field activity (e.g. flume, real fishway or physical model), into the following 3 categories (Fig. 4):

1. *Numerical* (41.6%): the internal flow field was examined only by numerical means (e.g. Ballu et al., 2018; Padgett et al., 2020; Plymesser & Cahoon, 2017).
2. *Numerical and In Situ* (10.9%): the numerical model was coupled with field measurements inside a real structure (e.g. Bravo-Córdoba et al., 2021; Marriner et al., 2014).
3. *Numerical and Laboratory Experiment* (47.4%):
   a. *Flume* (41.6% - within the category): the numerical study was coupled with simplified experiments conducted inside a rectilinear flume (e.g. Abeyratne et al., 2021; Kim et al., 2012; Miranda et al., 2021).
   b. *Physical Model* (58.4% - within the category): the numerical model was coupled with measurements conducted in an ad-hoc reproduction of a real structure (e.g. Lewandoski et al., 2021; Oertel & Schlenkhoff, 2012).

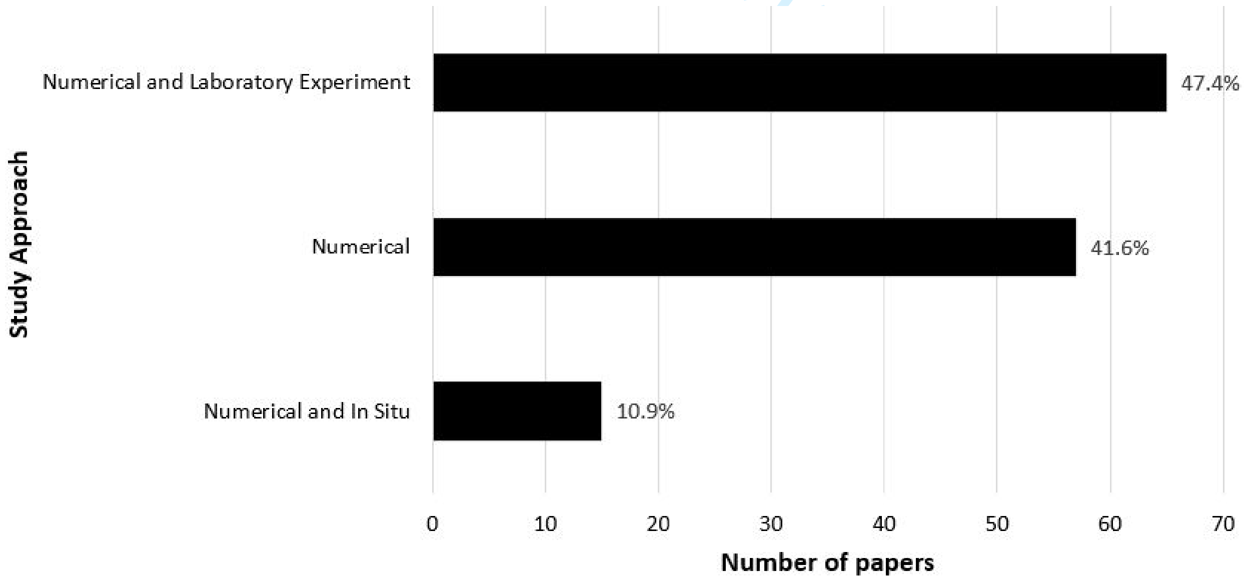

Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated in the figure.

In more than half of the collection of papers (58.3%) numerical models were coupled with laboratory, either flume or physical model, or field experiment. This process, commonly called hybrid modeling, is mutually beneficial to both physical and numerical approaches (Bung, 2018; Leng & Chanson, 2020b). Results from physical experiments are based on the reconstruction of the flow field features through the interpolation of a finite number of sampling velocity points and are, therefore, limited by the maximum resolution obtainable in the interpolated raster (Roth et al., 2022). Numerical methods offer the possibility to overcome this resolution limit with high quality vectorial fields, if an adequately dense computational grid and a suitable closure model to simulate turbulence phenomena are provided. For example, when it comes to the analysis of turbulent flow, the availability of high quality flow fields is crucial to properly identify the sizes of eddies, as they constitute a potential source of hindrance and loss of balance for fish inside the flow (Lacey et al., 2012; Silva et al. 2012). Additionally, CFD generates the full flow field distribution, and allows a quick and low cost implementation of geometry changes and flow conditions (An et al., 2016; Heimerl et al., 2008). In contrast, sufficiently detailed hydrometric measurements may be limited by excessive costs, restricted access to some locations due to safety rules or physical impossibility to reach preferred gauging positions (Duguay et al., 2017; Leng & Chanson, 2020a). On the other hand, physical experiments offer a realistic image of the flow features, provide critical support for numerical model validation that is necessary to acquire meaningful results (Amaral et al., 2019; Bates et al., 2005), as well as reliable values for setting boundary conditions, a crucial factor for model accuracy (Cao et al., 2021). A significant level of expertise (of both the numerical and physical process) is required to define and implement a CFD model in a suitable way (Leng & Chanson, 2020b). In general, the main advantage of coupling physical experiments with numerical models is the prospect of a mutually complementary practice that maximizes strengths and minimizes weaknesses for each (Leng & Chanson, 2020c).

In 41.6% of the analyzed papers, the study of the flow field was performed by the application of a numerical model alone, without coupling it with a physical experimental version or field measurements (Fig. 4). This approach has the advantage of avoiding costs of field work or laboratory experiments, providing a flexible and prompt application technique to analyze the flow field (Heimerl et al., 2008). Studying internal hydrodynamics of fishways with CFD models also allows saving time and resources otherwise allocated to building a structure in real life and subsequently evaluating it with flow field measurements (Cao et al., 2021). In many cases though, field assessments are crucial in determining fishway effectiveness, especially for non-salmonid species (Hershey, 2021; Katopodis & Williams, 2012; Silva et al., 2018). Moreover, the possibility of investigating different fishway configurations at the same time, together with the ease of implementing changes in geometrical setups, without the rigidity characterizing field or laboratory experiments, can play a substantial role towards a quicker and more economical design of effective and functioning structures (Abeyratne et al., 2021; Barton et al., 2009). This is valid, as long as the CFD model represents the flow field and hydrodynamic parameters well. In fact, an essential aspect in the application of CFD modeling is to ascertain that the reproduction of the physical processes reflects reality (Khan, 2006), especially in studies based on numerical models only. The reliability of a numerical model is assessed through a process of validation of the flow field and hydrodynamic parameters. Within hybrid approach studies, where the numerical model was applied together with a laboratory or field experiment, the validation of the CFD model was performed through a direct comparison with real data obtained and measured by the same researchers involved in the study.

When it comes to exclusively numerical studies, the situation is different since no direct flow field comparison is immediately available. Typically, in these kinds of studies, the quality assessment of the model was carried out by comparing simulation results with previously available data, using one of the two following approaches:

1. Using data from another study where a laboratory experiment or field study was performed, and creating the geometry for the new numerical model based on that existing setup (e.g. Ballu et al., 2018; Stamou et al., 2018). This “pristine” shape of the model is then validated on the same boundary conditions measured in the experiment or field study, comparing the flow topology or the parameter values in some crucial areas of the structure (e.g. velocity at the slot opening or turbulent kinetic energy in the pools). After a satisfactory validation process, tweaks and changes are made to the original model to further explore the effects on hydrodynamics.
2. Using as a reference the flow field from another paper’s case study, where a theoretical model or fishway geometry was described but either not directly tested or missing some information relative to flow parameters, and iteratively fine tuning the boundary conditions or slightly tweaking the geometry in order to get the same flow distribution as the original study (e.g. Quaranta et al., 2016, 2017).

Typically, the aspect that distinguished the first from the second approach was the availability of a previous study specifying the boundary conditions. The two approaches were inherently very close.

Overall, when applying CFD, the main difference between hybrid and exclusively numerical studies was in the modeling validation process. In hybrid studies, the CFD tool was either validated with a laboratory or field experiment or used to enhance physical investigations. In the numerically exclusive studies, the model’s suitability to reproduce the flow field was examined more directly. While model validation was always performed in hybrid studies, in exclusively numerical studies this procedure was carried out in 86% of the cases - with 14% not specifying details on how it was conducted. Improved validation of CFD models may be obtained with the wider use of available hydraulic relationships (e.g. depth-discharge; velocity profiles) from physical modeling studies of technical fishways (e.g. Ead et al., 2004; Katopodis, 1992; Katopodis et al., 1997; Wu et al., 1999).

3.4 HYDRODYNAMIC MODELS

Choosing the most suitable numerical model to represent the flow field in a fishway is a delicate operation, that requires a certain level of experience from the modeler (Mahl et al., 2021). The set of modeling equations, assumptions and approximations should be adapted to the particular layout of the fishway that has to be represented (Bates et al., 2005). A strict and precise digitization of fishway geometry is fundamental for high simulation accuracy, yet the more detailed the description, the more computationally demanding the numerical modeling task becomes (Andersson, 2012; Padgett et al., 2020).

In general, it is recognized that applying low computationally demanding one-dimensional models for fishways may lead to oversimplifications of the physical process, as the inherently three-dimensional nature of the flow is neglected (Fuentes-Pérez et al., 2018). In 1D models, variations only in one spatial dimension (along the length of the watercourse) are considered, simplifying the analysis by assuming that changes in flow properties occur only in the direction of the flow. With the excessively straightforward assumptions and the absence of transversal and vertical components of velocity, 1D models do not allow calculation of hydrodynamic parameters, like turbulent kinetic energy and energy dissipation rate, fundamental to assess fish passage suitability (Santos et al., 2012; Umeda et al., 2017). Only 1.5% of the analyzed papers tested 1D models to reproduce fishway hydrodynamics, and they were mainly intended as a preliminary analysis phase for a more complex model by interpreting the flow field from the one-dimensional simulation to select appropriate turbulence approximations to be adopted in 3D models to catch the flow distribution, or by using the resulting values of hydraulic parameters as guidance for the boundary conditions of the following 3D models (e.g. Umeda et al., 2017). The potential use of this method in a preliminary design or test phase is primarily highlighted as a tool for estimating discharges and water levels as input data for more complex hydrodynamic models (Fuentes-Pérez et al., 2018).

While the internal flow of fishways is commonly recognized in CFD studies as a three-dimensional phenomenon (Gong et al., 2021; Klein & Oertel, 2015), there are some particular cases in which a 2D approximation can help save time and resources. Actually, physical modeling demonstrated that for VSFs with low slopes (< 5%), in a large area of internal pools, flow is approximately bidimensional as the vertical component of velocity assumes significant values just in the narrow section of the slot (Wu et al. 1999). Several numerical studies assumed 2D flow in VSF with gentle slopes (e.g. Ballu et al., 2018; Bombač et al., 2017; Tran et al., 2016). In these conditions, the use of a 2D model with Shallow Water Equations (SWE) approximation is justified and can provide useful results in terms of identification of fish resting zones and flow topology (Bermúdez et al., 2010; Stamou et al., 2018). However, the success of a fishway is highly related to the passage of fish through the slot and, so, it is essential to verify the flow characteristics in that zone (Cea et al., 2007). The papers that adopted a 2D model to study the flow field (8.8%) applied it to low slope VSF only (e.g. Bermúdez et al., 2010; Bombač et al., 2015; Cea et al., 2007), as this approximation would be inadequate for steeper VSFs and other types of fish passes with more pronounced three-dimensional characteristics of the flow.

For most of the CFD applications analyzed, the need for three-dimensional models is widely recognized (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2022; Maniecki, 2018). There are certain zones (like in the proximity of the slot) and some ranges of discharge and bed slope for which simplistic approximations fail to capture important features of flow topology (Cea et al., 2007; Chorda et al., 2010). For example, neglecting the vertical component of velocity in 2D models, can lead to an overestimation of turbulence parameters and water levels, in the presence of highly turbulent flows (Lauchlan Arrowsmith & Zhu, 2014). Therefore, although being more complicated and time consuming, 3D CFD is the irreplaceable way to reliably capture the flow numerically (Ballu et al., 2018; Bombač et al., 2014). Moreover, the higher flexibility of the meshing algorithms used by 3D CFD allows more dynamical changes in geometry and layout compared to 2D models (Lauchlan Arrowsmith & Zhu, 2014). Three-dimensional CFD was used in 91.2% of the papers.

In addition, among 3D CFD papers, 4.8% adopted the so called Smoothed Particle Hydrodynamics method (SPH), a 3D meshless approach in which the fluid domain is discretized in particles and the equations of motion are solved with a Lagrangian point of view (e.g. Novak et al., 2019, 2021). In contrast to traditional approaches (with Eulerian perspective), SPH grants more flexibility in the geometry definition, overcoming the limitations of the more rigid process of mesh creation, and its suitability to model 3D flows within fishways has been proved in several cases (e.g. Novak et al., 2019). However, being a meshless methodology, SPH's application is often limited by the need of a significant computational power - required for the discretization of the fluid domain in elementary particles - and the inherent weaknesses within the definition of the boundary conditions near solid walls, creating a problem of continuity between fluid and solid domains (Novak et al., 2019).

3.5 TURBULENCE AND EQUATIONS

Three-dimensional CFD was the most recurrent method adopted to study fishways throughout the analyzed papers, with many sets of equations and turbulence approximations. The three-dimensional nature of flow within fishways is related to the turbulence generated internally. The correct solution of Navier-Stokes equations is crucial to determine velocities and turbulent quantities accurately, especially since these parameters influence the passage success of fish through the structure (Cea et al., 2007). The equations of motion can be solved directly (DNS, Direct Numerical Simulation) to obtain the most precise flow fields. With currently available computational capacities, as well as simulation times needed for this type of method, application of CFD for DNS is excessive (Padgett et al., 2020). This is also highlighted by the fact that DNS was not used in the simulations, but other approximation methods were adopted in all the papers analyzed (Fig. 5).

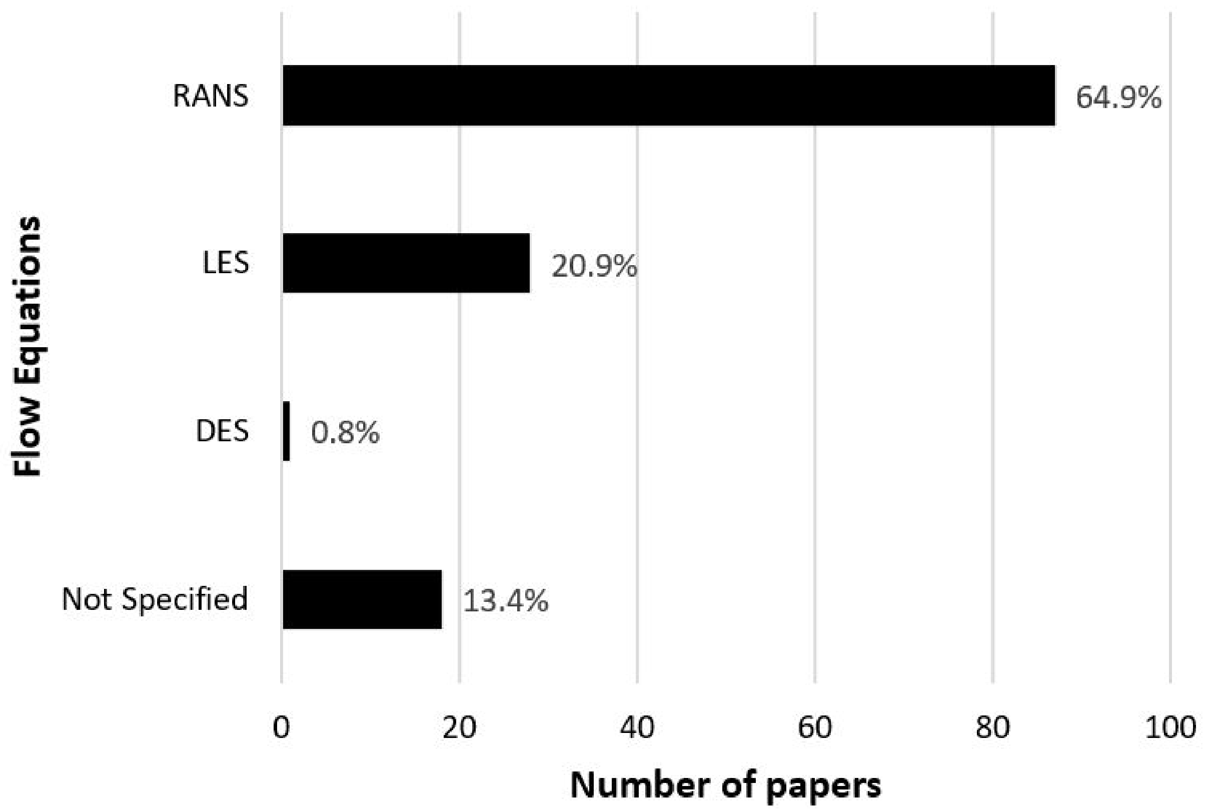

Fig. 5 - Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure models: k-ε and k-ω. Papers where the equations or turbulence model type was not made explicit are included under the category Not Specified. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one set of flow equations contributed to the count for each set of equations dealt with.

