

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

Original

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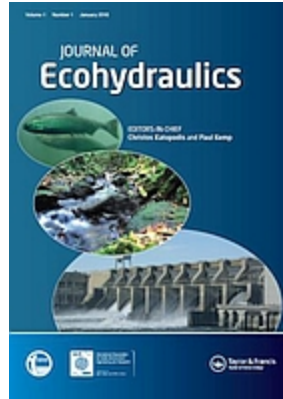
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Computational Fluid Dynamics in fishway research - a systematic review on upstream fish passage solutions

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Keywords:	CFD, ecohydraulics, fish pass, hydrodynamic modeling, numerical simulation, turbulence
Abstract:	<p>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.</p>

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1 2 3 4 1 **Computational Fluid Dynamics in fishway research -** 5 6 7 2 **a systematic review on upstream fish passage solutions** 8 9 10 3

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39 16 **RUNNING HEAD:** Use of Computational Fluid Dynamics in fishway research
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18 ABSTRACT

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

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39 **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),

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3 94 the application of boundary conditions at the inlet and outlet of the model, and the solution of the
4 95 equations of motion within the discretized volume (Andersson, 2012). By using CFD-models, the
5 96 flow can be described, and its hydrodynamic characteristics may be analyzed with only the known
6 97 discharge, water levels and the geometry of the fishway (Andersson, 2012).
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9 98 The application of CFD for fishways allows testing of different geometrical configurations and flow
10 99 conditions with flexibility and at low cost (An et al., 2016; Bates et al., 2005). There is no widely
11 100 recognized standard procedure to simulate the flow inside fishways with CFD. Each study makes
12 101 particular modeling choices based on the expertise of the software user (Andersson, 2012; Leng &
13 102 Chanson, 2020b), and a systematic overview of methods applied is lacking. In this context, the main
14 103 objective of this paper is to elucidate the current state-of-the-art relative to the application of CFD
15 104 related to fishways by identifying, analyzing and critically reviewing available primary literature.
16 105 Specifically, we summarize spatial-temporal parameters, scope and application fields, modeling
17 106 procedures and approximations related to the use of CFD in fishways. We limited the review to
18 107 upstream migration solutions and internal flow field analysis, as numerical modeling applications
19 108 for fishway entrance positioning (e.g. Andersson et al., 2016; Lindberg et al., 2013) and downstream
20 109 passage (e.g. Feigenwinter et al., 2019; Zöschg et al., 2023) are still few, more site-specific, and not
21 110 easily classifiable.
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29 112 2. METHODS

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31 113 A complete search of the available primary scientific literature on CFD and fishways was conducted
32 114 on *Scopus* and *Web of Science* databases. The collection encompassed all the literature available in
33 115 the two engines up until the end of 2023. The initial search and identification of papers were
34 116 performed through the definition of a series of keywords, including general terms relating to
35 117 numerical modeling, hydrodynamics and fishways: *CFD*, *computational fluid dynamics*, *fish ladder*,
36 118 *fish pass*, *fish passage*, *fishway*, *hydrodynamic modeling*, *hydrodynamics*, *numerical simulation*. All
37 119 the possible (meaningful) permutations of these words were explored, and the abstract of each
38 120 paper was read to identify those that were suitable for this study. A paper was considered relevant
39 121 only if dealing with a numerical model used to study the hydrodynamics within an upstream fish
40 122 passage solution, and in that case the full manuscript was then read for further analysis. Papers
41 123 unavailable online or not written in English were excluded from the study. When reading the
42 124 selected full manuscripts, if referenced relevant papers that had not emerged in the search query
43 125 were found, they were also included in the collection of papers.
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49 126 The analysis of the full manuscripts included an initial critical reading of the paper followed by the
50 127 collection of selected information to fill a summary database. The database was devised to assess
51 128 the different ways computational fluid dynamics was applied in analyzing the upstream fishway
52 129 from different perspectives. The database included the following classification/analysis parameters:
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- 55 130 • Year of publication of the paper
- 56 131 • Country (and continent) in which the study was carried out;
- 57 132 • Type of fishway studied and modeled (e.g. vertical slot, pool and weir, nature-like, etc.);
- 58 133 • Aim of the paper (the reason why a numerical model was used for the analysis of a fishway);
- 59 134 • 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.

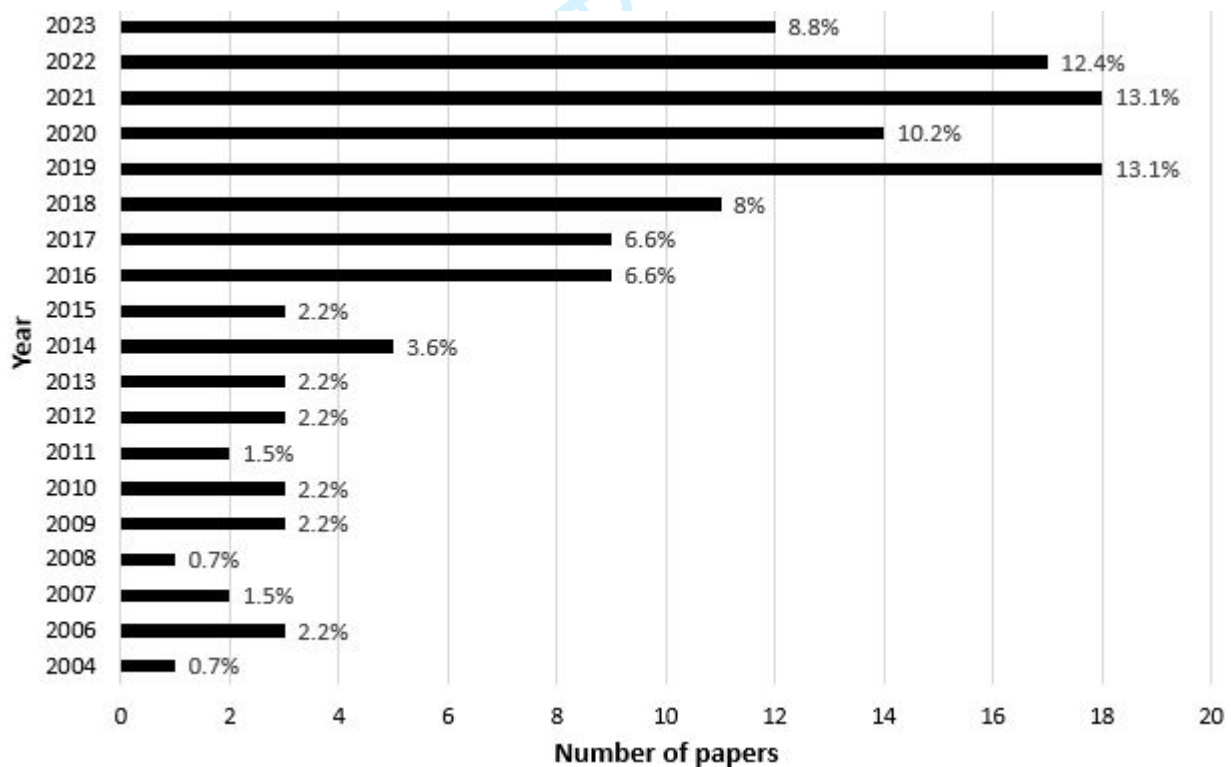


Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

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.