The most frequent alternatives to DNS found in the analyzed papers were Reynolds-Averaged Navier-Stokes equations (RANS) and Large Eddy Simulation (LES), representing 64.9% and 20.9% of the collection, respectively - with 6.6% of the papers applying both methods to compare their performance.

RANS was the most used method (64.9%), providing a reasonable balance between result accuracy and computational cost (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2018). Since RANS are based on time averaging of the dynamic variables of the Navier-Stokes equations, they perform well in capturing the average flow field, yet are weaker in assessing the turbulent parameters, as they depend on the unsteady and time varying features of the flow (Chorda et al., 2010; Fuentes-Pérez et al., 2018). For example, several studies outlined the over- or underestimation of turbulent kinetic energy from RANS (e.g. Baki et al., 2016; Sanagiotto et al., 2019; Tran et al., 2016). In general, the precision of turbulence parameters estimation depends on the type of closure model adopted for a specific problem. In RANS, the approaches used mainly consist of the so called two-equation models, solving a pair of additional transport equations to obtain a characteristic length and velocity of the turbulence process (Andersson, 2012). According to our review, the most used approach was the k-ε model, implemented in 83.1% of the RANS applications, while the k-ω model was adopted only in 10.1% of the cases. In the remaining 6.7% of the RANS applications the equation model used was not specified. Even if both equation models are recognized as adequate for general-purpose applications of RANS (Andersson, 2012), the disproportionally high use of the k-ε model emerging from our search, is related to the higher computational time associated with the k-ω model. Nevertheless, the performance of k-ω is higher in zones close to solid boundaries and in contexts with separating or swirling flows (Ducrocq et al., 2017). In particular, within the k-ω model applications, the improved Shear-Stress Transport (SST) k-ω model was adopted in the majority of the cases (90%), combining the benefits of both k-ε and k-ω approximations and allowing a strengthened performance in representing adverse pressure gradient and separating flows (Padgett et al., 2020; Zhang et al., 2023). However, since both equation models depend on the Boussinesq eddy viscosity approach, RANS suffer from inherent deficiencies deriving from the approximation that considers turbulence as an isotropic phenomenon (Andersson, 2012). This contributes to limiting the precision of RANS in fishways, where, inside the pools, turbulence is considered strongly anisotropic (Duguay et al., 2017). However, fishways are still considered a suitable field of application for RANS, as the inner flow topology is represented well overall, despite the limits in wakes zones and complex flows (Mahl et al., 2021; Sanagiotto et al., 2019).

When the flow is highly turbulent, the LES method could be a valid option to improve modeling accuracy (Fuentes-Pérez et al., 2022), and it was applied in 20.9% of the cases. Filtering out the small but keeping the large turbulent scales from Navier-Stokes equations, the LES method offers a more complete description of the instantaneous flow field, overcoming the limits of time-averaging that characterize RANS (Chen & Tfwala, 2018). Actually, higher accuracy is linked to the direct simulation of large eddies, being more difficult to model due to their anisotropic nature, while small eddies can be considered closer to isotropy and thus approximated with subgrid stress models (Andersson, 2012). In the reviewed papers dealing with LES method, the turbulence closure model adopted for small scales was always the standard Smagorinsky one, where the isotropic stress is linked to the anisotropic one through an eddy-viscosity approximation (Andersson, 2012). However, the cost for improved modeling performance is a longer simulation time and a finer refinement of the computational mesh (Padgett et al., 2020; Pope, 2001). Since the correct assessment of flow suitability for fish passage is related to highly turbulent zones in the pools (e.g. near a slot, weir, orifice or baffle), and fish responses depend on the instantaneous features of the flow field, the increase in computational resources is often needed for a more accurate assessment on how well the structure functions (Silva et al., 2012). In addition, some specific hydrodynamic and biological applications, such as studying the impact of non-uniformity at flow boundaries (Fuentes-Pérez et al., 2018), and the use of the IPOS (turbulence intensity, periodicity, orientation and scale) framework (Roth et al., 2022), require LES simulation as the level of turbulence detail provided by other methods would be insufficient.

A way to overcome the limitations of both methods is to adopt a hybrid approximation between RANS and LES, called Detached Eddy Simulation (DES). This approach takes the best features of both models and keeps computational mesh requirements moderate, switching between the two models according to the distance from the solid boundaries (Mahl et al., 2021). Blending the application of LES in free flow and RANS in the proximity of a wall (Gisen et al., 2017), DES provides improved simulation results both in terms of quality of the flow fields (higher level of details in the turbulent scales and time-varying parameters can be reached with respect to RANS) and of computational efforts (lower run times are needed compared to pure LES) (Roth et al., 2022). However, the detached eddy simulation method was poorly tested in the reviewed literature (0.8% of the papers) being applied only to study the suitability of two VSF configurations with the IPOS framework (Roth et al., 2022). Considering the several advantages of the DES model and possible improved outcomes, this approach may be suitable for future applications that require a high level of detail in the description of the turbulent flow features at an overall more efficient use of computational resources.

The remaining 13.4% did not specify the adopted approach to simulate the equations of motion. Most of these papers were also not focused on the application of CFD to study the flow, but used it as a backup to check for the correct flow representation in laboratory or field experiments (e.g. Abdelaziz et al., 2013; Oertel & Schlenkhoff, 2012; Plymesser & Cahoon, 2017).

In general, selecting the turbulence model that best fits a specific configuration is considered as one of the principal challenges in numerical modeling (Benchikh Le Hocine et al., 2019; Duguay et al., 2017). The complexity of the physical phenomena together with the variety of the possible geometry layouts requires significant modeler competence. However, some general evaluations may be undertaken. Since LES models aim to represent three-dimensional time varying flow fields, more detail and precision is required in the model setup, as well as a longer process for mesh construction and validation - compared to RANS - and time to achieve a converged solution (Quaresma et al., 2018). Therefore, while LES application is restricted to more specific experiments and research fields, at a smaller spatial scale, RANS are able to reach solution convergence even with a coarser mesh, making this method more suitable for large models and more flexible for general fishway applications (Fuentes-Pérez et al., 2018). Moreover, underestimation, overestimation and errors are always possible, especially for high discharges and hydrodynamically complex scenarios, emphasizing the need to always ensure adequate validation of the numerical model.

3.6 SOFTWARE

In addition to the equations of motion, software choice is another important step in numerical modeling. In general, most of the authors relied on well-known simulators (licensed or open source), as custom-made codes, even if tailored for the case study, require considerable effort to produce a result that does not significantly differ in modeling accuracy from the one produced by other known software (Stamou et al., 2018).

Commercial licensed codes were used in more than half (52.5%) of the paper collection, with FLOW-3D and Ansys (Fluent and CFX) being the most common choices (Fig. 6). In addition to providing a handy and straightforward modeling environment, they have the advantage of being widely applied, tested and verified in a large number of different studies and applications (Khan, 2006). Despite an adequate quality in results is nowadays granted by both commercial and open-source software, the former bestow more user-friendliness to readily generate grids of different shapes and geometries, making them suitable for a wide range of applications and still often preferred over open-source ones (Fuentes-Pérez et al., 2022).

However, the access to the source script is restricted in commercial software, and licensing fees often represent a factor limiting use (Duguay et al., 2017). Open source codes overcome these issues with no license fees, and a complete and free access to the source code, which can then be adjusted and modified according to the specific needs of the researcher. Several studies (19%) showed the implementation of open source software, with OpenFOAM (12.4%) and DualSPHysics (4.4%) being the most used ones (Fig. 6). OpenFOAM was successfully applied to study the flow field within both vertical slot, pool and weir and nature-like fishways (e.g. Duguay et al., 2017; Miranda et al., 2021; Santos et al., 2022). Also, DualSPHysics was applied to study the flow field in vertical slot and nature-like fishways, according to the SPH method, and it delivered suitable results in both cases (e.g. Gomes et al., 2022; Novak et al., 2021). The main drawback of open source codes, to date, is the computational mesh generation process. While in licensed codes the mesh construction is semi-automatic and handled directly within the modeling environment, in open source codes it often relies on external meshing programs with a manual and iterative procedure (Fuentes-Pérez et al., 2022).

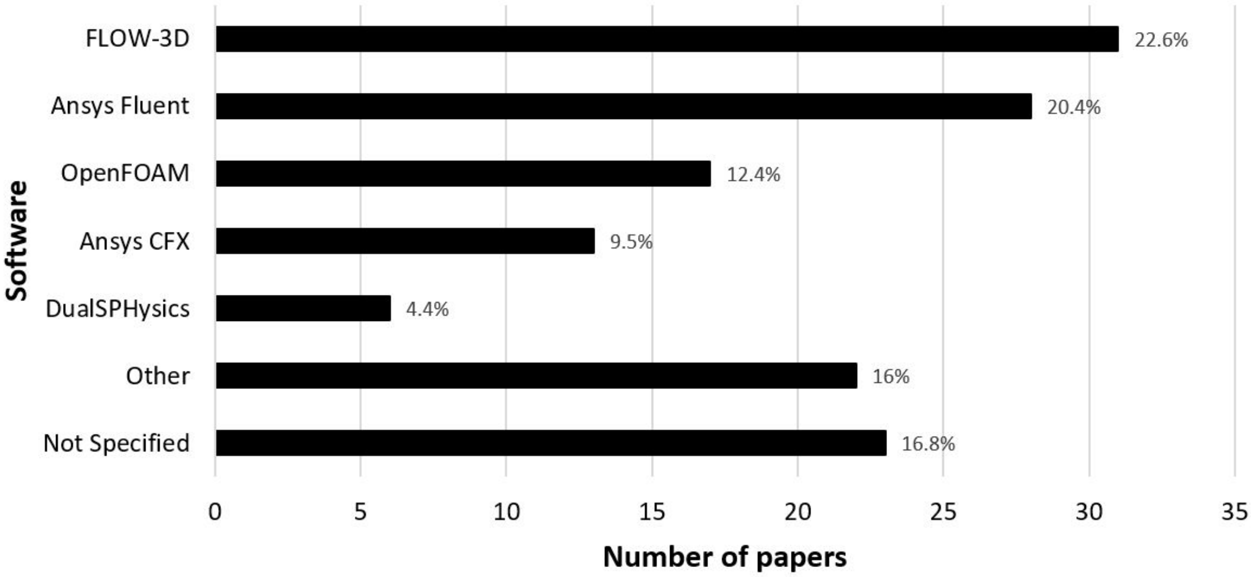

Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code (EFDC), FENFLOSS, Hydro3D, IBER, MIKE 3FM, PCFLOW2D, River2D, SSIIM, Star-CCM+, Star-CD, TELEMAC-2D and XFlow. Not Specified includes papers where the applied software name was not made explicit. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one software contributed to the count for each software dealt with.

Some other numerical codes (16%), both commercial and open-source, were also found in this review effort (Fig. 6). They consisted of 1D, 2D or 3D codes, whose number of applications was not considered sufficient to count them as a distinct software category within the database. The 3D codes were used in 9.5% of the papers and were: Environmental Fluid Dynamic Code (EFDC), FENFLOSS, Hydro3D, MIKE 3FM, SSIIM, Star-CCM+, Star-CD and XFlow. The 2D codes were used in 6.5% of the papers and were: CCHE2D, IBER, PCFLOW2D, River2D and TELEMAC-2D. The 1D codes were used in 1.5% of the cases, in combination with OpenFOAM and Ansys Fluent: in the former case HEC-RAS was used, while the latter did not specify the used software. Finally, in 16.8% of the collection a numerical code was applied without specifying the software name (Fig. 6).

3.7 FISHWAY SUITABILITY ASSESSMENT

Hydrodynamics is a fundamental part in assessing the effectiveness of a fish passage structure and several approaches, set of equations, and numerical software were shown in the previous sections to describe different kinds of applicable procedures to define flow field properties in a reliable way. The realistic definition of the flow features, reflecting the physical process occurring in a built structure, constitutes a necessary step in the analysis of fish passages but it is obviously important to also consider how fish respond to flow. Knowledge about species specific physiology, biology and ecology is fundamental. In particular, identifying numerical reference values for hydrodynamic parameters that link turbulence metrics to fish swimming capability and behavior is a vital need for the design and construction of well-functioning, efficient fishways (Silva et al., 2018).

Since the suitability assessment of a fishway is of primary interest, how fish were considered within the CFD studies was a significant topic for analysis (Fig. 7).

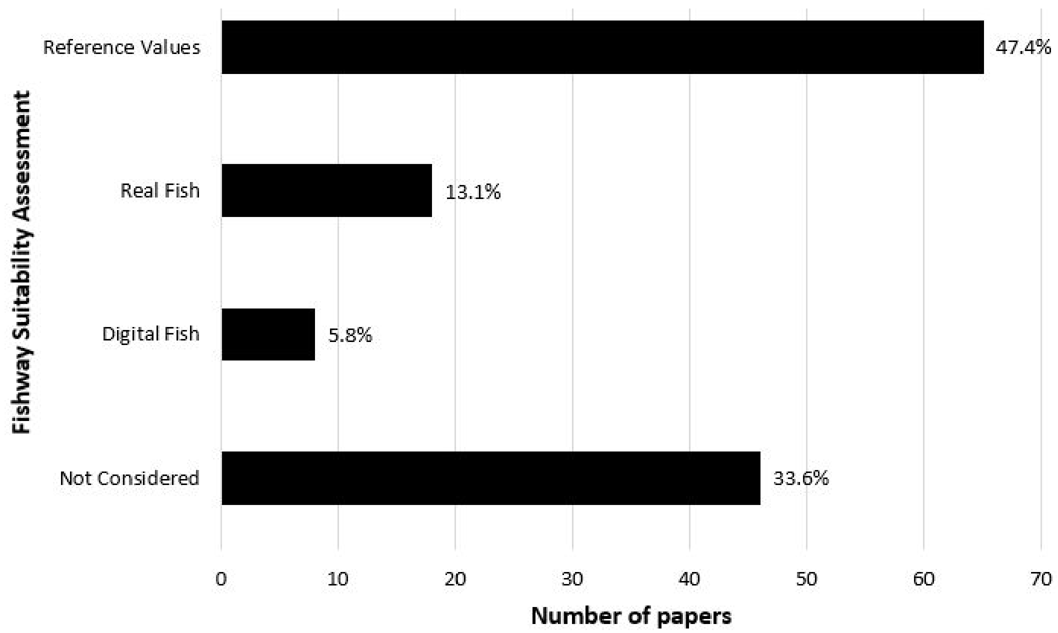

Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. Digital Fish: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; Real Fish: coupling numerical simulation with a parallel direct experiment testing fish response to the flow; Reference Values: comparison between numerically generated flow field and hydrodynamic reference values from the literature - proxy for fish swimming abilities; Not Considered: papers without any reference to fish movement patterns, swimming efforts, or literature values. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one of the detected methods contributed to the count for each method dealt with.

The results show that more than two thirds of the paper collection (66.3%) included fish in the study (Fig. 7), in the following ways:

1. *Digital fish* (5.8%), i.e. application of an individual based model (IBM) to virtually reproduce the movement and trajectories of a “digital fish” inside a previously numerically computed flow field (e.g. Kulic et al., 2021; Zielinski et al., 2018).
2. *Real fish* (13.1%), i.e. direct test of fish swimming inside an experimental setup or a real structure (e.g. Gao et al., 2016; Haselbauer & Martinez, 2007).
3. *Reference values* (47.4%), i.e. suitability assessment of the flow, via comparison of hydrodynamic metrics with related literature reference values available for the target fish (e.g. Quaranta et al., 2019; Zhu et al., 2020).

The first approach (5.8% of the papers) developed and incorporated a numerical algorithm within a CFD computed velocity field to virtually reproduce the behavior of an individual fish. A “numerical fish” (Individual Based Model, IBM) was defined, considering both environmental and biological stimuli acting on an average fish, in an attempt to simulate the internal sensory process that fish may use to decide how to respond in a flow field (Gao et al., 2016). The fish algorithm was always based on real fish trajectories in hydrodynamic environments obtained from other studies, and the final trajectories obtained numerically were challenged ex-post with real trajectories from real life studies in the same fishway.

The second approach (13.1% of the paper collection) consisted of coupling numerical modeling of the flow with experiments where real fish were directly tested, either in the laboratory using a physical model or a flume, or in a field experiment with an existing fish pass. Within this category, in 77.8% of the cases fish were tested in a laboratory experiment, while in the remaining 22.2% they were observed in a real facility. Fish observations were mainly performed through videorecording (45%), Passive Integrated Transponder (PIT) telemetry techniques (15%) or visual inspection by operators (25%) - with some cases where a combination of approaches was adopted: PIT telemetry and videorecording (5%), digital fish and videorecording (10%). The experiments were generally followed by a data post-processing phase, including video examination and analysis (e.g. Amaral et al., 2019), PIT tag sequences detection (e.g. Lewandoski et al., 2021), or blood test analysis from a previous study (e.g. Shahabi et al., 2021, 2023) to define fish trajectories within the flow, energy expenditure, accumulated stress or other fish-relevant parameters. In papers where fish were visually observed by human operators (e.g. Romão et al., 2021) the standard procedure was to manually count fish passing through a specific location.

Species families represented in the references collected were mainly *Cyprinidae* (63.8%), followed by *Anguillidae* (6.3%) and *Cobitidae* (4.2%). The rest of the families (25.7%) were all fish (*Salmonidae, Catostomidae, Galaxiidae, Characidae, Anostomidae, Leuciscidae, Oxudercidae*), except one shrimp (*Palaemonidae*) and one lamprey (*Petromyzontidae)*. The most studied species was the Iberian barbel (*Luciobarbus bocagei*), with 21.3% of the publications, followed by grass carp (*Ctenopharyngodon idella*), 16.7%, and Japanese eel (*Anguilla japonica),* 6.3%. An additional 22 species were represented but just tested once (2.4%), but together making up 55.7% of the papers. Tab. 1 lists all the species found in the collection that were really tested in an experiment (category *Real Fish*).

Tab. 1 - List of the different species tested in real life experiments within the collection (category Real Fish). Both common and scientific names of the species are shown, together with the percentage of occurrence of each species (values relative to the category Real Fish). The percentage of occurrence indicated in the last row is relative to each species listed.

Species	Papers Occurrence
Iberian barbel (*Luciobarbus bocagei*)	21.3%
Grass carp (*Ctenopharyngodon idella*)	16.7%
Japanese eel (*Anguilla japonica*)	6.3%
Algae shrimp (*Macrobrachium japonicum*), Bighead carp (*Hypophthalmichthys nobilis*), Brown trout (*Salmo trutta*), Cebacek (*Pseudorasbora parva*), Common galaxias (*Galaxias maculatus*), Gitterorfe (*Acrossochelius paradoxus*), *Gobiobotia intermedia*, Iberian straightmouth nase (*Pseudochondrostoma polylepis*), Lambari (*Astyanax bimaculatus*), Piau (*Leporinus reinhardti*), sea lamprey (*Petromyzon marinus*), silver carp (*Hypophthalmichthys molitrix*), south Iberian barbel (*Luciobarbus sclateri*), south Iberian chub (*Squalius pyrenaicus*), *Spinibarbus hollandi*, Stone loach (three species: *Triplophysa leptosome*, *Triplophysa wuweiensis*, *Triplophysa yarkandensis*), Taiwanese freshwater goby (*Rhinogobius candidius*), white sucker (*Catostomus commersonii*), Ya-fish (*Schizothorax prenanti*), *Zacco pachycephalus*	2.4%

In the third approach, the suitability analysis of the flow of numerically conducted studies was assessed against reference values relating to flow velocity and turbulence. Hydrodynamic metrics and related reference values (Tab. 2 for a non-exhaustive but representative list) found in the scientific literature for the target fish species were discussed and compared with the CFD model results in 47.4% of the complete collection of papers (71.5% of papers considering fish). Flow velocity was used as a reference value to assess passage suitability in 98.4% of these papers. Flow velocity represents a crucial parameter to assess fish passage suitability, as it relates to the limited capacity of fish for speed and endurance (Katopodis and Gervais 2016). Fish ability to navigate through and overcome flow velocities, depends on its distribution and absolute values, particularly near slot or orifice openings and within the pools for adequate fish resting zones (Cea et al., 2007; Quaranta et al., 2019). With regards to turbulence metrics 63.4% of the papers considered Turbulent Kinetic Energy (TKE), whose excessive values could increase swimming energy and confuse fish (Quaranta et al., 2017; Santos et al. 2012; Li P. et al. 2021), while two-fifths of the papers (39.7%) applied the Volumetric Power Dissipation (P) - inherently linked to the suitability of recirculation zones in the pools (Quaranta et al., 2017) - and 14.3% used Reynolds Shear Stress (RSS), as it can affect fish stability and even lead to injuries or mortality (Silva et al., 2012). Additional turbulence related parameters that may also be considered for suitability evaluation, such as flow vorticity, eddy sizes and their orientation, were seldom used in the analyzed papers. For example, just 12.7% included vorticity in the analysis and just 1.6% provided a discussion on eddy features using the IPOS framework (i.e. Roth et al., 2022). Moreover, 6.3% included an analysis on the pressure distribution within the flow near baffles and solid surfaces (e.g. Zeng et al., 2022).

Tab. 2 – Non-exhaustive list of the most common hydrodynamic metrics and related tested reference values in fishway literature. The following parameters of the flow are reported: Velocity (V), Turbulent Kinetic Energy (TKE), Reynolds Shear Stress (RSS), Volumetric Power Dissipation (P) and Eddy Size. The common and scientific names of species, the average body size with standard deviation - Total Length (TL) or Fork Length (FL) -, the context where the reference numerical value was detected and the scientific reference paper the parameter values were obtained from are listed.

Metric	Tested Reference Values	Fish Species	Fish Size	Experimental Environment	Reference
V	Preference for zones with **0.2 < V < 0.4 m/s**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	Condition that 30-50% of the pool volume must be kept with **V < 0.3 m/s**.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Passage preference in zones close to the side walls with **0.1 < V < 0.3 m/s**.	Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm	Experimental VSF	Li G. et al. (2021)
	Avoidance of dam tailrace areas with velocities higher than **V > 2.4 m/s**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
TKE	Preference for areas (close to the flume bottom) with **TKE < 0.05 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	TKE > 0.05 m^2/s^2 categorized as high **TKE < 0.05 m^2/s^2** categorized as low within the turning pools.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Barbel performed better also for **0.061 < TKE < 0.071 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	17.2 < TL < 26cm	Experimental VSF with two different slot configurations (lateral and central baffle)	Romão et al. (2017)
	Chub performed an higher number of upstream movements in the lateral baffle configuration with **TKE < 0.059 m^2/s^2** (maximum value).	South iberian chub (*Squalius pyrenaicus*)	11.1 < TL < 15.4cm		
	Preference for **TKE < 0.05 m^2/s^2**.	Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguay et al. (2018)
	Preference for the substrate configuration with **TKE < 0.25 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 17.4 ± 2cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
	Preference for **TKE < 0.03 m^2/s^2** (inhibited at **TKE = 0.24 m^2/s^2**).	Atlantic salmon smolts (*Salmo solar*)	TL = 14.70 ± 1.05cm	In Situ and CFD study of an Hydropower plant intake race	Silva et al. (2020)
	Passage preference in zones close to the side walls with **TKE < 0.015 m^2/s^2**.	Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm	Experimental VSF	Li G. et al. (2021)
	Preference for pool resting zones with **TKE < 0.063 m^2/s^2**.	Rainbow trout (*Oncorhynchus mykiss*)	TL = 15 ± 3cm	Pool and Weir fishway (with W-weirs)	Shahabi et al. (2021)
	Avoidance of dam tailrace areas with **TKE > 0.12 m^2/s^2**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
RSS	Injuries/Mortality for **RSS > 700 N/m^2**.	Juvenile Coho salmon (*Oncorhynchus kisutch*)	/	CFD and In Situ study of turbine mortality	Čada et al. (2006)
	Experimental range: **0.02 < RSS < 73.4 N/m^2**. No damage observed within the range but disorientation/displacements occurred.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
	Fish spent less time in areas close to **RSS = 60 N/m^2** (experiment range: 20 < RSS < 60 N/m^2).	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	Avoidance of dam tailrace areas with **RSS > 21 N/m^2**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
P	**P = 150-200 W/m^3**	Salmonids	/	Pool-type fishways	Larinier (2002)
	P = 100-150 W/m^3	Cyprinids	/	Pool-type fishways	Larinier (2002)
	P < 100 W/m^3	Weak swimmers	/	Pool-type fishways	Larinier (2002)
Eddy Size	Instability when **Eddy Size > 76%** fish body length.	Creek chub (*Semotilus atromaculatus*)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Tritico & Cotel (2010)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguay et al. (2018)
	Spatially averaged turbulent length scale range was: **0.42 - 0.64m**. It was comparable with sea lamprey total length affecting stability in the flow.	Sea lamprey (*Petromyzon marinus*)	TL = 47 ± 4cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)
		White sucker (*Catostomus commersonii*)	TL = 29 ± 7cm		

One third of the paper collection focused solely on the description of the flow field hydrodynamics without any reference to fish movement patterns, swimming efforts, or literature reference values (Fig. 7). These papers were categorized as *Not Considered*, as they were either limited to just pure hydraulic analysis of the flow (e.g. assessing the most suitable set of hydrodynamics equations to depict the flow field in a fishway), or the discussion about fish and flow suitability was excessively vague and qualitative to be included in one of the other categories. *Not Considered* was the second highest category (Fig. 7), highlighting that lack of integrating knowledge on fish abilities and responses to hydrodynamics persists as a substantial deficiency in the international literature. This identifies a priority research area for future CFD studies or applications. Actually, several papers from the complete collection (30%) explicitly recognized that aspects related to fish movement and behavior need additional investigation for more realistic fish passage assessments (e.g. Amaral et al., 2019; Mao et al., 2012; Zhao et al., 2022). Fish movements and trajectories in real structures, as well as the identification of additional reference levels for hydrodynamic parameters for an increasing number of different species and consequent coupling with relevant flow field characteristics, is a crucial aspect in the design of more efficient river connectivity remedial measures.

4. CONCLUSIONS

This study provides an up-to-date overview of the application of Computational Fluid Dynamics (CFD) in relation to hydrodynamic analysis and suitability assessment of fishways for upstream migration. A systematic review of the available literature to the end of 2023 was undertaken, and the following conclusions were drawn:

1) The number of numerical studies significantly increased in the last 8 years (2016-2023), following recent technological advancements, with a higher number of studies on technical fishways than on nature-like ones. Among the technical structures, Vertical Slot Fishway (VSF) was the most recurrent typology, followed by Pool and Weir (PW). Among the Nature-Like solutions (NLF), rock ramps were the primal focus, followed by bypass channels.
2) Different modeling procedures were identified, based on whether the numerical model was used alone or coupled with other laboratory or field experiments (i.e. hybrid modeling). Hybrid modeling was the most frequent approach, owning to the benefit of overcoming some of the inherent limitations of physical or numerical models when applied separately, and allowing for a more direct validation of both models to increase result robustness (Leng & Chanson, 2020c). Purely numerical models show several cost advantages such as saving time and money, providing flexibility in applying geometry changes to the examined fish passage structures and offering a timely design process, as long as an appropriate validation process is carried out to check for the reliability of the output.
3) Three-dimensional CFD is fundamental to fully reproduce the physical phenomena within fishways, as the effectiveness of a fishway depends greatly on zones where the flow is highly turbulent and fast (Cea et al., 2007). However, in a few special cases (e.g. low slope VSFs), the flow may be considered bidimensional and a 2D model may yield acceptable results, saving computational time (Stamou et al., 2018). One dimensional models are often inappropriate as they consider just the longitudinal component of velocity and do not allow for a complete simulation of the flow field in fishways, but they can be useful in a preliminary phase to define

input parameters prior to the application of a more sophisticated model (Fuentes-Pérez et al., 2018).

4) Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently used set of equations to describe hydrodynamics, striking a balance between accuracy and computational cost, and may be suitable for fishway applications despite some limitations in turbulent parameter assessment (Chorda et al., 2010). Large Eddy Simulation (LES) is preferred for highly turbulent zones but requires higher computational resources (Padgett et al., 2020). Detached Eddy Simulation (DES), largely overcomes the limitations of the two previous computational schemes, combining the application of LES in the bulk flow and of RANS closer to walls for improved simulations (Gisen et al., 2017), yet it was poorly represented in the reviewed CFD studies. More frequent use of this method is suggested for an overall more efficient use of computational resources.
5) Well-known commercial software were predominantly represented in the collection, compared to open-source or custom-made codes, because of their user-friendly interfaces and convenient handiness in the meshing process (Fuentes-Pérez et al., 2022). Despite such advantages, licensing fee requirements and customizing limitations, prompted several researchers to explore the possibilities of open-source software, that represent a cost-free alternative with complete access to the source code and more scripting flexibility (Duguay et al., 2017).
6) Suitability for fish passage in numerical studies of fishways was performed following three main approaches: a) reproducing fish behavior and decision-making process virtually, through IBM algorithms; b) testing and monitoring with live fish experiments in laboratory or field studies; and c) comparing obtained flow fields to literature hydrodynamic reference values relative to target fish species. The analysis revealed that the latter approach was the most frequent and, therefore, the combination with a direct counterpart experiment is often missing in most fishway CFD investigations.