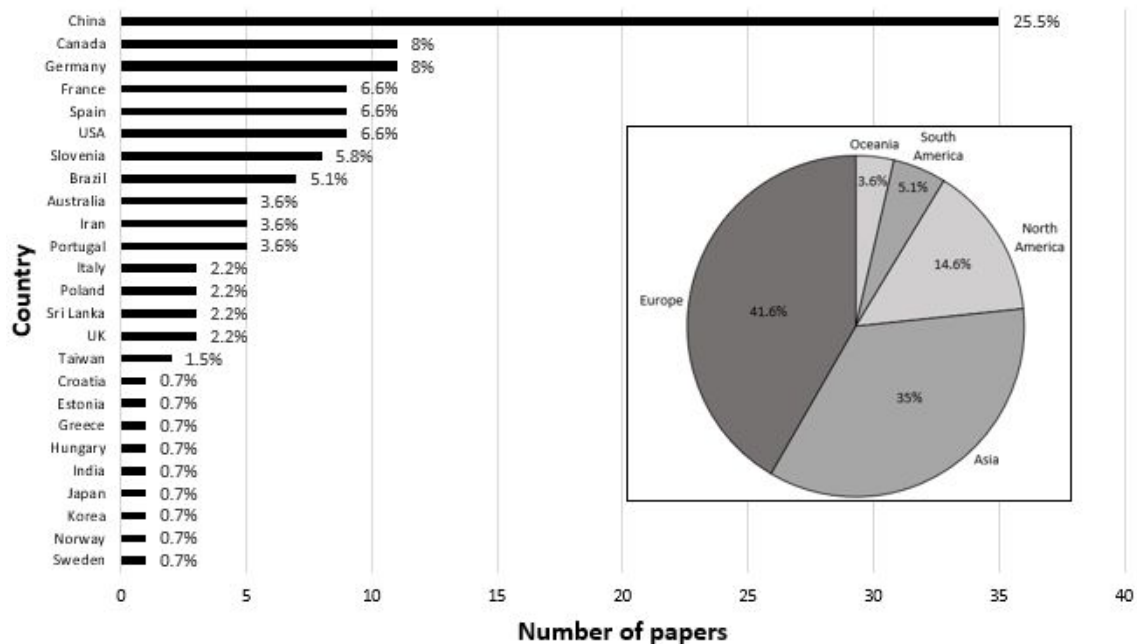


Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

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 steep pass, 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. Calluud 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).

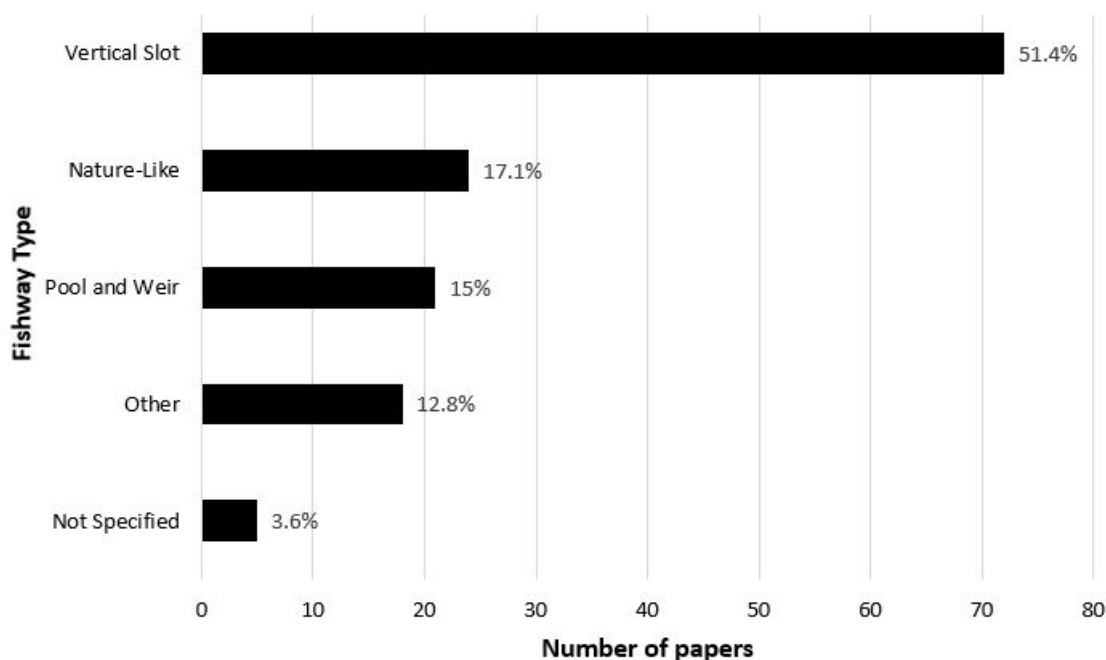


Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steep pass, eel pass, flat W-weir, island fishway, locks in dam, 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

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3 213 numerical modeling of NLF is a more challenging procedure and the simulation is often performed
4 214 over a simplified geometry. For example, for rock ramps, boulders were modelled with a spherical
5 215 shape instead of an irregular shape closer to reality (e.g. Baki et al., 2016). Similarly, the natural
6 216 roughness of a bypass channel bed was simulated through Manning's approximation, quantifying
7 217 the uneven river bed granulometry with a single coefficient (e.g. Tran et al., 2016).

10 218 The third most studied fish pass type was the PW, comprising 15% of the paper collection (Fig. 3).
11 219 Generally considered one of the most common technical fishway built, the PW geometry consists
12 220 of a series of basins divided by cross-walls, over a sloping channel, that are connected through a
13 221 weir and/or an orifice (Katopodis 1992; Santos et al., 2012). Various sub-types of fish passage
14 222 structures were included within this category (i.e. Ice Harbor, Pool and Orifice, Fish-Bone) and
15 223 several examples of numerical applications were found: from internal flow field analysis (e.g.
16 224 Abdelaziz et al., 2013; Abeyratne et al., 2021; Shahabi et al., 2023), to testing of different layouts
17 225 and geometries (e.g. Li S. et al., 2022; Zhong et al., 2021), and investigating the applicability and
18 226 reliability of different modeling software (e.g. Chen & Tfwala, 2018).

23 227 Fishways types other than those in the previous three categories were also represented in the
24 228 sample, including eel passes, flat W-weirs, island-type fishways, locks in dams, pole-type fishways,
25 229 small culverts and Denil variants such as the Steeppass. Since the number of studies involving these
26 230 kinds of structures was very small, they were grouped together in the category *Other*, and
27 231 contributed to 12.8% of the papers collected (Fig. 3). Additionally, 3.6% described an application of
28 232 numerical modeling for upstream fish passage purposes but without explicitly indicating the
29 233 structure type - e.g. studies within a flume of different cylinder arrangements over a sloping flow
30 234 channel (e.g. Chorda et al., 2019; Ducrocq et al., 2017). Since the methods and aims of these studies
31 235 were overall similar to the other ones, they were included in the collection under the category *Not*
32 236 *Specified* (Fig. 3).

36 237 The aim of each of the 137 papers (i.e. why CFD has been applied to study the internal
37 238 hydrodynamics of fishways) was analyzed and subsequently classified into 7 different categories:

- 40 239 1. Application to theoretical fish passage geometries (experimental setups, inferences from
41 240 other studies) or to non-specified existing structures, studying the relationship between
42 241 modifications of the geometric layout and consequent changes in the flow field (32.8%): to
43 242 assess the impact of fishway geometry changes on hydrodynamics and describe the internal
44 243 hydraulic topology (e.g. Heimerl et al., 2008; Kim et al., 2012; Miranda et al., 2021).
- 45 244 2. Relationship between internal flow field and fish swimming ability (28.5%): to evaluate
46 245 suitability of flow structure and flow parameters with respect to target fish species
47 246 swimming abilities (e.g. Khan, 2006; Li M. et al., 2022; Mao et al., 2012).
- 48 247 3. Application to real structures (18.3%): to study the efficiency of an existing fishway (e.g.
49 248 Bombač et al., 2015), to improve the geometrical design of an existing one (e.g. Bung, 2018)
50 249 or to support the design phase of a new one (e.g. Song et al., 2019).
- 51 250 4. Suitability of different flow equations for internal fishway flow representation (7.3%): to
52 251 compare different equation systems and evaluate the best option (e.g. Stamou et al., 2018)
53 252 or to assess the suitability of the hydraulic model under determined hydrodynamic
54 253 conditions (e.g. Barton et al., 2009).
- 55 254 5. Comparison of different fish passage structures (5.1%): to evaluate which was the best
56 255 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).