In general, our findings reveal increasing and widespread use of CFD in fishway science and show CFD is a potentially powerful tool for studying and improving the efficiency of fish passage solutions. Reliability has grown substantially with recent advancements in computer science and computational power, allowing fish ecology researchers and fishway designers to test old and new geometry configurations at relatively low cost (Heimerl et al., 2008). Despite the higher reliability, accessibility and time-saving use of numerical modeling, compared to laboratory or field experiments, adequate expertise on numerical software and simulated physical phenomena are required to use the correct equations and computational approximation techniques (Leng & Chanson, 2020c). Awareness about what and how well the hydrodynamic environment is simulated, as well as ensuring an appropriate model validation procedure, are crucial to obtain realistic and accurate results (Leng & Chanson, 2020b). With an aim to maximize efficiency for upstream passage of all fish willing to overcome a river obstacle, there is an urgent need for further study of the interactions between fish movement behavior and hydrodynamic features, especially turbulence, in real fishways or laboratory models. In particular, most needed are innovative studies that link fish trajectories with relevant hydrodynamic metrics encountered along routes of movement, to identify preferred values and thresholds not to be exceeded (Silva et al., 2012, 2018). Such research represents a promising way to expand the currently limited knowledge for a larger number of fish species and life-stages and obtain valuable data for designing more efficient fishways with the support of CFD.

ACKNOWLEDGEMENTS

This specific research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available as Supplementary Material.

Author contribution statement

FT, CC and CK conceived the idea presented. FT collected and analyzed the papers. FT wrote the manuscript with support from CC, CK and DN. All authors discussed the results and contributed to the final manuscript.

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Computational Fluid Dynamics in fishway research - a systematic review on upstream fish passage solutions

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RUNNING HEAD: Use of Computational Fluid Dynamics in fishway research

ABSTRACT

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to model the dynamic behavior of fluids, and it is increasingly applied in the study of fishways, allowing flexible, timesaving, and low-cost analysis of flow fields. Applications and methodologies, however, vary substantially between different scientific studies and no overview is currently available in the primary literature. Here we review published papers on CFD use in upstream fish passage solutions to identify and describe related spatial-temporal considerations, application fields, scopes and modeling procedures. Vertical slot was the most studied fishway type, followed by nature-like fishways and pool and weir fishways. Most often the CFD model was coupled with laboratory or field experiments, but only sometimes associated with actual fish behavior (observations or values from ~~the~~ literature). Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently adopted set of equations, followed by Large Eddy Simulation (LES), but other promising approaches - scarcely applied so far - were also identified and suggested for future applications - e.g. Detached Eddy Simulation (DES). In general, the use of commercial software was prevalent compared to open-source, with Ansys (Fluent and CFX) and FLOW-3D being the most common softwares. The importance of model validation is highlighted, especially for merely numerical studies, together with the need for three-dimensional CFD to correctly represent the features of turbulent flows. Overall, ecohydraulic studies on the interaction between fish movements and hydrodynamics are needed to complement the CFD-analysis and improve the design of more efficient fish passage solutions.

Keywords: CFD, ecohydraulics, fish pass, hydrodynamic modeling, numerical simulation, turbulence

1. INTRODUCTION

Hydropower production is one of the most accessible and reliable sources of renewable energy in the world (Brown et al., 2011). Hydroelectric production, however, comes with a high cost for the ecology in rivers and beyond ~~(Olden et al., 2015; Vezza et al., 2014; Wu et al., 2019)~~(Olden et al., 2015; Vezza et al., 2014; Wu et al., 2019). For mobile and migratory species, especially fish, dams and reservoirs constitute an anthropogenic barrier for their natural upstream and downstream movements (Lucas & Baras, 2001). Currently, river fragmentation and consequent alteration of natural flow regimes is considered as one of the main causes of decline in freshwater ecosystem complexity and biodiversity (Dudgeon et al., 2006; Sparks, 1995), with half of the rivers on Earth negatively affected by dams (Nilsson et al. 2005).

When dam removal is not an option, other remedial strategies are necessary to restore river ecology (Katopodis & Williams, 2012; Silva et al., 2018). One of the most widespread solutions to restore longitudinal connectivity is represented by fishways, engineering solutions that create an ecological corridor to allow fish to pass barriers (Clay, 1995; Larinier, 2002). There are many types and shapes of these structures, but they can be generally divided into technical and nature-like fishways (Schmutz & Mielach, 2013). Technical fishways allow fish to overcome the drop created by the dam, through a sloping channel split into a sequence of compartments by dividing walls, creating less abrupt hydrodynamic conditions that are intended to be suitable for the movements of target species (Katopodis, 2005). Nature-like fishways, on the other hand, are low-slope bypass channels that mimic the natural conditions of a small water course connecting the original river upstream and downstream of the obstacle, or rock ramps mimicking river rapids. Fishway effectiveness depends on how well species abilities are matched with generated hydrodynamics within these structures as well as at fish entrances (Hershey, 2021; Katopodis, 2005). Typically, nature-like fishways, due to their more gentle and diversified flow fields, are usually easier for the fish to pass while limits in the available space often make their entrance more distant from the obstacle and therefore harder to find for upstream moving fish, compared to technical fishways (Hershey, 2021; Katopodis, 2005; Kelley et al., 2023).

The functionality of a fishway, is the result of a series of events involving fish swimming capability and behavior in encountered visual, acoustic and hydrodynamic conditions (Mawer et al., 2023; Silva et al., 2018; Williams et al., 2012). Hydrodynamics and, more specifically, velocity and turbulent conditions are considered the main drivers of fish passage performance (Goodwin et al., 2006; Katopodis, 2005; Tan et al., 2018). Indeed, special consideration has always been given to the description and analysis of the flow field inside a fishway (Katopodis, 1992). In the past, this was performed by taking measurements (typically of the velocity field) inside real facilities or by creating physical models in a laboratory environment (Katopodis, 1992; Leroy et al., 2018). With the recent technological advancements in computer science, the use of numerical models for fishway analysis has progressively become more accessible and reliable (Amaral et al., 2019; Stamou et al., 2018). In particular, the reduction in simulation times and increase in processing capacity has led to a widespread application of Computational Fluid Dynamics (CFD) to address fishway design issues ~~(Barton et al., 2009; Duguay et al., 2017; Shahabi et al., 2023)~~(Barton et al., 2009; Duguay et al., 2017; Shahabi et al., 2023).

CFD is a numerical technique that solves the complex equations of fluid motion in various environmental contexts (Bates et al., 2005). The model consists of the definition and discretization of a computational geometry in elementary particles (meshless methods) or cells (meshed method), the application of boundary conditions at the inlet and outlet of the model, and the solution of the equations of motion within the discretized volume (Andersson, 2012). By using CFD-models, the flow can be described, and its hydrodynamic characteristics may be analyzed with only the known discharge, water levels and the geometry of the fishway (Andersson, 2012).

The application of CFD for fishways allows testing of different geometrical configurations and flow conditions with flexibility and at low cost (An et al., 2016; Bates et al., 2005). There is no widely recognized standard procedure to simulate the flow inside fishways with CFD. Each study makes particular modeling choices based on the expertise of the software user (Andersson, 2012; Leng & Chanson, 2020b), and a systematic overview of methods applied is lacking. In this context, the main objective of this paper is to elucidate the current state-of-the-art relative to the application of ~~computational fluid dynamics~~CFD related to fishways by identifying, analyzing and critically reviewing available primary literature. Specifically, we summarize spatial-temporal parameters, scope and application fields, modeling procedures and approximations related to the use of CFD in fishways. We limited the review to upstream migration solutions and internal flow field analysis, as numerical modeling applications for fishway entrance positioning (e.g. Andersson et al., 2016; Lindberg et al., 2013) and downstream passage (e.g. Feigenwinter et al., 2019; Zöschg et al., 2023) are still few, more site-specific, and not easily classifiable.

2. METHODS

A complete search of the available primary scientific literature on CFD and fishways was conducted on *Scopus* and *Web of Science* databases. The collection encompassed all the literature available in the two engines up until the end of 2023. The initial search and identification of papers were performed through the definition of a series of keywords, including general terms relating to numerical modeling, hydrodynamics and fishways: ~~*fishway,*~~ *CFD, computational fluid dynamics, fish ladder, fish pass, fish passage,* ~~*computational fluid dynamics, CFD, hydrodynamics,*~~ *fishway, hydrodynamic modeling, hydrodynamics, numerical simulation*. All the possible (meaningful) permutations of these words were explored, and the abstract of each paper was read to identify those that were suitable for this study. A paper was considered relevant only if dealing with a numerical model used to study the hydrodynamics within an upstream fish passage solution, and in that case the full manuscript was then read for further analysis. Papers unavailable online or not written in English were excluded from the study. When reading the selected full manuscripts, if referenced relevant papers that had not emerged in the search query were found, they were also included in the collection of papers.

The analysis of the full manuscripts included an initial critical reading of the paper followed by the collection of selected information to fill a summary database. The database was devised to assess the different ways computational fluid dynamics was applied in analyzing the upstream fishway from different perspectives. The database included the following classification/analysis parameters:

- Year of publication of the paper
- Country (and continent) in which the study was carried out;

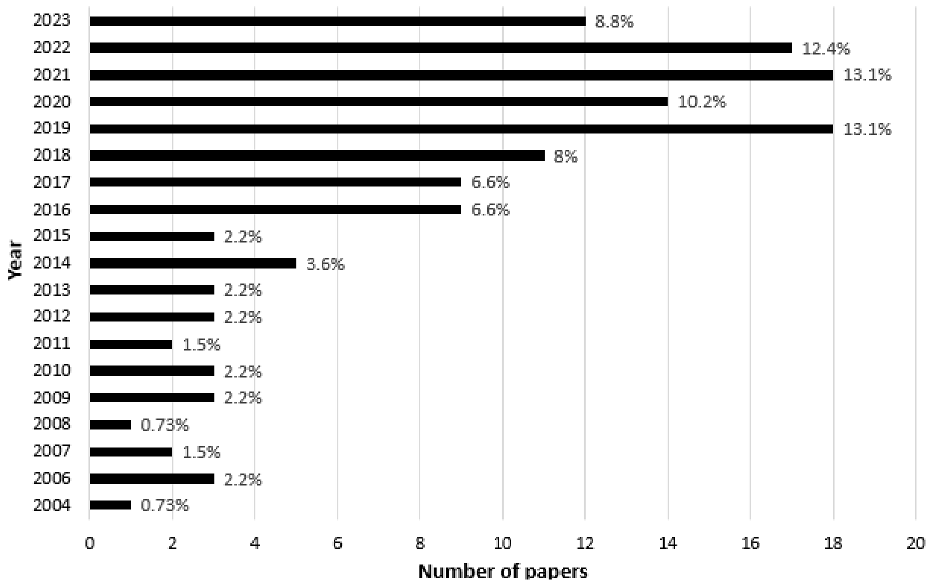
- Type of fishway studied and modeled (e.g. vertical slot, pool and weir, nature-like, etc.);
- Aim of the paper (the reason why a numerical model was used for the analysis of a fishway);
- Approach type (if the numerical model was coupled with physical experiments or applied alone);
- Equations of flow, turbulence approximation, and type of software used;
- Assessment of passage suitability (if and how fish biology and ecology were included in the study).

The database was progressively completed and analyzed in *Microsoft Excel* and can be found in the *Supplementary Material*.

3. RESULTS AND DISCUSSION

3.1 OVERVIEW

The complete paper collection consisted of 137 scientific articles published over a period of 19 years (from 2004 to 2023). The number of papers per year shows a consistent increase in the last 7-8 years (Fig. 1). In general, the number of papers focusing on applying CFD for fishway flow analysis followed the recent advancements in computation resources and power (Stamou et al., 2018). Whereas, until 2015, this number was limited to a maximum of five papers per year, more than three quarters of the collection (78.8%) were papers published from 2016 to 2023.



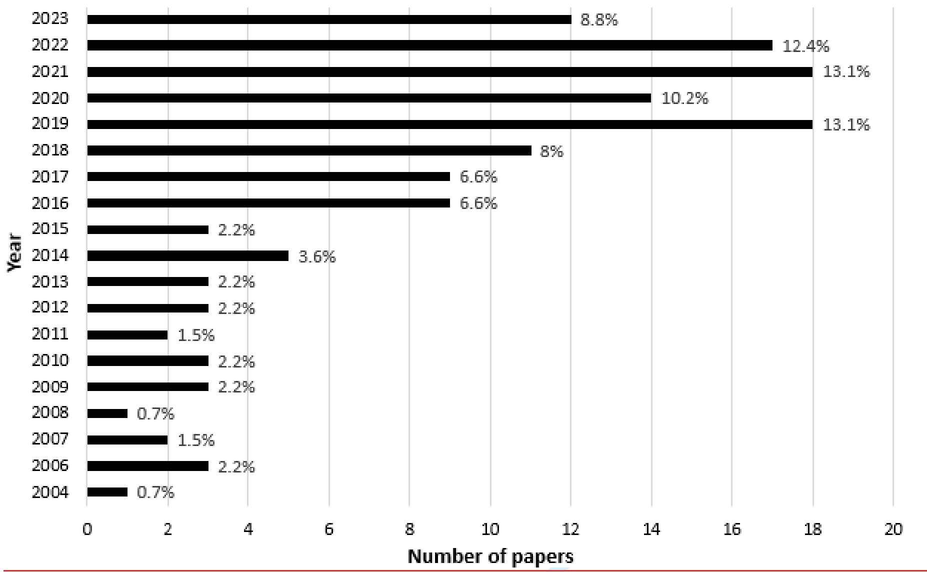


Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

CFD studies were conducted in five continents, encompassing research ~~centres~~centers (first author affiliation) from 25 different countries (Fig. 2). The leading continents were Europe (41.6%) and Asia (35%). China was the country with the highest number of papers (25.5%), followed by Canada and Germany (8%). France, Spain and USA accounted for 6.6% of the collection, followed by Slovenia (5.8%) and Brazil (5.1%). Australia, Iran and Portugal contributed with 3.6% each, while Italy, Poland, Sri Lanka and UK with 2.2%. The rest of the countries (belonging to Europe and Asia), accounted for the remaining 8% of the final sample.

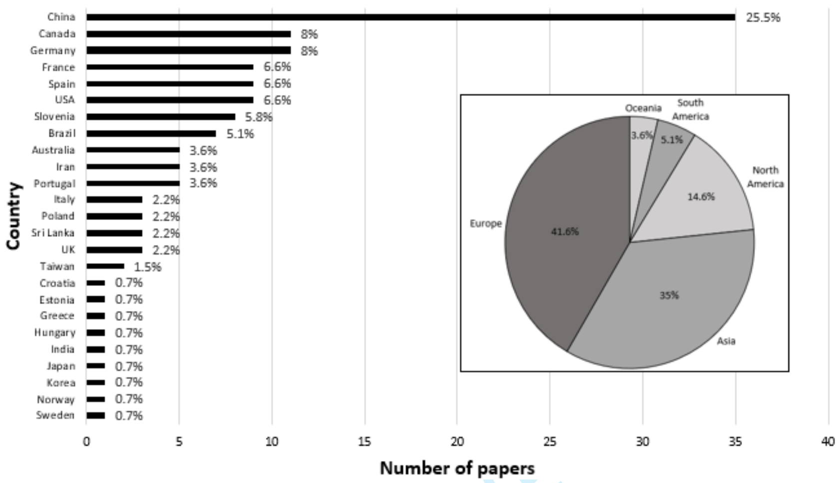


Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

3.2 TYPE OF FISHWAYS AND AIM OF THE CFD APPLICATION

As Fig. 3 indicates, technical fishways - e.g. *Vertical Slot* (VSF), *Pool and Weir* (PW) - represented the most studied types in the examined scientific literature (66.4%), while 17.1% focused on *Nature-Like* fishways (NLF) and 12.8% included various less ~~selected~~studied fishway typologies~~,~~ (i.e. Denil steeppass, eel pass, flat W-weir, island fishway, locks in dam, pole fishway, small culvert), collected under the category *Other*. In 3.6% of the collection, the structure type was not specified (Fig. 3).