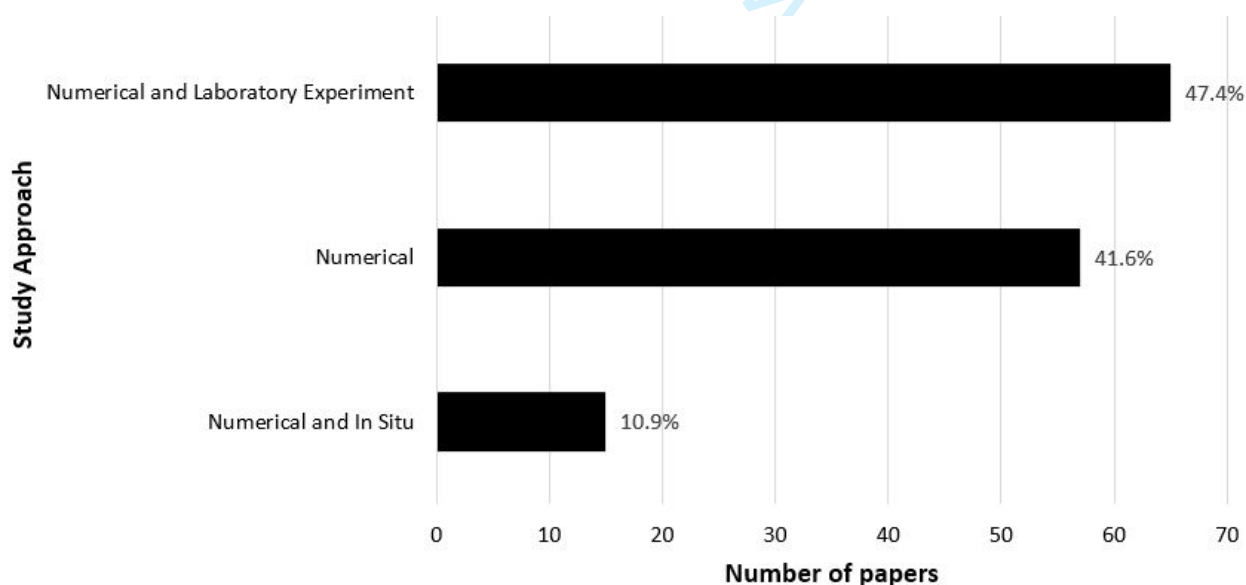


Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated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

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3 285 In more than half of the collection of papers (58.3%) numerical models were coupled with
4 286 laboratory, either flume or physical model, or field experiment. This process, commonly called
5 287 hybrid modeling, is mutually beneficial to both physical and numerical approaches (Bung, 2018;
6 288 Leng & Chanson, 2020b). Results from physical experiments are based on the reconstruction of the
7 289 flow field features through the interpolation of a finite number of sampling velocity points and are,
8 290 therefore, limited by the maximum resolution obtainable in the interpolated raster (Roth et al.,
9 291 2022). Numerical methods offer the possibility to overcome this resolution limit with high quality
10 292 vectorial fields, if an adequately dense computational grid and a suitable closure model to simulate
11 293 turbulence phenomena are provided. For example, when it comes to the analysis of turbulent flow,
12 294 the availability of high quality flow fields is crucial to properly identify the sizes of eddies, as they
13 295 constitute a potential source of hindrance and loss of balance for fish inside the flow (Lacey et al.,
14 296 2012; Silva et al. 2012). Additionally, CFD generates the full flow field distribution, and allows a quick
15 297 and low cost implementation of geometry changes and flow conditions (An et al., 2016; Heimerl et
16 298 al., 2008). In contrast, sufficiently detailed hydrometric measurements may be limited by excessive
17 299 costs, restricted access to some locations due to safety rules or physical impossibility to reach
18 300 preferred gauging positions (Duguay et al., 2017; Leng & Chanson, 2020a). On the other hand,
19 301 physical experiments offer a realistic image of the flow features, provide critical support for
20 302 numerical model validation that is necessary to acquire meaningful results (Amaral et al., 2019;
21 303 Bates et al., 2005), as well as reliable values for setting boundary conditions, a crucial factor for
22 304 model accuracy (Cao et al., 2021). A significant level of expertise (of both the numerical and physical
23 305 process) is required to define and implement a CFD model in a suitable way (Leng & Chanson,
24 306 2020b). In general, the main advantage of coupling physical experiments with numerical models is
25 307 the prospect of a mutually complementary practice that maximizes strengths and minimizes
26 308 weaknesses for each (Leng & Chanson, 2020c).

27 309 In 41.6% of the analyzed papers, the study of the flow field was performed by the application of a
28 310 numerical model alone, without coupling it with a physical experimental version or field
29 311 measurements (Fig. 4). This approach has the advantage of avoiding costs of field work or laboratory
30 312 experiments, providing a flexible and prompt application technique to analyze the flow field
31 313 (Heimerl et al., 2008). Studying internal hydrodynamics of fishways with CFD models also allows
32 314 saving time and resources otherwise allocated to building a structure in real life and subsequently
33 315 evaluating it with flow field measurements (Cao et al., 2021). In many cases though, field
34 316 assessments are crucial in determining fishway effectiveness, especially for non-salmonid species
35 317 (Hershey, 2021; Katopodis & Williams, 2012; Silva et al., 2018). Moreover, the possibility of
36 318 investigating different fishway configurations at the same time, together with the ease of
37 319 implementing changes in geometrical setups, without the rigidity characterizing field or laboratory
38 320 experiments, can play a substantial role towards a quicker and more economical design of effective
39 321 and functioning structures (Abeyratne et al., 2021; Barton et al., 2009). This is valid, as long as the
40 322 CFD model represents the flow field and hydrodynamic parameters well. In fact, an essential aspect
41 323 in the application of CFD modeling is to ascertain that the reproduction of the physical processes
42 324 reflects reality (Khan, 2006), especially in studies based on numerical models only. The reliability of
43 325 a numerical model is assessed through a process of validation of the flow field and hydrodynamic
44 326 parameters. Within hybrid approach studies, where the numerical model was applied together with
45 327 a laboratory or field experiment, the validation of the CFD model was performed through a direct
46 328 comparison with real data obtained and measured by the same researchers involved in the study.

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3 329 When it comes to exclusively numerical studies, the situation is different since no direct flow field
4 330 comparison is immediately available. Typically, in these kinds of studies, the quality assessment of
5 331 the model was carried out by comparing simulation results with previously available data, using one
6 332 of the two following approaches:
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- 9 333 1. Using data from another study where a laboratory experiment or field study was performed,
10 334 and creating the geometry for the new numerical model based on that existing setup (e.g.
11 335 Ballu et al., 2018; Stamou et al., 2018). This “pristine” shape of the model is then validated
12 336 on the same boundary conditions measured in the experiment or field study, comparing the
13 337 flow topology or the parameter values in some crucial areas of the structure (e.g. velocity at
14 338 the slot opening or turbulent kinetic energy in the pools). After a satisfactory validation
15 339 process, tweaks and changes are made to the original model to further explore the effects
16 340 on hydrodynamics.
- 17 339 2. Using as a reference the flow field from another paper’s case study, where a theoretical
18 340 model or fishway geometry was described but either not directly tested or missing some
19 341 information relative to flow parameters, and iteratively fine tuning the boundary conditions
20 342 or slightly tweaking the geometry in order to get the same flow distribution as the original
21 343 study (e.g. Quaranta et al., 2016, 2017).
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27 346 Typically, the aspect that distinguished the first from the second approach was the availability of a
28 347 previous study specifying the boundary conditions. The two approaches were inherently very close.
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30 348 Overall, when applying CFD, the main difference between hybrid and exclusively numerical studies
31 349 was in the modeling validation process. In hybrid studies, the CFD tool was either validated with a
32 350 laboratory or field experiment or used to enhance physical investigations. In the numerically
33 351 exclusive studies, the model’s suitability to reproduce the flow field was examined more directly.
34 352 While model validation was always performed in hybrid studies, in exclusively numerical studies this
35 353 procedure was carried out in 86% of the cases - with 14% not specifying details on how it was
36 354 conducted. Improved validation of CFD models may be obtained with the wider use of available
37 355 hydraulic relationships (e.g. depth-discharge; velocity profiles) from physical modeling studies of
38 356 technical fishways (e.g. Ead et al., 2004; Katopodis, 1992; Katopodis et al., 1997; Wu et al., 1999).
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45 358 **3.4 HYDRODYNAMIC MODELS**