The most studied fishway type was the VSF, that is considered the most effective technical measure to restore longitudinal connectivity in fragmented rivers, due to its adaptability to up- and downstream water level fluctuations, and its ability to allow fish passing through the slot at its preferred depth (Katopodis and Williams, 2012; Quaranta et al., 2017). Even though the flow pattern generated inside VSFs has been studied in both laboratory and in-situ experiments for several years (e.g. Calluaud et al., 2014; Liu et al., 2006; Rajaratnam et al., 1992; Wu et al., 1999), numerical modeling provides additional insights and a more thorough assessment of several geometry changes without the need for building physical models or experimenting with real fishways (An et al., 2016). Different types of VSF structures were studied numerically, testing the effects of different geometry additions and layout modifications. For example, Barton et al. (2009) studied the impact of a reduced slope on the flow within a VSF, Marriner et al. (2014, 2016) assessed the hydraulics of turning pools inside a larger VSF, and Romão et al. (2021) compared the efficiency of a Multi-Slot Fishway (MSF) with a standard VSF. Several studies focused on the numerical assessment of the flow in both standard and non-standard VSF layouts. Interestingly, more than one half of the entire paper collection (51.4%) was focused on VSFs (Fig. 3).

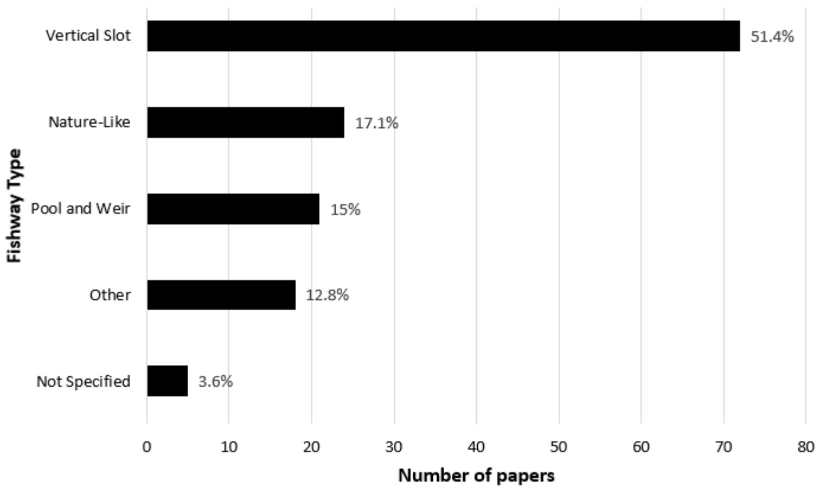


Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steeppass, eel pass, flat W-weir, ~~Island~~island fishway, ~~Locks~~locks in dam, pole fishway, small culvert), while the category Not Specified includes papers where the fishway type was not made explicit. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one fishway structure contributed to the count for each fishway type dealt with.

NLF were the second most studied type, being the main focus of 17.1% of the scrutinized papers (Fig. 3). NLF is a category that included several types of structures and layouts, mainly focused on mimicking the natural conditions inside a river (Zhou et al., 2020). Two types of NLF were identified in the examined literature: bypass channels (29.2% of NLF), with the main aim to create an alternative route simulating hydrodynamics, slope and morphology of the original river, and rock ramps (70.8% of NLF) that form a continuous path connected with the river bed and various arrangements of different sized boulders. NLF aim to obtain improved passage efficiency for a large set of species through a variability of flow patterns closer to what fish encounter in nature, compared to the more artificial and repetitive flow fields occurring in technical fishways (Katopodis, 2005). The geometry of NLFs though is typically more difficult to model numerically, as they include structures with no side walls and paths with highly irregular flows through boulders of different dimensions and shapes. Additionally, experiments conducted with idealized bed roughness configurations, such as a regular pattern of nearly spherically-shape boulders (Golpira et al., 2022) or even single hemispheres (Shamloo et al., 2001), showed that flow regimes and hydrodynamic characteristics are highly variable with discharge and submergence levels. Therefore, overall numerical modeling of NLF is a more challenging procedure and the simulation is often performed over a simplified geometry. For example, for rock ramps, boulders were modelled with a spherical shape instead of an irregular shape closer to reality (e.g. Baki et al., 2016). Similarly, the natural roughness of a bypass channel bed was simulated through Manning's approximation, quantifying the uneven river bed granulometry with a single coefficient (e.g. Tran et al., 2016).

The third most studied fish pass type was the PW, comprising 15% of the paper collection (Fig. 3). Generally considered one of the most common technical fishway built, the PW geometry consists of a series of basins divided by cross-walls, over a sloping channel, that are connected through a weir and/or an orifice (Katopodis 1992; Santos et al., 2012). Various sub-types of fish passage structures were included within this category (i.e. Ice Harbor, Pool and Orifice, Fish-Bone) and several examples of numerical applications were found: from internal flow field analysis ~~(e.g. Abdelaziz et al., 2013; Abeyratne et al., 2021; Shahabi et al., 2023)~~(e.g. Abdelaziz et al., 2013; Abeyratne et al., 2021; Shahabi et al., 2023), to testing of different layouts and geometries (e.g. Li S. et al., 2022; Zhong et al., 2021), and investigating the applicability and reliability of different modeling software (e.g. Chen & Tfwala, 2018).

Fishways types other than those in the previous three categories were also represented in the sample, including eel passes, flat W-weirs, island-type fishways, locks in dams, pole-type fishways, small culverts and Denil variants such as the Steeppass. Since the number of studies involving these kinds of structures was very small, they were grouped together in the category *Other*, and contributed to 12.8% of the papers collected (Fig. 3). Additionally, 3.6% described an application of numerical modeling for upstream fish passage purposes but without explicitly indicating the structure type - e.g. studies within a flume of different cylinder arrangements over a sloping flow channel (e.g. Chorda et al., 2019; Ducrocq et al., 2017). Since the methods and aims of these studies were overall similar to the other ones, they were included in the collection under the category *Not Specified* (Fig. 3).

The aim of each of the 137 papers (i.e. why CFD has been applied to study the internal hydrodynamics of fishways) was analyzed and subsequently classified into 7 different categories:

1. Application to theoretical fish passage geometries (experimental setups, inferences from other studies) or to non-specified existing structures, studying the relationship between modifications of the geometric layout and consequent changes in the flow field (32.8%): to assess the impact of fishway geometry changes on hydrodynamics and describe the internal hydraulic topology (e.g. Heimerl et al., 2008; Kim et al., 2012; Miranda et al., 2021).
2. Relationship between internal flow field and fish swimming ability (28.5%): to evaluate suitability of flow structure and flow parameters with respect to target fish species swimming abilities (e.g. Khan, 2006; Li M. et al., 2022; Mao et al., 2012).
3. Application to real structures (18.3%): to study the efficiency of an existing fishway (e.g. Bombač et al., 2015), to improve the geometrical design of an existing one (e.g. Bung, 2018) or to support the design phase of a new one (e.g. Song et al., 2019).
4. Suitability of different flow equations for internal fishway flow representation (7.3%): to compare different equation systems and evaluate the best option (e.g. Stamou et al., 2018) or to assess the suitability of the hydraulic model under determined hydrodynamic conditions (e.g. Barton et al., 2009).
5. Comparison of different fish passage structures (5.1%): to evaluate which was the best option for a specific location or fish reference zone (e.g. Klein & Oertel, 2015; Quaresma et al., 2018).
6. Choice of the appropriate turbulence closure model (5.8%): application of different turbulence approximation equations with respect to the same structure and evaluation of the best option (e.g. Cea et al., 2007; Santos et al., 2022).
7. Software performance comparisons (2.2%): application of different computational software (commercial and open source) to simulate the flow inside the same fishway and evaluate the most suitable choice (e.g. Duguay et al., 2017; Fuentes-Pérez et al., 2022).

3.3 MODELING APPROACHES

The different ways numerical modeling was used to study fishways were classified, considering if the numerical model was applied alone or coupled with another type of experiment or field activity (e.g. flume, real fishway or physical model), into the following 3 categories (Fig. 4):

1. *Numerical* (41.6%): the internal flow field was examined only by numerical means (e.g. Ballu et al., 2018; Padgett et al., 2020; Plymesser & Cahoon, 2017).
2. *Numerical and In Situ* (10.9%): the numerical model was coupled with field measurements inside a real structure (e.g. Bravo-Córdoba et al., 2021; Marriner et al., 2014).
3. *Numerical and Laboratory Experiment* (47.4%):
    a. *Flume* (41.6% - within the category): the numerical study was coupled with simplified experiments conducted inside a rectilinear flume (e.g. Abeyratne et al., 2021; Kim et al., 2012; Miranda et al., 2021).
    b. *Physical Model* (58.4% - within the category): the numerical model was coupled with measurements conducted in an ad-hoc reproduction of a real structure (e.g. Lewandoski et al., 2021; Oertel & Schlenkhoff, 2012).

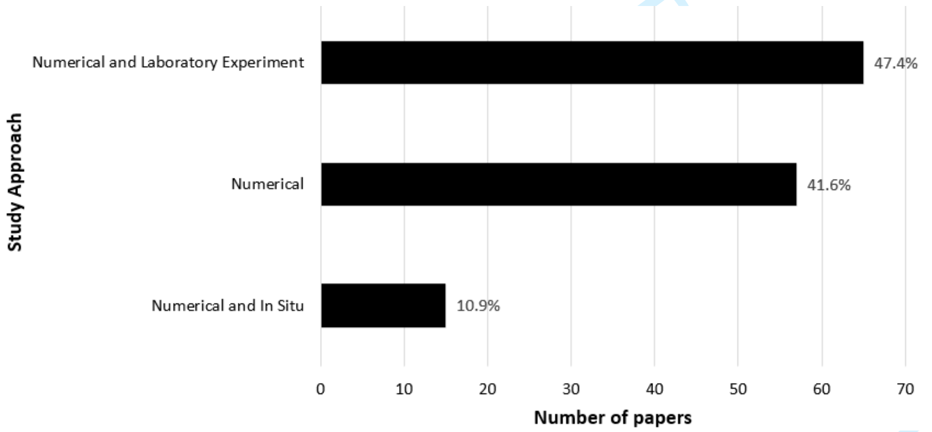


Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated in the figure.

In more than half of the collection of papers (58.3%) numerical models were coupled with laboratory, either flume or physical model, or field experiment. This process, commonly called hybrid modeling, is mutually beneficial to both physical and numerical approaches (Bung, 2018; Leng & Chanson, 2020b). Results from physical experiments are based on the reconstruction of the flow field features through the interpolation of a finite number of sampling velocity points and are, therefore, limited by the maximum resolution obtainable in the interpolated raster (Roth et al., 2022). Numerical methods offer the possibility to overcome this resolution limit with high quality vectorial fields, if an adequately dense computational grid and a suitable closure model to simulate turbulence phenomena are provided. For example, when it comes to the analysis of turbulent flow, the availability of high quality flow fields is crucial to properly identify the sizes of eddies, as they constitute a potential source of hindrance and loss of balance for fish inside the flow (Lacey et al., 2012; Silva et al. 2012). Additionally, CFD generates the full flow field distribution, and allows a quick and low cost implementation of geometry changes and flow conditions (An et al., 2016; Heimerl et al., 2008). In contrast, sufficiently detailed hydrometric measurements may be limited by excessive costs, restricted access to some locations due to safety rules or physical impossibility to reach preferred gauging positions (Duguay et al., 2017; Leng & Chanson, 2020a). On the other hand, physical experiments offer a realistic image of the flow features, provide critical support for numerical model validation that is necessary to acquire meaningful results (Amaral et al., 2019; Bates et al., 2005), as well as reliable values for setting boundary conditions, a crucial factor for model accuracy (Cao et al., 2021). A significant level of expertise (of both the numerical and physical process) is required to define and implement a CFD model in a suitable way (Leng & Chanson, 2020b). In general, the main advantage of coupling physical experiments with numerical models is the prospect of a mutually complementary practice that maximizes strengths and minimizes weaknesses for each (Leng & Chanson, 2020c).

In 41.6% of the analyzed papers, the study of the flow field was performed by the application of a numerical model alone, without coupling it with a physical experimental version or field measurements (Fig. 4). This approach has the advantage of avoiding costs of field work or laboratory experiments, providing a flexible and prompt application technique to analyze the flow field (Heimerl et al., 2008). Studying internal hydrodynamics of fishways with CFD models also allows saving time and resources otherwise allocated to building a structure in real life and subsequently evaluating it with flow field measurements (Cao et al., 2021). In many cases though, field assessments are crucial in determining fishway effectiveness, especially for non-salmonid species (Hershey, 2021; Katopodis & Williams, 2012; Silva et al., 2018). Moreover, the possibility of investigating different fishway configurations at the same time, together with the ease of implementing changes in geometrical setups, without the rigidity characterizing field or laboratory experiments, can play a substantial role towards a quicker and more economical design of effective and functioning structures (Abeyratne et al., 2021; Barton et al., 2009). This is valid, as long as the CFD model represents the flow field and hydrodynamic parameters well. In fact, an essential aspect in the application of CFD modeling is to ascertain that the reproduction of the physical processes reflects reality (Khan, 2006), especially in studies based on numerical models only. The reliability of a numerical model is assessed through a process of validation of the flow field and hydrodynamic parameters. Within hybrid approach studies, where the numerical model was applied together with a laboratory or field experiment, the validation of the CFD model was performed through a direct comparison with real data obtained and measured by the same researchers involved in the study. When it comes to exclusively numerical studies, the situation is different since no direct flow field comparison is immediately available. Typically, in these kinds of studies, the quality assessment of the model was carried out by comparing simulation results with previously available data, using one of the two following approaches:

1. Using data from another study where a laboratory experiment or field study was performed, and creating the geometry for the new numerical model based on that existing setup (e.g.

Ballu et al., 2018; Stamou et al., 2018). This “pristine” shape of the model is then validated on the same boundary conditions measured in the experiment or field study, comparing the flow topology or the parameter values in some crucial areas of the structure (e.g. velocity at the slot opening or turbulent kinetic energy in the pools). After a satisfactory validation process, tweaks and changes are made to the original model to further explore the effects on hydrodynamics.

2. Using as a reference the flow field from another paper’s case study, where a theoretical model or fishway geometry was described but either not directly tested or missing some information relative to flow parameters, and iteratively fine tuning the boundary conditions or slightly tweaking the geometry in order to get the same flow distribution as the original study (e.g. Quaranta et al., 2016, 2017).

Typically, the aspect that distinguished the first from the second approach was the availability of a previous study specifying the boundary conditions. The two approaches were inherently very close.

Overall, when applying CFD, the main difference between hybrid and exclusively numerical studies was in the modeling validation process. In hybrid studies, the CFD tool was either validated with a laboratory or field experiment or used to enhance physical investigations. In the numerically exclusive studies, the model’s suitability to reproduce the flow field was examined more directly. While model validation was always performed in hybrid studies, in exclusively numerical studies this procedure was carried out in 86% of the cases - with 14% not specifying details on how it was conducted. Improved validation of CFD models may be obtained with the wider use of available hydraulic relationships (e.g. depth-discharge; velocity profiles) from physical modeling studies of technical fishways (e.g. Ead et al., 2004; Katopodis, 1992; Katopodis et al., 1997; Wu et al., 1999).