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47 359 Choosing the most suitable numerical model to represent the flow field in a fishway is a delicate
48 360 operation, that requires a certain level of experience from the modeler (Mahl et al., 2021). The set
49 361 of modeling equations, assumptions and approximations should be adapted to the particular layout
50 362 of the fishway that has to be represented (Bates et al., 2005). A strict and precise digitization of
51 363 fishway geometry is fundamental for high simulation accuracy, yet the more detailed the
52 364 description, the more computationally demanding the numerical modeling task becomes
53 365 (Andersson, 2012; Padgett et al., 2020).
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57 366 In general, it is recognized that applying low computationally demanding one-dimensional models
58 367 for fishways may lead to oversimplifications of the physical process, as the inherently three-
59 368 dimensional nature of the flow is neglected (Fuentes-Pérez et al., 2018). In 1D models, variations
60 369 only in one spatial dimension (along the length of the watercourse) are considered, simplifying the

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3 370 analysis by assuming that changes in flow properties occur only in the direction of the flow. With
4 371 the excessively straightforward assumptions and the absence of transversal and vertical
5 372 components of velocity, 1D models do not allow calculation of hydrodynamic parameters, like
6 373 turbulent kinetic energy and energy dissipation rate, fundamental to assess fish passage suitability
7 374 (Santos et al., 2012; Umeda et al., 2017). Only 1.5% of the analyzed papers tested 1D models to
8 375 reproduce fishway hydrodynamics, and they were mainly intended as a preliminary analysis phase
9 376 for a more complex model by interpreting the flow field from the one-dimensional simulation to
10 377 select appropriate turbulence approximations to be adopted in 3D models to catch the flow
11 378 distribution, or by using the resulting values of hydraulic parameters as guidance for the boundary
12 379 conditions of the following 3D models (e.g. Umeda et al., 2017). The potential use of this method in
13 380 a preliminary design or test phase is primarily highlighted as a tool for estimating discharges and
14 381 water levels as input data for more complex hydrodynamic models (Fuentes-Pérez et al., 2018).

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20 382 While the internal flow of fishways is commonly recognized in CFD studies as a three-dimensional
21 383 phenomenon (Gong et al., 2021; Klein & Oertel, 2015), there are some particular cases in which a
22 384 2D approximation can help save time and resources. Actually, physical modeling demonstrated that
23 385 for VSFs with low slopes (< 5%), in a large area of internal pools, flow is approximately bidimensional
24 386 as the vertical component of velocity assumes significant values just in the narrow section of the
25 387 slot (Wu et al. 1999). Several numerical studies assumed 2D flow in VSF with gentle slopes (e.g.
26 388 Ballu et al., 2018; Bombač et al., 2017; Tran et al., 2016). In these conditions, the use of a 2D model
27 389 with Shallow Water Equations (SWE) approximation is justified and can provide useful results in
28 390 terms of identification of fish resting zones and flow topology (Bermúdez et al., 2010; Stamou et al.,
29 391 2018). However, the success of a fishway is highly related to the passage of fish through the slot
30 392 and, so, it is essential to verify the flow characteristics in that zone (Cea et al., 2007). The papers
31 393 that adopted a 2D model to study the flow field (8.8%) applied it to low slope VSF only (e.g.
32 394 Bermúdez et al., 2010; Bombač et al., 2015; Cea et al., 2007), as this approximation would be
33 395 inadequate for steeper VSFs and other types of fish passes with more pronounced three-
34 396 dimensional characteristics of the flow.

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40 397 For most of the CFD applications analyzed, the need for three-dimensional models is widely
41 398 recognized (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2022; Maniecki, 2018). There are
42 399 certain zones (like in the proximity of the slot) and some ranges of discharge and bed slope for which
43 400 simplistic approximations fail to capture important features of flow topology (Cea et al., 2007;
44 401 Chorda et al., 2010). For example, neglecting the vertical component of velocity in 2D models, can
45 402 lead to an overestimation of turbulence parameters and water levels, in the presence of highly
46 403 turbulent flows (Lauchlan Arrowsmith & Zhu, 2014). Therefore, although being more complicated
47 404 and time consuming, 3D CFD is the irreplaceable way to reliably capture the flow numerically (Ballu
48 405 et al., 2018; Bombač et al., 2014). Moreover, the higher flexibility of the meshing algorithms used
49 406 by 3D CFD allows more dynamical changes in geometry and layout compared to 2D models
50 407 (Lauchlan Arrowsmith & Zhu, 2014). Three-dimensional CFD was used in 91.2% of the papers.

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55 408 In addition, among 3D CFD papers, 4.8% adopted the so called Smoothed Particle Hydrodynamics
56 409 method (SPH), a 3D meshless approach in which the fluid domain is discretized in particles and the
57 410 equations of motion are solved with a Lagrangian point of view (e.g. Novak et al., 2019, 2021). In
58 411 contrast to traditional approaches (with Eulerian perspective), SPH grants more flexibility in the
59 412 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).

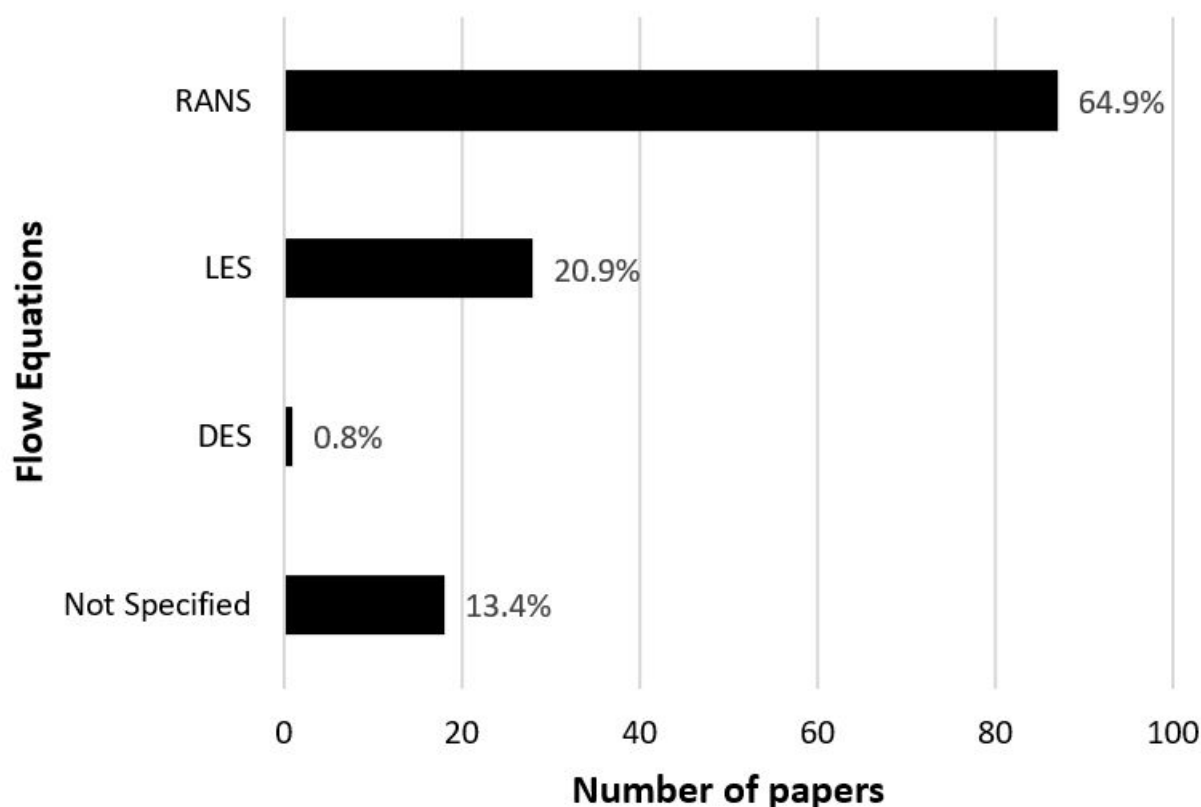


Fig. 5 - Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure models: $k-\epsilon$ and $k-\omega$. 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.

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3 437 The most frequent alternatives to DNS found in the analyzed papers were Reynolds-Averaged
4 438 Navier-Stokes equations (RANS) and Large Eddy Simulation (LES), representing 64.9% and 20.9% of
5 439 the collection, respectively - with 6.6% of the papers applying both methods to compare their
6 440 performance.

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9 441 RANS was the most used method (64.9%), providing a reasonable balance between result accuracy
10 442 and computational cost (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2018). Since RANS are
11 443 based on time averaging of the dynamic variables of the Navier-Stokes equations, they perform well
12 444 in capturing the average flow field, yet are weaker in assessing the turbulent parameters, as they
13 445 depend on the unsteady and time varying features of the flow (Chorda et al., 2010; Fuentes-Pérez
14 446 et al., 2018). For example, several studies outlined the over- or underestimation of turbulent kinetic
15 447 energy from RANS (e.g. Baki et al., 2016; Sanagiotto et al., 2019; Tran et al., 2016). In general, the
16 448 precision of turbulence parameters estimation depends on the type of closure model adopted for a
17 449 specific problem. In RANS, the approaches used mainly consist of the so called two-equation models,
18 450 solving a pair of additional transport equations to obtain a characteristic length and velocity of the
19 451 turbulence process (Andersson, 2012). According to our review, the most used approach was the
20 452 k- ϵ model, implemented in 83.1% of the RANS applications, while the k- ω model was adopted only
21 453 in 10.1% of the cases. In the remaining 6.7% of the RANS applications the equation model used was
22 454 not specified. Even if both equation models are recognized as adequate for general-purpose
23 455 applications of RANS (Andersson, 2012), the disproportionately high use of the k- ϵ model emerging
24 456 from our search, is related to the higher computational time associated with the k- ω model.
25 457 Nevertheless, the performance of k- ω is higher in zones close to solid boundaries and in contexts
26 458 with separating or swirling flows (Ducrocq et al., 2017). In particular, within the k- ω model
27 459 applications, the improved Shear-Stress Transport (SST) k- ω model was adopted in the majority of
28 460 the cases (90%), combining the benefits of both k- ϵ and k- ω approximations and allowing a
29 461 strengthened performance in representing adverse pressure gradient and separating flows (Padgett
30 462 et al., 2020; Zhang et al., 2023). However, since both equation models depend on the Boussinesq
31 463 eddy viscosity approach, RANS suffer from inherent deficiencies deriving from the approximation
32 464 that considers turbulence as an isotropic phenomenon (Andersson, 2012). This contributes to
33 465 limiting the precision of RANS in fishways, where, inside the pools, turbulence is considered strongly
34 466 anisotropic (Duguay et al., 2017). However, fishways are still considered a suitable field of
35 467 application for RANS, as the inner flow topology is represented well overall, despite the limits in
36 468 wakes zones and complex flows (Mahl et al., 2021; Sanagiotto et al., 2019).

37 469 When the flow is highly turbulent, the LES method could be a valid option to improve modeling
38 470 accuracy (Fuentes-Pérez et al., 2022), and it was applied in 20.9% of the cases. Filtering out the small
39 471 but keeping the large turbulent scales from Navier-Stokes equations, the LES method offers a more
40 472 complete description of the instantaneous flow field, overcoming the limits of time-averaging that
41 473 characterize RANS (Chen & Tfwala, 2018). Actually, higher accuracy is linked to the direct simulation
42 474 of large eddies, being more difficult to model due to their anisotropic nature, while small eddies can
43 475 be considered closer to isotropy and thus approximated with subgrid stress models (Andersson,
44 476 2012). In the reviewed papers dealing with LES method, the turbulence closure model adopted for
45 477 small scales was always the standard Smagorinsky one, where the isotropic stress is linked to the
46 478 anisotropic one through an eddy-viscosity approximation (Andersson, 2012). However, the cost for
47 479 improved modeling performance is a longer simulation time and a finer refinement of the
48 480 computational mesh (Padgett et al., 2020; Pope, 2001). Since the correct assessment of flow

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3 481 suitability for fish passage is related to highly turbulent zones in the pools (e.g. near a slot, weir,
4 482 orifice or baffle), and fish responses depend on the instantaneous features of the flow field, the
5 483 increase in computational resources is often needed for a more accurate assessment on how well
6 484 the structure functions (Silva et al., 2012). In addition, some specific hydrodynamic and biological
7 485 applications, such as studying the impact of non-uniformity at flow boundaries (Fuentes-Pérez et
8 486 al., 2018), and the use of the IPOS (turbulence intensity, periodicity, orientation and scale)
9 487 framework (Roth et al., 2022), require LES simulation as the level of turbulence detail provided by
10 488 other methods would be insufficient.

11 489 A way to overcome the limitations of both methods is to adopt a hybrid approximation between
12 490 RANS and LES, called Detached Eddy Simulation (DES). This approach takes the best features of both
13 491 models and keeps computational mesh requirements moderate, switching between the two models
14 492 according to the distance from the solid boundaries (Mahl et al., 2021). Blending the application of
15 493 LES in free flow and RANS in the proximity of a wall (Gisen et al., 2017), DES provides improved
16 494 simulation results both in terms of quality of the flow fields (higher level of details in the turbulent
17 495 scales and time-varying parameters can be reached with respect to RANS) and of computational
18 496 efforts (lower run times are needed compared to pure LES) (Roth et al., 2022). However, the
19 497 detached eddy simulation method was poorly tested in the reviewed literature (0.8% of the papers)
20 498 being applied only to study the suitability of two VSF configurations with the IPOS framework (Roth
21 499 et al., 2022). Considering the several advantages of the DES model and possible improved outcomes,
22 500 this approach may be suitable for future applications that require a high level of detail in the
23 501 description of the turbulent flow features at an overall more efficient use of computational
24 502 resources.

25 503 The remaining 13.4% did not specify the adopted approach to simulate the equations of motion.
26 504 Most of these papers were also not focused on the application of CFD to study the flow, but used it
27 505 as a backup to check for the correct flow representation in laboratory or field experiments (e.g.
28 506 Abdelaziz et al., 2013; Oertel & Schlenkhoff, 2012; Plymesser & Cahoon, 2017).

29 507 In general, selecting the turbulence model that best fits a specific configuration is considered as one
30 508 of the principal challenges in numerical modeling (Benchikh Le Hocine et al., 2019; Duguay et al.,
31 509 2017). The complexity of the physical phenomena together with the variety of the possible
32 510 geometry layouts requires significant modeler competence. However, some general evaluations
33 511 may be undertaken. Since LES models aim to represent three-dimensional time varying flow fields,
34 512 more detail and precision is required in the model setup, as well as a longer process for mesh
35 513 construction and validation - compared to RANS - and time to achieve a converged solution
36 514 (Quaresma et al., 2018). Therefore, while LES application is restricted to more specific experiments
37 515 and research fields, at a smaller spatial scale, RANS are able to reach solution convergence even
38 516 with a coarser mesh, making this method more suitable for large models and more flexible for
39 517 general fishway applications (Fuentes-Pérez et al., 2018). Moreover, underestimation,
40 518 overestimation and errors are always possible, especially for high discharges and hydrodynamically
41 519 complex scenarios, emphasizing the need to always ensure adequate validation of the numerical
42 520 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).

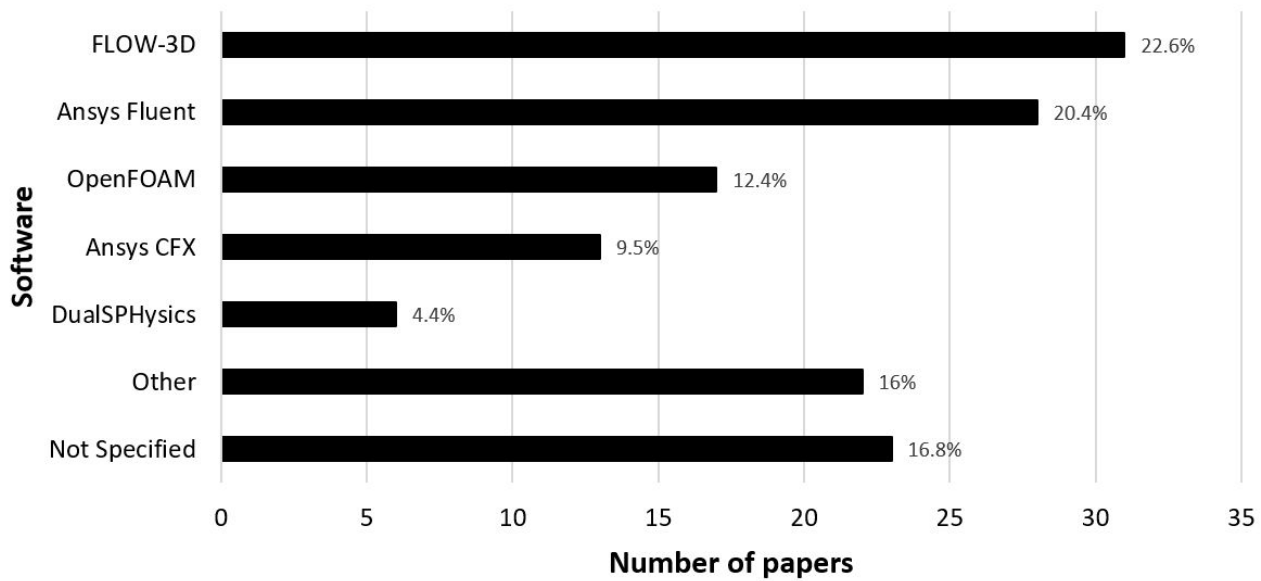


Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code (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).