3.4 HYDRODYNAMIC MODELS

Choosing the most suitable numerical model to represent the flow field in a fishway is a delicate operation, that requires a certain level of experience from the modeler (Mahl et al., 2021). The set of modeling equations, assumptions and approximations should be adapted to the particular layout of the fishway that has to be represented (Bates et al., 2005). A strict and precise digitization of fishway geometry is fundamental for high simulation accuracy, yet the more detailed the description, the more computationally demanding the numerical modeling task becomes (Andersson, 2012; Padgett et al., 2020).

In general, it is recognized that applying low computationally demanding one-dimensional models for fishways may lead to oversimplifications of the physical process, as the inherently three-dimensional nature of the flow is neglected (Fuentes-Pérez et al., 2018). In 1D models, variations only in one spatial dimension (along the length of the watercourse) are considered, simplifying the analysis by assuming that changes in flow properties occur only in the direction of the flow. With the excessively straightforward assumptions and the absence of transversal and vertical components of velocity, 1D models do not allow calculation of hydrodynamic parameters, like turbulent kinetic energy and energy dissipation rate, fundamental to assess fish passage suitability (Santos et al., 2012; Umeda et al., 2017). Only 1.5% of the analyzed papers tested 1D models to reproduce fishway hydrodynamics, and they were mainly intended as a preliminary analysis phase for a more complex model by interpreting the flow field from the one-dimensional simulation to select appropriate turbulence approximations to be adopted in 3D models to catch the flow distribution, or by using the resulting values of hydraulic parameters as guidance for the boundary conditions of the following 3D models (e.g. Umeda et al., 2017). The potential use of ~~these~~this method in a preliminary design or test phase is primarily highlighted as a tool for estimating discharges and water levels as input data for more complex hydrodynamic models (Fuentes-Pérez et al., 2018).

While the internal flow of fishways is commonly recognized in CFD studies as a three-dimensional phenomenon (Gong et al., 2021; Klein & Oertel, 2015), there are some particular cases in which a 2D approximation can help save time and resources. Actually, physical modeling demonstrated that for VSFs with low slopes (< 5%), in a large area of internal pools, flow is approximately bidimensional as the vertical component of velocity assumes significant values just in the narrow section of the slot (Wu et al. 1999). Several numerical studies assumed 2D flow in VSF with gentle slopes (e.g. Ballu et al., 2018; Bombač et al., 2017; Tran et al., 2016). In these conditions, the use of a 2D model with Shallow Water Equations (SWE) approximation is justified and can provide useful results in terms of identification of fish resting zones and flow topology (Bermúdez et al., 2010; Stamou et al., 2018). However, the success of a fishway is highly related to the passage of fish through the slot and, so, it is essential to verify the flow characteristics in that zone (Cea et al., 2007). The papers that adopted a 2D model to study the flow field (8.8%) applied it to low slope VSF only (e.g. Bermúdez et al., 2010; Bombač et al., 2015; Cea et al., 2007), as this approximation would be inadequate for steeper VSFs and other types of fish passes with more pronounced three-dimensional characteristics of the flow.

For most of the CFD applications analyzed, the need for three-dimensional models is widely recognized (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2022; Maniecki, 2018). There are certain zones (like in the proximity of the slot) and some ranges of discharge and bed slope for which simplistic approximations fail to capture important features of flow topology (Cea et al., 2007; Chorda et al., 2010). For example, neglecting the vertical component of velocity in 2D models, can lead to an overestimation of turbulence parameters and water levels, in the presence of highly turbulent flows (Lauchlan Arrowsmith & Zhu, 2014). Therefore, although being more complicated and time consuming, 3D CFD is the irreplaceable way to reliably capture the flow numerically (Ballu et al., 2018; Bombač et al., 2014). Moreover, the higher flexibility of the meshing algorithms used by 3D CFD allows more dynamical changes in geometry and layout compared to 2D models (Lauchlan Arrowsmith & Zhu, 2014). Three-dimensional CFD was used in 91.2% of the papers.

In addition, among 3D CFD papers, 4.8% adopted the so called Smoothed Particle Hydrodynamics method (SPH), a 3D meshless approach in which the fluid domain is discretized in particles and the equations of motion are solved with a Lagrangian point of view (e.g. Novak et al., 2019, 2021). In contrast to traditional approaches (with Eulerian perspective), SPH grants more flexibility in the geometry definition, overcoming the limitations of the more rigid process of mesh creation, and its suitability to model 3D flows within fishways has been proved in several cases (e.g. Novak et al., 2019). However, being a meshless methodology, SPH's application is often limited by the need of a significant computational power - required for the discretization of the fluid domain in elementary particles - and the inherent weaknesses within the definition of the boundary conditions near solid walls, creating a problem of continuity between fluid and solid domains (Novak et al., 2019).

3.5 TURBULENCE AND EQUATIONS

Three-dimensional CFD was the most recurrent method adopted to study fishways throughout the analyzed papers, with many sets of equations and turbulence approximations. The three-dimensional nature of flow within fishways is related to the turbulence generated internally. The correct solution of Navier-Stokes equations is crucial to determine velocities and turbulent quantities accurately, especially since these parameters influence the passage success of fish through the structure (Cea et al., 2007). The equations of motion can be solved directly (DNS, Direct Numerical Simulation) to obtain the most precise flow fields. With currently available computational capacities, as well as ~~time and resources~~simulation times needed for this type of ~~application~~method, application of CFD for DNS is excessive (Padgett et al., 2020). This is also highlighted by the fact that DNS was not used in the simulations, but other approximation methods were ~~used~~adopted in all the papers analyzed (Fig. 5).

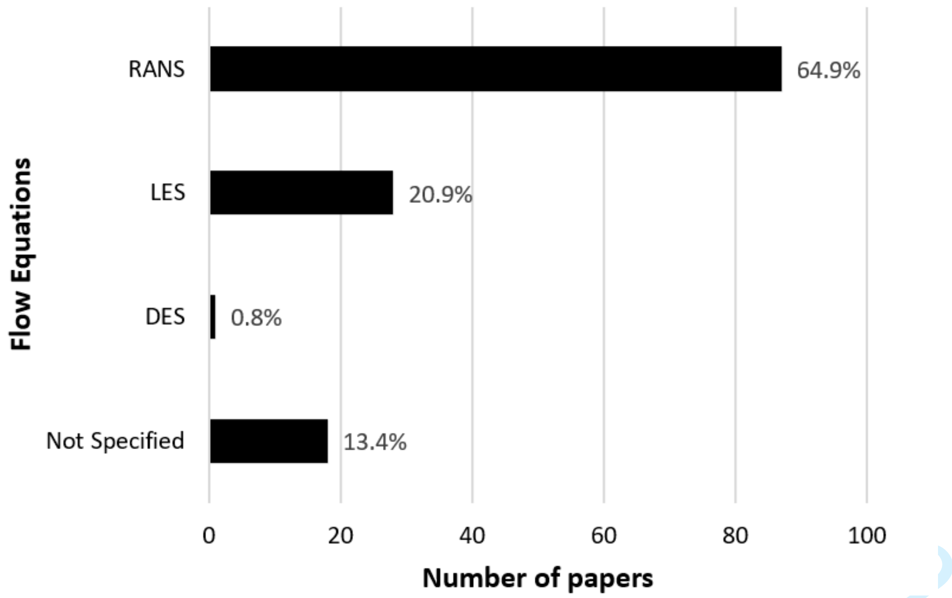


Fig. 5 - ~~Flow~~Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure models: k-ε and k-ω. Papers where the equations or turbulence model type was not made explicit are included under the category Not Specified. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one set of flow equations contributed to the count for each set of equations dealt with.

The most frequent alternatives to DNS found in the analyzed papers were Reynolds-Averaged Navier-Stokes equations (RANS) and Large Eddy Simulation (LES), representing 64.9% and 20.9% of the collection, respectively - with 6.6% of the papers applying both methods to compare their performance.

RANS was the most used method (64.9%), providing a reasonable balance between result accuracy and computational cost (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2018). Since RANS are based on time averaging of the dynamic variables of the Navier-Stokes equations, they perform well in capturing the average flow field, yet are weaker in assessing the turbulent parameters, as they depend on the unsteady and time varying features of the flow (Chorda et al., 2010; Fuentes-Pérez et al., 2018). For example, several studies outlined the over- or underestimation of turbulent kinetic energy from RANS (e.g. Baki et al., 2016; Sanagiotto et al., 2019; Tran et al., 2016). In general, the precision of turbulence parameters estimation depends on the type of closure model adopted for a specific problem. In RANS, the approaches used mainly consist of the so called two-equation models, solving a pair of additional transport equations to obtain a characteristic length and velocity of the turbulence process (Andersson, 2012). According to our review, the most used approach was the k-ε model, implemented in 83.1% of the RANS applications, while the k-ω model was adopted only in 10.1% of the cases. In the remaining 6.7% of the RANS applications the equation model used was not specified. Even if both equation models are recognized as adequate for general-purpose applications of RANS (Andersson, 2012), the disproportionally high use of the k-ε model emerging from our search, is related to the higher computational time associated with the k-ω model. Nevertheless, the performance of k-ω is higher in zones close to solid boundaries and in contexts with separating or swirling flows (Ducrocq et al., 2017). In particular, within the k-ω model applications, the improved Shear-Stress Transport (SST) k-ω model was adopted in the majority of the cases (90%), combining the benefits of both k-ε and k-ω approximations and allowing a strengthened performance in representing adverse pressure gradient and separating flows (Padgett et al., 2020; Zhang et al., 2023). However, since both equation models depend on the Boussinesq eddy viscosity approach, RANS suffer from inherent deficiencies deriving from the approximation that considers turbulence as an isotropic phenomenon (Andersson, 2012). This contributes to limiting the precision of RANS in fishways, where, inside the pools, turbulence is considered strongly anisotropic (Duguay et al., 2017). However, fishways are still considered a suitable field of application for RANS, as the inner flow topology is represented well overall, despite the limits in wakes zones and complex flows (Mahl et al., 2021; Sanagiotto et al., 2019).

When the flow is highly turbulent, the LES method could be a valid option to improve modeling accuracy (Fuentes-Pérez et al., 2022), and it was applied in 20.9% of the cases. Filtering out the small but keeping the large turbulent scales from Navier-Stokes equations, the LES method offers a more complete description of the instantaneous flow field, overcoming the limits of time-averaging that characterize RANS (Chen & Tfwala, 2018). Actually, higher accuracy is linked to the direct simulation of large eddies, being more difficult to model due to their anisotropic nature, while small eddies can be considered closer to isotropy and thus approximated with subgrid stress models (Andersson, 2012). In the reviewed papers dealing with LES method, the turbulence closure model adopted for small scales was always the standard Smagorinsky one, where the isotropic stress is linked to the anisotropic one through an eddy-viscosity approximation (Andersson, 2012). However, the cost for improved modeling performance is a longer simulation time and a finer refinement of the computational mesh (Padgett et al., 2020; Pope, 2001). Since the correct assessment of flow suitability for fish passage is related to highly turbulent zones in the pools (e.g. near a slot, weir, orifice or baffle), and fish responses depend on the instantaneous features of the flow field, the increase in computational resources is often needed for a more accurate assessment on how well the structure functions (Silva et al., 2012). In addition, some specific hydrodynamic and biological applications, such as studying the impact of non-uniformity at flow boundaries (Fuentes-Pérez et al., 2018), and the use of the IPOS (turbulence intensity, periodicity, orientation and scale) framework (Roth et al., 2022), require LES simulation as the level of turbulence detail provided by other methods would be insufficient.

A way to overcome the limitations of both methods is to adopt a hybrid approximation between RANS and LES, called Detached Eddy Simulation (DES). This approach takes the best features of both models and keeps computational mesh requirements moderate, switching between the two models according to the distance from the solid boundaries (Mahl et al., 2021). Blending the application of LES in free flow and RANS in the proximity of a wall (Gisen et al., 2017), DES provides improved simulation results both in terms of quality of the flow fields (higher level of details in the turbulent scales and time-varying parameters can be reached with respect to RANS) and of computational efforts (lower run times are needed compared to pure LES) (Roth et al., 2022). However, the detached eddy simulation method was poorly tested in the reviewed literature (0.8% of the papers) being applied only to study the suitability of two VSF configurations with the IPOS framework (Roth et al., 2022). Considering the several advantages of the DES model and possible improved outcomes, this approach may be suitable for future applications that require a high level of detail in the description of the turbulent flow features at an overall more efficient use of computational resources.

The remaining 13.4% did not specify the adopted approach to simulate the equations of motion. Most of these papers were also not focused on the application of CFD to study the flow, but used it as a backup to check for the correct flow representation in laboratory or field experiments (e.g. Abdelaziz et al., 2013; Oertel & Schlenkhoff, 2012; Plymesser & Cahoon, 2017).

In general, selecting the turbulence model that best fits a specific configuration is considered as one of the principal challenges in numerical modeling (Benchikh Le Hocine et al., 2019; Duguay et al., 2017). The complexity of the physical phenomena together with the variety of the possible geometry layouts requires significant modeler competence. However, some general evaluations may be undertaken. Since LES models aim to represent three-dimensional time varying flow fields, more detail and precision is required in the model setup, as well as a longer process for mesh construction and validation - compared to RANS - and time to achieve a converged solution (Quaresma et al., 2018). Therefore, while LES application is restricted to more specific experiments and research fields, at a smaller spatial scale, RANS are able to reach solution convergence even with a coarser mesh, making this method more suitable for large models and more flexible for general fishway applications (Fuentes-Pérez et al., 2018). Moreover, underestimation, overestimation and errors are always possible, especially for high discharges and hydrodynamically complex scenarios, emphasizing the need to always ensure adequate validation of the numerical model.

3.6 SOFTWARE

In addition to the equations of motion, software choice is another important step in numerical modeling. In general, most of the authors relied on well-known simulators (licensed or open source), as custom-made codes, even if tailored for the case study, require considerable effort to produce a result that does not significantly differ in modeling accuracy from the one produced by other known software (Stamou et al., 2018).

Commercial licensed codes were used in more than half (52.5%) of the paper collection, with FLOW-3D and Ansys (Fluent and CFX) being the most common choices (Fig. 6). In addition to providing a handy and straightforward modeling environment, they have the advantage of being widely applied, tested and verified in a large number of different studies and applications (Khan, 2006). Despite an adequate quality in results is nowadays granted by both commercial and open-source software, the former bestow more user-friendliness to readily generate grids of different shapes and geometries, making them suitable for a wide range of applications and still often preferred over open-source ones (Fuentes-Pérez et al., 2022).

~~Despite advantages in terms of user friendly interfaces and adaptability to case studies in commercial software,~~However, the access to the source script is restricted in commercial software, and licensing fees often represent a factor limiting use (Duguay et al., 2017). Open source codes overcome these issues with no license fees, and a complete and free access to the source code, which can then be adjusted and modified according to the specific needs of the researcher. Several studies (19%) showed the implementation of open source software, with OpenFOAM (12.4%) and DualSPHysics (4.4%) being the most used ones (Fig. 6). OpenFOAM was successfully applied to study the flow field within both vertical slot, pool and weir and nature-like fishways (e.g. Duguay et al., 2017; Miranda et al., 2021; Santos et al., 2022). Also, DualSPHysics was applied to study the flow field in vertical slot and nature-like fishways, according to the SPH method, and it delivered suitable results in both cases (e.g. Gomes et al., 2022; Novak et al., 2021). The main drawback of open source codes, to date, is the computational mesh generation process. While in licensed codes the mesh construction is semi-automatic and handled directly within the modeling environment, in open source codes it often relies on external meshing programs with a manual and iterative procedure (Fuentes-Pérez et al., 2022).