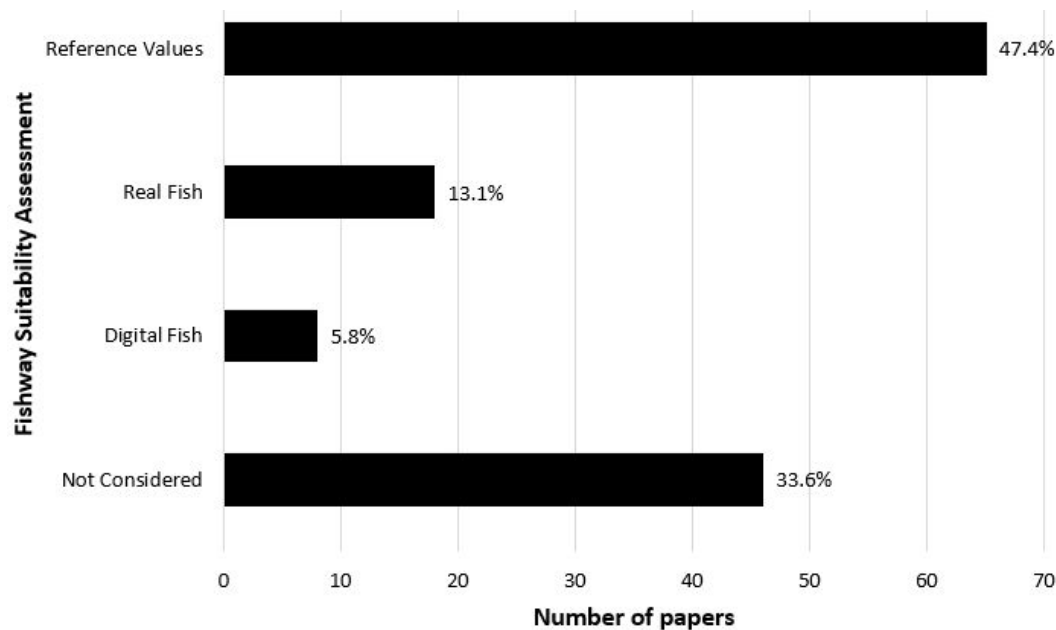


Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. *Digital Fish*: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; *Real Fish*: coupling numerical simulation with a parallel 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 (<i>Luciobarbus bocagei</i>)	21.3%
Grass carp (<i>Ctenopharyngodon idella</i>)	16.7%
Japanese eel (<i>Anguilla japonica</i>)	6.3%
Algae shrimp (<i>Macrobrachium japonicum</i>), Bighead carp (<i>Hypophthalmichthys nobilis</i>), Brown trout (<i>Salmo trutta</i>), Cebacek (<i>Pseudorasbora parva</i>), Common galaxias (<i>Galaxias maculatus</i>), Gitterorfe (<i>Acrossocheilus paradoxus</i>), Gobiobotia (<i>Gobiobotia intermedia</i>), Iberian straightmouth nase (<i>Pseudochondrostoma polylepis</i>), Lambari (<i>Astyanax bimaculatus</i>), Piau (<i>Leporinus reinhardti</i>), sea lamprey (<i>Petromyzon marinus</i>), silver carp (<i>Hypophthalmichthys molitrix</i>), south Iberian barbel (<i>Luciobarbus sclateri</i>), south Iberian chub (<i>Squalius pyrenaicus</i>), Spinibarbus (<i>Spinibarbus hollandi</i>), Stone loach (three species: <i>Triplophysa leptosome</i> , <i>Triplophysa wuweiensis</i> , <i>Triplophysa yarkandensis</i>), Taiwanese freshwater goby (<i>Rhinogobius candidus</i>), white sucker (<i>Catostomus commersonii</i>), Ya-fish (<i>Schizothorax prenanti</i>), Zacco (<i>Zacco pachycephalus</i>)	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 (<i>Luciobarbus bocagei</i>)	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 (<i>Schizothorax prenanti</i>)	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 (<i>Oncorhynchus nerka</i>)	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)
	Preference for areas (close to the flume bottom) with $TKE < 0.05$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	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 (<i>Luciobarbus bocagei</i>)	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 (<i>Squalius pyrenaicus</i>)	11.1 < TL < 15.4cm	Experimental VSF with two different slot configurations (lateral and central baffle)	Romão et al. (2017)
	Preference for $TKE < 0.05$ m ² /s ² .	Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguy et al. (2018)
	Preference for the substrate configuration with $TKE < 0.25$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 17.4 ± 2cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Anaral et al. (2019)
TKE	Preference for $TKE < 0.03$ m ² /s ² (inhibited at $TKE = 0.24$ m ² /s ²).	Atlantic salmon smolts (<i>Salmo salar</i>)	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 (<i>Schizothorax prenanti</i>)	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 (<i>Oncorhynchus mykiss</i>)	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 (<i>Oncorhynchus nerka</i>)	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)
	Injuries/Mortality for $RSS > 700$ N/m ² .	Juvenile Coho salmon (<i>Oncorhynchus kisutch</i>)	/	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 (<i>Luciobarbus bocagei</i>)	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 (<i>Luciobarbus bocagei</i>)	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 (<i>Oncorhynchus nerka</i>)	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)
	$P = 150-200$ W/m ³	Salmonids	/	Pool-type fishways	Lariner (2002)
	$P < 100$ W/m ³	Cyprinids Weak swimmers	/	Pool-type fishways	Lariner (2002)
RSS	Instability when Eddy Size > 76% fish body length.	Creek chub (<i>Semotilus atromaculatus</i>)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Tritico & Cole (2010)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (<i>Luciobarbus bocagei</i>)	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 (<i>Oncorhynchus mykiss</i>)	FL = 8.6 ± 0.6cm	Baffled experimental flume	Duguy 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 (<i>Petromyzon marinus</i>)	TL = 47 ± 4cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)
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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.

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, owing 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

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3 721 input parameters prior to the application of a more sophisticated model (Fuentes-Pérez et al.,
4 722 2018).

- 6 723 4) Reynolds-Averaged Navier-Stokes equations (RANS) was the most frequently used set of
7 724 equations to describe hydrodynamics, striking a balance between accuracy and computational
8 725 cost, and may be suitable for fishway applications despite some limitations in turbulent
9 726 parameter assessment (Chorda et al., 2010). Large Eddy Simulation (LES) is preferred for highly
11 727 turbulent zones but requires higher computational resources (Padgett et al., 2020). Detached
12 728 Eddy Simulation (DES), largely overcomes the limitations of the two previous computational
13 729 schemes, combining the application of LES in the bulk flow and of RANS closer to walls for
15 730 improved simulations (Gisen et al., 2017), yet it was poorly represented in the reviewed CFD
16 731 studies. More frequent use of this method is suggested for an overall more efficient use of
18 732 computational resources.
- 19 733 5) Well-known commercial software were predominantly represented in the collection, compared
20 734 to open-source or custom-made codes, because of their user-friendly interfaces and convenient
22 735 handiness in the meshing process (Fuentes-Pérez et al., 2022). Despite such advantages,
23 736 licensing fee requirements and customizing limitations, prompted several researchers to explore
24 737 the possibilities of open-source software, that represent a cost-free alternative with complete
26 738 access to the source code and more scripting flexibility (Duguay et al., 2017).
- 27 739 6) Suitability for fish passage in numerical studies of fishways was performed following three main
28 740 approaches: a) reproducing fish behavior and decision-making process virtually, through IBM
29 741 algorithms; b) testing and monitoring with live fish experiments in laboratory or field studies;
31 742 and c) comparing obtained flow fields to literature hydrodynamic reference values relative to
32 743 target fish species. The analysis revealed that the latter approach was the most frequent and,
33 744 therefore, the combination with a direct counterpart experiment is often missing in most
35 745 fishway CFD investigations.

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37 746 In general, our findings reveal increasing and widespread use of CFD in fishway science and show
38 747 CFD is a potentially powerful tool for studying and improving the efficiency of fish passage solutions.
39 748 Reliability has grown substantially with recent advancements in computer science and
40 749 computational power, allowing fish ecology researchers and fishway designers to test old and new
42 750 geometry configurations at relatively low cost (Heimerl et al., 2008). Despite the higher reliability,
43 751 accessibility and time-saving use of numerical modeling, compared to laboratory or field
45 752 experiments, adequate expertise on numerical software and simulated physical phenomena are
46 753 required to use the correct equations and computational approximation techniques (Leng &
47 754 Chanson, 2020c). Awareness about what and how well the hydrodynamic environment is simulated,
48 755 as well as ensuring an appropriate model validation procedure, are crucial to obtain realistic and
50 756 accurate results (Leng & Chanson, 2020b). With an aim to maximize efficiency for upstream passage
51 757 of all fish willing to overcome a river obstacle, there is an urgent need for further study of the
52 758 interactions between fish movement behavior and hydrodynamic features, especially turbulence,
54 759 in real fishways or laboratory models. In particular, most needed are innovative studies that link fish
55 760 trajectories with relevant hydrodynamic metrics encountered along routes of movement, to identify
56 761 preferred values and thresholds not to be exceeded (Silva et al., 2012, 2018). Such research
58 762 represents a promising way to expand the currently limited knowledge for a larger number of fish
59 763 species and life-stages and obtain valuable data for designing more efficient fishways with the
60 764 support of CFD.

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11 769 **Data availability statement**
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13 770 The data that support the findings of this study are available as Supplementary Material.
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17 772 **Author contribution statement**
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19 773 FT, CC and CK conceived the idea presented. FT collected and analyzed the papers. FT wrote the
20 774 manuscript with support from CC, CK and DN. All authors discussed the results and contributed to
21 775 the final manuscript.
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11 1 **Computational Fluid Dynamics in fishway research -**
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13 2 **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

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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;

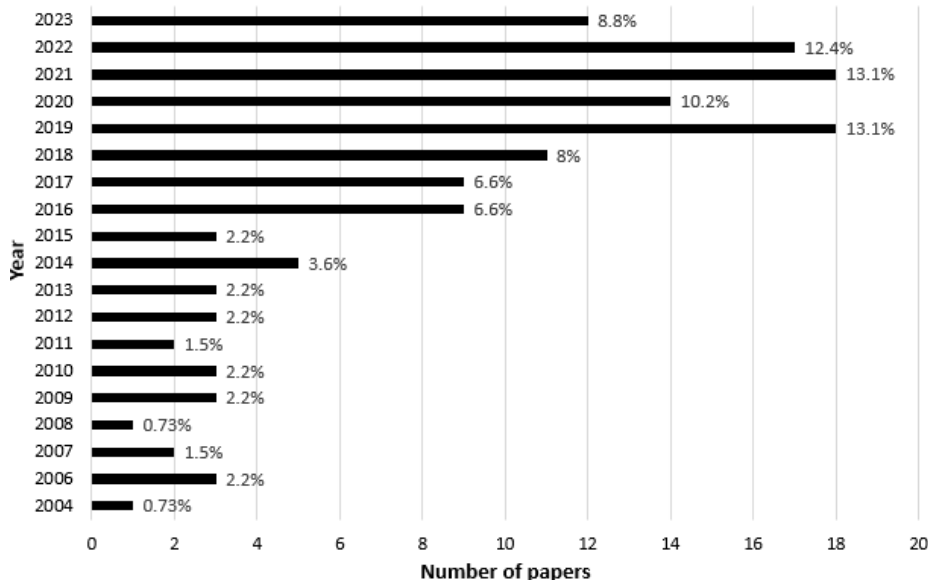
- Type of fishway studied and modeled (e.g. vertical slot, pool and weir, nature-like, etc.);
- Aim of the paper (the reason why a numerical model was used for the analysis of a fishway);
- Approach type (if the numerical model was coupled with physical experiments or applied alone);
- Equations of flow, 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.



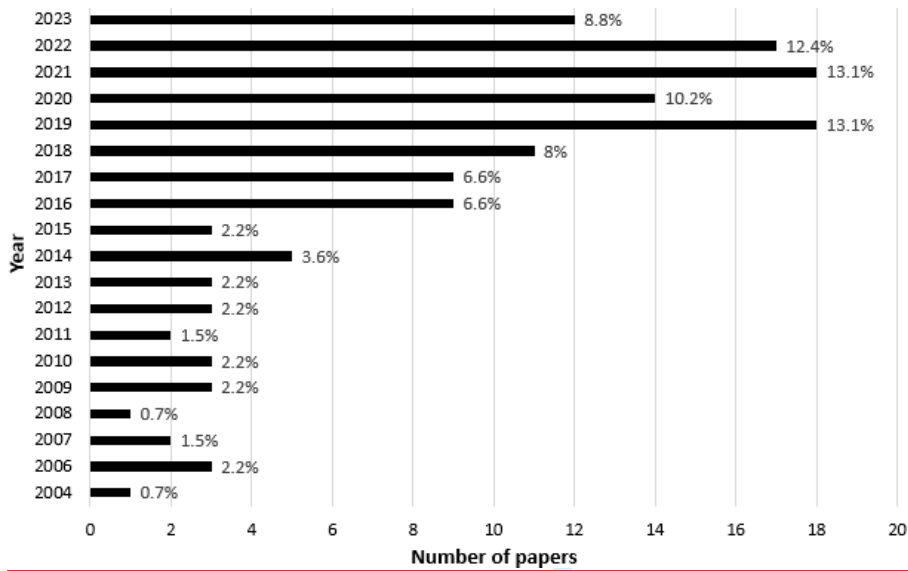


Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

CFD studies were conducted in five continents, encompassing research centres (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.

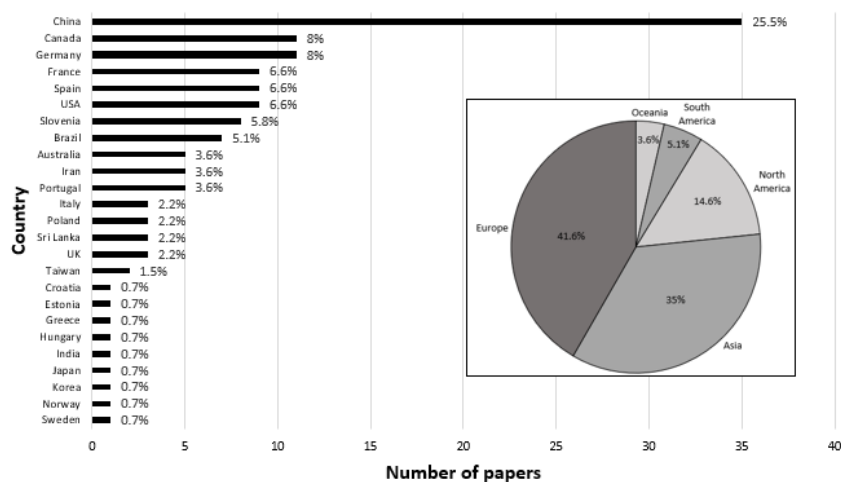


Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

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. Calluud 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).