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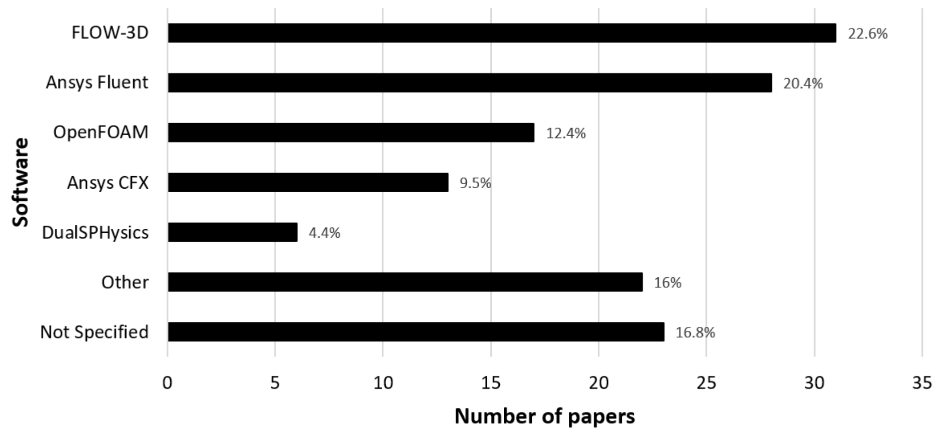

Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code (EFDC), FENFLOSS, Hydro3D, IBER, MIKE 3FM, PCFLOW2D, River2D, SSIIM, Star-CCM+, Star-CD, ~~XFlow, CCHE2D, IBER, PCFLOW2D, River2D and~~ TELEMAC-2D and XFlow. Not Specified includes papers where the applied software name was not made explicit. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one software contributed to the count for each software dealt with.

Some other numerical codes (16%), both commercial and open-source, were also found in this review effort (Fig. 6). They consisted of 1D, 2D or 3D codes, whose number of applications was not considered sufficient to count them as a distinct software category within the database. The 3D codes were used in 9.5% of the papers and were: Environmental Fluid Dynamic Code (EFDC), FENFLOSS, Hydro3D, MIKE 3FM, SSIIM, Star-CCM+, Star-CD and XFlow. The 2D codes were used in 6.5% of the papers and were: CCHE2D, IBER, PCFLOW2D, River2D and TELEMAC-2D. The 1D codes were used in 1.5% of the cases, in combination with OpenFOAM and Ansys Fluent: in the former case HEC-RAS was used, while the latter did not specify the used software. Finally, in 16.8% of the collection a numerical code was applied without specifying the software name (Fig. 6).

3.7 FISHWAY SUITABILITY ASSESSMENT

Hydrodynamics is a fundamental part in assessing the effectiveness of a fish passage structure and several approaches, set of equations, and numerical software were shown in the previous sections to describe different kinds of applicable procedures to define flow field properties in a reliable way. The realistic definition of the flow features, reflecting the physical process occurring in a built structure, constitutes a necessary step in the analysis of fish passages but it is obviously important to also consider how fish respond to flow. Knowledge about species specific physiology, biology and ecology is fundamental. In particular, identifying numerical reference values for hydrodynamic parameters that link turbulence metrics to fish swimming capability and behavior is a vital need for the design and construction of well-functioning, efficient fishways (Silva et al., 2018).

Since the suitability assessment of a fishway is of primary interest, how fish were considered within the CFD studies was a significant topic for analysis (Fig. 7).

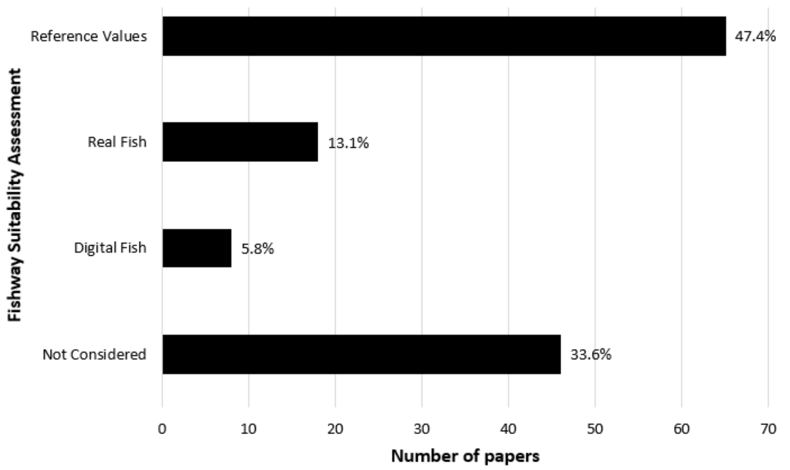

Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. Digital Fish: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; Real Fish: coupling numerical simulation with a parallel direct experiment testing fish response to the flow; Reference Values: comparison between numerically generated flow field and hydrodynamic reference values from the literature - proxy for fish swimming abilities; Not Considered: papers without any reference to fish movement patterns, swimming efforts, or literature values. Percentages of contribution to the collection are indicated in the figure. Papers dealing with more than one of the detected methods contributed to the count for each method dealt with.

The results show that more than two thirds of the paper collection (66.3%) included fish in the study (Fig. 7), in the following ways:

1. *Digital fish* (5.8%), i.e. application of an individual based model (IBM) to virtually reproduce the movement and trajectories of a "digital fish" inside a previously numerically computed flow field (e.g. Kulic et al., 2021; Zielinski et al., 2018).
2. *Real fish* (13.1%), i.e. direct test of fish swimming inside an experimental setup or a real structure (e.g. Gao et al., 2016; Haselbauer & Martinez, 2007).
3. *Reference values* (47.4%), i.e. suitability assessment of the flow, via comparison of hydrodynamic metrics with related literature reference values available for the target fish (e.g. Quaranta et al., 2019; Zhu et al., 2020).

The first approach (5.8% of the papers) developed and incorporated a numerical algorithm within a CFD computed velocity field to virtually reproduce the behavior of an individual fish. A "numerical fish" (Individual Based Model, IBM) was defined, considering both environmental and biological stimuli acting on an average fish, in an attempt to simulate the internal sensory process that fish may use to decide how to respond in a flow field (Gao et al., 2016). The fish algorithm was always based on real fish trajectories in hydrodynamic environments obtained from other studies, and the final trajectories obtained numerically were challenged ex-post with real trajectories from real life studies in the same fishway.

The second approach (13.1% of the paper collection) consisted of coupling numerical modeling of the flow with experiments where real fish were directly tested, either in the laboratory using a physical model or a flume, or in a field experiment with an existing fish pass. Within this category, in 77.8% of the cases fish were tested in a laboratory experiment, while in the remaining 22.2% they were observed in a real facility. Fish observations were mainly performed through videorecording (45%), Passive Integrated Transponder (PIT) telemetry techniques (15%) or visual inspection by operators (25%) - with some cases where a combination of approaches was adopted: PIT telemetry and videorecording (5%), digital fish and videorecording (10%). The experiments were generally followed by a data post-processing phase, including video examination and analysis (e.g. Amaral et al., 2019), PIT tag sequences detection (e.g. Lewandoski et al., 2021), or blood test analysis from a previous study ~~(e.g. Shahabi et al., 2021, 2023)~~(e.g. Shahabi et al., 2021, 2023) to define fish trajectories within the flow, energy expenditure, accumulated stress or other fish-relevant parameters. In papers where fish were visually observed by human operators (e.g. Romão et al., 2021) the standard procedure was to manually count fish passing through a specific location.

Species families represented in the references collected were mainly *Cyprinidae* (63.8%), followed by *Anguillidae* (6.3%) and *Cobitidae* (4.2%). The rest of the families (25.7%) were all fish (*Salmonidae, Catostomidae, Galaxiidae, Characidae, Anostomidae, Leuciscidae, Oxudercidae*), except one shrimp (*Palaemonidae*) and one lamprey (*Petromyzontidae)*. The most studied species was the Iberian barbel (*Luciobarbus bocagei*), with 21.3% of the publications, followed by grass carp (*Ctenopharyngodon idella*), 16.7%, and Japanese eel (*Anguilla japonica),* 6.3%. An additional 22 species were represented but just tested once (2.4%), but together making up 55.7% of the papers. Tab. 1 lists all the species found in the collection that were really tested in an experiment (category *Real Fish*).

Tab. 1 - List of the different species tested in real life experiments within the collection (category Real Fish). Both common and scientific names of the species are shown, together with the percentage of occurrence of each species (values relative to the category Real Fish). The percentage of occurrence indicated in the last row is relative to each species listed.

Species	Papers Occurrence
Iberian barbel (*Luciobarbus bocagei*)	21.3%
Grass carp (*Ctenopharyngodon idella*)	16.7%
Japanese eel (*Anguilla japonica*)	6.3%
Algae shrimp (*Macrobrachium japonicum*), Bighead carp (*Hypophthalmichthys nobilis*), Brown trout (*Salmo trutta*), Cebacek (*Pseudorasbora parva*), Common galaxias (*Galaxias maculatus*), Gitterorfe (*Acrossochelius paradoxus*), *Gobiobotia intermedia*, Iberian straightmouth nase (*Pseudochondrostoma polylepis*), Lambari (*Astyanax bimaculatus*), Piau (*Leporinus reinhardti*), sea lamprey (*Petromyzon marinus*), silver carp (*Hypophthalmichthys molitrix*), south Iberian barbel (*Luciobarbus sclateri*), south Iberian chub (*Squalius pyrenaicus*), *Spinibarbus hollandi*, Stone loach (three species: *Triplophysa leptosome*, *Triplophysa wuweiensis*, *Triplophysa yarkandensis*), Taiwanese freshwater goby (*Rhinogobius candidius*), white sucker (*Catostomus commersonii*), Ya-fish (*Schizothorax prenanti*), *Zacco pachycephalus*	2.4%

In the third approach, the suitability analysis of the flow of numerically conducted studies was assessed against reference values relating to flow velocity and turbulence. Hydrodynamic metrics and related reference values (Tab. 2 for a non-exhaustive but representative list) found in the scientific literature for the target fish species were discussed and compared with the CFD model results in 47.4% of the complete collection of papers (71.5% of papers considering fish). Flow velocity was used as a reference value to assess passage suitability in 98.4% of these papers. Flow velocity represents a crucial parameter to assess fish passage suitability, as it relates to the limited capacity of fish for speed and endurance (Katopodis and Gervais 2016). Fish ability to navigate through and overcome flow velocities, depends on its distribution and absolute values, particularly near slot or orifice openings and within the pools for adequate fish resting zones (Cea et al., 2007; Quaranta et al., 2019). With regards to turbulence metrics 63.4% of the papers considered Turbulent Kinetic Energy (TKE), whose excessive values could increase swimming energy and confuse fish ~~(Quaranta et al., 2017; Santos et al. 2012; Li P. et al. 2021)~~(Quaranta et al., 2017; Santos et al. 2012; Li P. et al. 2021), while two-fifths of the papers (39.7%) applied the Volumetric Power Dissipation (P) - inherently linked to the suitability of recirculation zones in the pools (Quaranta et al., 2017) -

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ha formattato: Tipo di carattere: Corsivo, Colore carattere: Testo 2 and 14.3% used Reynolds Shear Stress (RSS), as it can affect fish stability and even lead to injuries or mortality (Silva et al., 2012). Additional turbulence related parameters that may also be considered for suitability evaluation, such as flow vorticity, eddy sizes and their orientation, were seldom used in the analyzed papers. For example, just 12.7% included vorticity in the analysis and just 1.6% provided a discussion on eddy features using the IPOS framework (i.e. Roth et al., 2022). Moreover, 6.3% included an analysis on the pressure distribution within the flow near baffles and solid surfaces (e.g. ~~Zeng et al., 2022).~~ Zeng et al., 2022).

Tab. 2 – Non-exhaustive list of the most common hydrodynamic metrics and related tested reference values in fishway literature. The following parameters of the flow are reported: Velocity (V), Turbulent Kinetic Energy (TKE), Reynolds Shear Stress (RSS), Volumetric Power Dissipation (P) and Eddy Size. The common and scientific names of species, the average body size with standard deviation - Total Length (TL) or Fork Length (FL) -, the context where the reference numerical value was detected and the scientific reference paper the parameter values were obtained from are listed.

Metric	Tested Reference Values	Fish Species	Fish Size	Experimental Environment	Reference
V	Preference for zones with **0.2 < V < 0.4 m/s**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	Condition that 30-50% of the pool volume must be kept with **V < 0.3 m/s**.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Passage preference in zones close to the side walls with **0.1 < V < 0.3 m/s**.	Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm	Experimental VSF	Li G. et al. (2021)
	Avoidance of dam tailrace areas with velocities higher than **V > 2.4 m/s**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
TKE	Preference for areas (close to the flume bottom) with **TKE < 0.05 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	TKE > 0.05 m^2/s^2 categorized as high **TKE < 0.05 m^2/s^2** categorized as low within the turning pools.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Barbel performed better also for **0.061 < TKE < 0.071 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	17.2 < TL < 26cm	Experimental VSF with two different slot configurations (lateral and central baffle)	Romão et al. (2017)
	Chub performed an higher number of upstream movements in the lateral baffle configuration with **TKE < 0.059 m^2/s^2** (maximum value).	South iberian chub (*Squalius pyrenaicus*)	11.1 < TL < 15.4cm		
	Preference for **TKE < 0.05 m^2/s^2**.	Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguay et al. (2018)
	Preference for the substrate configuration with **TKE < 0.25 m^2/s^2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 17.4 ± 2cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
	Preference for **TKE < 0.03 m^2/s^2** (inhibited at **TKE = 0.24 m^2/s^2**).	Atlantic salmon smolts (*Salmo salar*)	TL = 14.70 ± 1.05cm	In Situ and CFD study of an Hydropower plant intake race	Silva et al. (2020)
	Passage preference in zones close to the side walls with TKE **< 0.015 m^2/s^2**.	Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm	Experimental VSF	Li G. et al. (2021)
	Preference for pool resting zones with **TKE < 0.063 m^2/s^2**.	Rainbow trout (*Oncorhynchus mykiss*)	TL = 15 ± 3cm	Pool and Weir fishway (with W-weirs)	Shahabi et al. (2021)
	Avoidance of dam tailrace areas with **TKE > 0.12 m^2/s^2**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
RSS	Injuries/Mortality for **RSS > 700 N/m^2**.	Juvenile Coho salmon (*Oncorhynchus kisutch*)	/	CFD and In Situ study of turbine mortality	Čada et al. (2006)
	Experimental range: **0.02 < RSS < 73.4 N/m^2**. No damage observed within the range but disorientation/displacements occurred.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
	Fish spent less time in areas close to **RSS = 60 N/m^2** (experiment range: 20 < RSS < 60 N/m^2).	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	Avoidance of dam tailrace areas with **RSS > 21 N/m^2**.	Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
P	**P = 150-200 W/m^3**	Salmonids	/	Pool-type fishways	Larinier (2002)
	P = 100-150 W/m^3	Cyprinids	/	Pool-type fishways	Larinier (2002)
	P < 100 W/m^3	Weak swimmers	/	Pool-type fishways	Larinier (2002)
Eddy Size	Instability when **Eddy Size > 76%** fish body length.	Creek chub (*Semotilus atromaculatus*)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Tritico & Cotel (2010)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguay et al. (2018)
	Spatially averaged turbulent length scale range was: **0.42 - 0.64m**. It was comparable with sea lamprey total length affecting stability in the flow.	Sea lamprey (*Petromyzon marinus*)	TL = 47 ± 4cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)
		White sucker (*Catostomus commersonii*)	TL = 29 ± 7cm		

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One third of the paper collection focused solely on the description of the flow field hydrodynamics without any reference to fish movement patterns, swimming efforts, or literature reference values (Fig. 7). These papers were categorized as *Not Considered*, as they were either limited to just pure hydraulic analysis of the flow (e.g. assessing the most suitable set of hydrodynamics equations to depict the flow field in a fishway), or the discussion about fish and flow suitability was excessively vague and qualitative to be included in one of the other categories. *Not Considered* was the second highest category (Fig. 7), highlighting that lack of integrating knowledge on fish abilities and responses to hydrodynamics persists as a substantial deficiency in the international literature. This identifies a priority research area for future CFD studies or applications. Actually, several papers from the complete collection (30%) explicitly recognized that aspects related to fish movement and behavior need additional investigation for more realistic fish passage assessments (e.g. Amaral et al., 2019; Mao et al., 2012; Zhao et al., 2022). Fish movements and trajectories in real structures, as well as the identification of additional reference levels for hydrodynamic parameters for an increasing number of different species and consequent coupling with relevant flow field characteristics, is a crucial aspect in the design of more efficient river connectivity remedial measures.

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~~*Tab. 2 – Non-exhaustive list of the most common hydrodynamic metrics and related tested reference values in fishway literature. The following parameters of the flow are reported: Velocity (V), Turbulent Kinetic Energy (TKE), Reynolds Shear Stress (RSS), Volumetric Power Dissipation (P) and Eddy Size. The common and scientific names of species, the average body size with standard deviation – Total Length (TL) or Fork Length (FL) –, the context where the reference numerical value was detected and the scientific reference paper the parameter values were obtained from are listed.*~~

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	Condition that 30-50% of the pool volume must be kept with **V < 0.3 m/s**.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
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TKE	Preference for areas (close to the flume bottom) with **TKE < 0.05 m2/s2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
	TKE > 0.05 m2/s2 categorized as high **TKE < 0.05 m2/s2** categorized as low within the turning pools.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Barbel performed better also for **0.061 < TKE < 0.071 m2/s2**.	Iberian barbel (*Luciobarbus bocagei*)	17.2 < TL < 26cm	Experimental VSF with two different slot configurations (lateral and central baffle)	Romão et al. (2017)
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	Preference for the substrate configuration with **TKE < 0.25 m2/s2**.	Iberian barbel (*Luciobarbus bocagei*)	TL = 17.4 ± 2cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
	Preference for **TKE < 0.03 m2/s2** (inhibited at **TKE = 0.24 m2/s2**).	Atlantic salmon smolts (*Salmo salar*)	TL = 14.70 ± 1.05cm	In Situ and CFD study of an Hydropower plant intake race	Silva et al. (2020)
	Passage preference in zones close to the side walls with TKE **< 0.015 m2/s2**.	Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm	Experimental VSF	Li G. et al. (2021)
	Preference for pool resting zones with **TKE < 0.063 m2/s2**.	Rainbow trout (*Oncorhynchus mykiss*)	TL = 15 ± 3cm	Pool and Weir fishway (with W-weirs)	Shahabi et al. (2021)
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RSS	Injuries/Mortality for **RSS > 700 N/m2**.	Juvenile Coho salmon (*Oncorhynchus kisutch*)	/	CFD and In Situ study of turbine mortality	Čada et al. (2006)
	Experimental range: **0.02 < RSS < 73.4 N/m2**. No damage observed within the range but disorientation/displacements occurred.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
	Fish spent less time in areas close to **RSS = 60 N/m2** (experiment range: 20 < RSS < 60 N/m2).	Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
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	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Silva et al. (2012)
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	Spatially averaged turbulent length scale range was: **0.42 - 0.64m**. It was comparable with sea lamprey total length affecting stability in the flow.	Sea lamprey (*Petromyzon marinus*)	TL = 47 ± 4cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)
		White sucker (*Catostomus commersonii*)	TL = 29 ± 7cm		

4. CONCLUSIONS

This study provides an up-to-date overview of the application of Computational Fluid Dynamics (CFD) in relation to hydrodynamic analysis and suitability assessment of fishways for upstream migration. A systematic review of the available literature to the end of 2023 was undertaken, and the following conclusions were drawn:

1) The number of numerical studies significantly increased in the last 8 years (2016-2023), following recent technological advancements, with a higher number of studies on technical fishways than on nature-like ones. Among the technical structures, Vertical Slot Fishway (VSF) was the most recurrent typology, followed by Pool and Weir (PW). Among the Nature-Like solutions (NLF), rock ramps were the primal focus, followed by bypass channels.
2) Different modeling procedures were identified, based on whether the numerical model was used alone or coupled with other laboratory or field experiments (i.e. hybrid modeling). Hybrid modeling was the most frequent approach, owning to the benefit of overcoming some of the inherent limitations of physical or numerical models when applied separately, and allowing for a more direct validation of both models to increase result robustness (Leng & Chanson, 2020c). Purely numerical models show several cost advantages such as saving time and money, providing flexibility in applying geometry changes to the examined fish passage structures and offering a timely design process, as long as an appropriate validation process is carried out to check for the reliability of the output.
3) Three-dimensional CFD is fundamental to fully reproduce the physical phenomena within fishways, as the effectiveness of a fishway depends greatly on zones where the flow is highly turbulent and fast (Cea et al., 2007). However, in a few special cases (e.g. low slope VSFs), the flow may be considered bidimensional and a 2D model may yield acceptable results, saving computational time (Stamou et al., 2018). One dimensional models are often inappropriate as they consider just the longitudinal component of velocity and do not allow for a complete simulation of the flow field in fishways, but they can be useful in a preliminary phase to define input parameters prior to the application of a more sophisticated model (Fuentes-Pérez et al., 2018).
4) Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently used set of

equations to describe hydrodynamics, striking a balance between accuracy and computational cost, and may be suitable for fishway applications despite some limitations in turbulent parameter assessment (Chorda et al., 2010). Large Eddy Simulation (LES) is preferred for highly turbulent zones but requires higher computational resources (Padgett et al., 2020). Detached Eddy Simulation (DES), largely overcomes the limitations of the two previous computational schemes, combining the application of LES in the bulk flow and of RANS closer to walls for improved simulations (Gisen et al., 2017), yet it was poorly represented in the reviewed CFD studies. More frequent use of this method is suggested for an overall more efficient use of computational resources.

5) Well-known commercial software were predominantly represented in the collection, compared to open-source or custom-made codes, because of their user-friendly interfaces and convenient handiness in the meshing process (Fuentes-Pérez et al., 2022). Despite such advantages, licensing fee requirements and customizing limitations, prompted several researchers to explore the possibilities of open-source software, that represent a cost-free alternative with complete access to the source code and more scripting flexibility (Duguay et al., 2017).
6) Suitability for fish passage in numerical studies of fishways was performed following three main approaches: a) reproducing fish behavior and decision-making process virtually, through IBM algorithms; b) testing and monitoring with live fish experiments in laboratory or field studies; and c) comparing obtained flow fields to literature hydrodynamic reference values relative to target fish species. The analysis revealed that the latter approach was the most frequent and, therefore, the combination with a direct counterpart experiment is often missing in most fishway CFD investigations.

In general, our findings reveal increasing and widespread use of CFD in fishway science and show CFD is a potentially powerful tool for studying and improving the efficiency of fish passage solutions. Reliability has grown substantially with recent advancements in computer science and computational power, allowing fish ecology researchers and fishway designers to test old and new geometry configurations at relatively low cost (Heimerl et al., 2008). Despite the higher reliability, accessibility and time-saving use of numerical modeling, compared to laboratory or field experiments, adequate expertise on numerical software and simulated physical phenomena are required to use the correct equations and computational approximation techniques (Leng & Chanson, 2020c). Awareness about what and how well the hydrodynamic environment is simulated, as well as ensuring an appropriate model validation procedure, are crucial to obtain realistic and accurate results (Leng & Chanson, 2020b). With an aim to maximize efficiency for upstream passage of all fish willing to overcome a river obstacle, there is an urgent need for further study of the interactions between fish movement behavior and hydrodynamic features, especially turbulence, in real fishways or laboratory models. In particular, most needed are innovative studies that link fish trajectories with relevant hydrodynamic metrics encountered along routes of movement, to identify preferred values and thresholds not to be exceeded (Silva et al., 2012, 2018). Such research represents a promising way to expand the currently limited knowledge for a larger number of fish species and life-stages and obtain valuable data for designing more efficient fishways with the support of CFD.

ACKNOWLEDGEMENTS

This specific research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available as Supplementary Material.

Author contribution statement

FT, CC and CK conceived the idea presented. FT collected and analyzed the papers. FT wrote the manuscript with support from CC, CK and DN. All authors discussed the results and contributed to the final manuscript.

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ha formattato: Svedese (Svezia)

ha formattato: Tedesco (Germania)

ha formattato: Colore carattere: Collegamento ipertestuale

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ha formattato: Colore carattere: Collegamento ipertestuale

Formattato: Allineato a sinistra, Interlinea: multipla 1,08 ri

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Metric	Tested Reference Values
V	Preference for zones with **0.2 < V < 0.4 m/s**.
	Condition that 30-50% of the pool volume must be kept with **V < 0.3 m/s**.
	Passage preference in zones close to the side walls with **0.1 < V < 0.3 m/s**.
	Avoidance of dam tailrace areas with velocities higher than **V > 2.4 m/s**.
TKE	Preference for areas (close to the flume bottom) with **TKE < 0.05 m^2/s^2**.
	TKE > 0.05 m^2/s^2 categorized as high **TKE < 0.05 m^2/s^2** categorized as low within the turning pools.
	Barbel performed better also for **0.061 < TKE < 0.071 m^2/s^2**.
	Chub performed an higher number of upstream movements in the lateral baffle configuration with **TKE < 0.059 m^2/s^2** (maximum value).
	Preference for **TKE < 0.05 m^2/s^2**.
	Preference for the substrate configuration with **TKE < 0.25 m^2/s^2**.
	Preference for **TKE < 0.03 m^2/s^2** (inhibited at **TKE = 0.24 m^2/s^2**).
	Passage preference in zones close to the side walls with TKE **< 0.015 m^2/s^2**.

	Preference for pool resting zones with **TKE < 0.063 m²/s²**.
	Avoidance of dam tailrace areas with **TKE > 0.12 m²/s²**.
RSS	Injuries/Mortality for **RSS > 700 N/m²**.
	Experimental range: **0.02 < RSS < 73.4 N/m²**. No damage observed within the range but disorientation/displacements occurred.
	Fish spent less time in areas close to **RSS = 60 N/m²** (experiment range: 20 < RSS < 60 N/m²).
	Avoidance of dam tailrace areas with **RSS > 21 N/m²**.
P	**P = 150-200 W/m³**
	P = 100-150 W/m³
	P < 100 W/m³
Eddy Size	Instability when **Eddy Size > 76%** fish body length.
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.
	Spatially averaged turbulent length scale range was: **0.42 - 0.64m**. It was comparable with sea lamprey total length

Fish Species	Fish Size
Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm
	TL = 19.6 ± 3.1cm
	TL = 20.7 ± 2.4cm
/	/
Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm
Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm
Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm
	TL = 19.6 ± 3.1cm
	TL = 20.7 ± 2.4cm
/	/
Iberian barbel (*Luciobarbus bocagei*)	17.2 < TL < 26cm
South iberian chub (*Squalius pyrenaicus*)	11.1 < TL < 15.4cm
Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm
Iberian barbel (*Luciobarbus bocagei*)	TL = 17.4 ± 2cm
Atlantic salmon smolts (*Salmo salar*)	TL = 14.70 ± 1.05cm
Ya-fish (*Schizothorax prenanti*)	30 < TL < 50cm

Rainbow trout (*Oncorhynchus mykiss*)	TL = 15 ± 3cm
Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm
Juvenile Coho salmon (*Oncorhynchus kisutch*)	/
Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm
Iberian barbel (*Luciobarbus bocagei*)	TL = 18.6 ± 3.1cm
	TL = 19.6 ± 3.1cm
	TL = 20.7 ± 2.4cm
Sockeye salmon (*Oncorhynchus nerka*)	FL = 59.3 ± 0.6cm
Salmonids	/
Cyprinids	/
Weak swimmers	/
Creek chub (*Semotilus atromaculatus*)	TL = 12.2 ± 0.9cm
Iberian barbel (*Luciobarbus bocagei*)	TL = 15-25cm, 25-35cm
Juvenile Rainbow trout (*Oncorhyncus mykiss*)	FL = 8.6 ± 0.6cm
Sea lamprey (*Petromyzon marinus*)	TL = 47 ± 4cm
White sucker (*Catostomus commersonii*)	TL = 29 ± 7cm

Experimental Environment	Reference
Experimental Pool-type fishway	Santos et al. (2012)
CFD model of VSF with turning pools	Marriner et al. (2016)
Experimental VSF	Li G. et al. (2021)
CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
Experimental Pool-type fishway	Santos et al. (2012)
CFD model of VSF with turning pools	Marriner et al. (2016)
Experimental VSF with two different slot configurations (lateral and central baffle)	Romão et al. (2017)
Baffled experimental flume	Duguay et al. (2018)
Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
In Situ and CFD study of an Hydropower plant intake race	Silva et al. (2020)
Experimental VSF	Li G. et al. (2021)

Pool and Weir fishway (with W-weirs)	Shahabi et al. (2021)
CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
CFD and In Situ study of turbine mortality	Čada et al. (2006)
Experimental Pool and Orifice fishway	Silva et al. (2012)
Experimental Pool-type fishway	Santos et al. (2012)
CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
Pool-type fishways	Larinier (2002)
Pool-type fishways	Larinier (2002)
Pool-type fishways	Larinier (2002)
Flume experiment with different cylinders arrays	Tritico & Cotel (2010)
Experimental Pool and Orifice fishway	Silva et al. (2012)
Baffled experimental flume	Duguay et al. (2018)
Experimental VSF and CFD simulation	Lewandowski et al. (2021)

Species
Iberian barbel (*Luciobarbus bocagei*)
Grass carp (*Ctenopharyngodon idella*)
Japanese eel (*Anguilla japonica*)
Algae shrimp (*Macrobrachium japonicum*), Bighead carp (*Hypophthalmichthys nobilis*), Brown trout (*Salmo trutta*), Cebacek (*Pseudorasbora parva*), Common galaxias (*Galaxias maculatus*), Gitterorfe (*Acrossochelius paradoxus*), *Gobiobotia intermedia*, Iberian straightmouth nase (*Pseudochondrostoma polylepis*), Lambari (*Astyanax bimaculatus*), Piau (*Leporinus reinhardti*), sea lamprey (*Petromyzon marinus*), silver carp (*Hypophthalmichthys molitrix*), south Iberian barbel (*Luciobarbus sclateri*), south Iberian chub (*Squalius pyrenaicus*), *Spinibarbus hollandi*, Stone loach (three species: *Triplophysa leptosome*, *Triplophysa wuweiensis*, *Triplophysa yarkandensis*), Taiwanese freshwater goby (*Rhinogobius candidius*), white sucker (*Catostomus commersonii*), Ya-fish (*Schizothorax prenanti*), *Zacco pachycephalus*

Papers Occurrence
21.3%
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