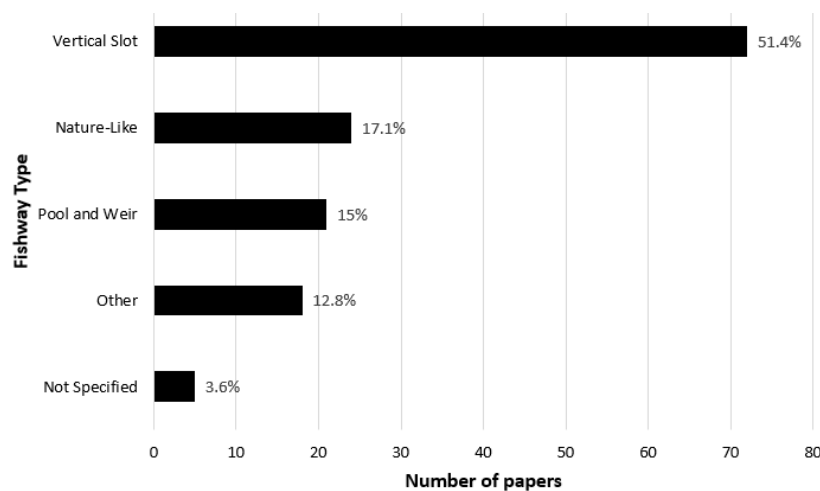


Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steep pass, eel pass, flat Weir, island fishway, Locks in dam, 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) (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. Bombac̆ 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).

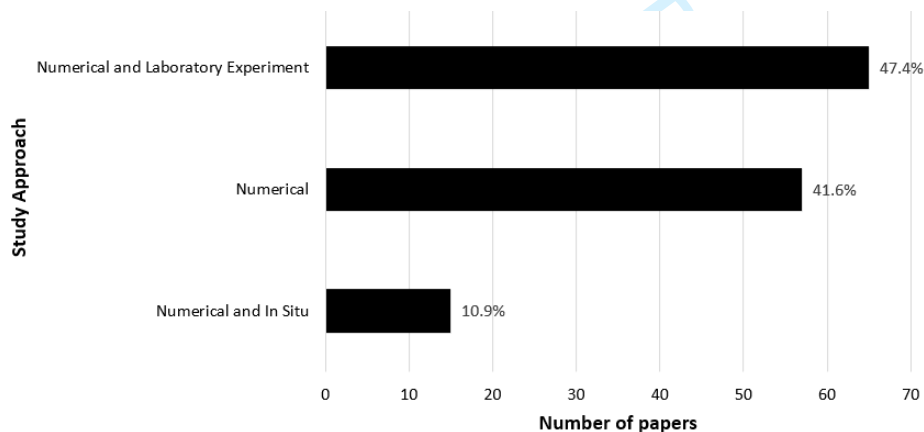


Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated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

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

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

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

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

33 34³⁶³ 35³⁶⁴ **3.4 HYDRODYNAMIC MODELS**

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

44³⁷² In general, it is recognized that applying low computationally demanding one-dimensional models
45³⁷³ for fishways may lead to oversimplifications of the physical process, as the inherently three-
46³⁷⁴ dimensional nature of the flow is neglected (Fuentes-Pérez et al., 2018). In 1D models, variations
47³⁷⁵ only in one spatial dimension (along the length of the watercourse) are considered, simplifying the
48³⁷⁶ analysis by assuming that changes in flow properties occur only in the direction of the flow. With
49³⁷⁷ the excessively straightforward assumptions and the absence of transversal and vertical
50³⁷⁸ components of velocity, 1D models do not allow calculation of hydrodynamic parameters, like
51³⁷⁹ turbulent kinetic energy and energy dissipation rate, fundamental to assess fish passage suitability
52³⁸⁰ (Santos et al., 2012; Umeda et al., 2017). Only 1.5% of the analyzed papers tested 1D models to
53³⁸¹ reproduce fishway hydrodynamics, and they were mainly intended as a preliminary analysis phase
54³⁸² for a more complex model by interpreting the flow field from the one-dimensional simulation to

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11 select appropriate turbulence approximations to be adopted in 3D models to catch the flow
12 distribution, or by using the resulting values of hydraulic parameters as guidance for the boundary
13 conditions of the following 3D models (e.g. Umeda et al., 2017). The potential use of [thesethis](#)
14 method in a preliminary design or test phase is primarily highlighted as a tool for estimating
15 discharges and water levels as input data for more complex hydrodynamic models (Fuentes-Pérez
16 et al., 2018).

17 While the internal flow of fishways is commonly recognized in CFD studies as a three-dimensional
18 phenomenon (Gong et al., 2021; Klein & Oertel, 2015), there are some particular cases in which a
19 2D approximation can help save time and resources. Actually, physical modeling demonstrated that
20 for VSFs with low slopes (< 5%), in a large area of internal pools, flow is approximately bidimensional
21 as the vertical component of velocity assumes significant values just in the narrow section of the
22 slot (Wu et al. 1999). Several numerical studies assumed 2D flow in VSF with gentle slopes (e.g.
23 Ballu et al., 2018; Bombač et al., 2017; Tran et al., 2016). In these conditions, the use of a 2D model
24 with Shallow Water Equations (SWE) approximation is justified and can provide useful results in
25 terms of identification of fish resting zones and flow topology (Bermúdez et al., 2010; Stamou et al.,
26 2018). However, the success of a fishway is highly related to the passage of fish through the slot
27 and, so, it is essential to verify the flow characteristics in that zone (Cea et al., 2007). The papers
28 that adopted a 2D model to study the flow field (8.8%) applied it to low slope VSF only (e.g.
29 Bermúdez et al., 2010; Bombač et al., 2015; Cea et al., 2007), as this approximation would be
30 inadequate for steeper VSFs and other types of fish passes with more pronounced three-
31 dimensional characteristics of the flow.

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

43 In addition, among 3D CFD papers, 4.8% adopted the so called Smoothed Particle Hydrodynamics
44 method (SPH), a 3D meshless approach in which the fluid domain is discretized in particles and the
45 equations of motion are solved with a Lagrangian point of view (e.g. Novak et al., 2019, 2021). In
46 contrast to traditional approaches (with Eulerian perspective), SPH grants more flexibility in the
47 geometry definition, overcoming the limitations of the more rigid process of mesh creation, and its
48 suitability to model 3D flows within fishways has been proved in several cases (e.g. Novak et al.,
49 2019). [However, being a meshless methodology, SPH's application is often limited by the need of a
50 significant computational power - required for the discretization of the fluid domain in elementary
51 particles - and the inherent weaknesses within the definition of the boundary conditions near solid
52 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).

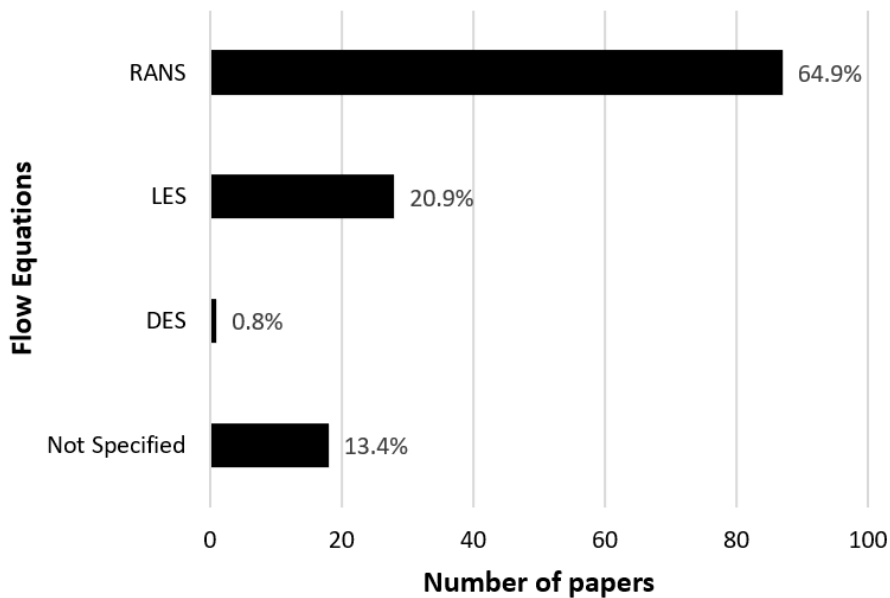


Fig. 5 - ~~Flow~~ Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure models: $k-\epsilon$ and $k-\omega$. 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

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

38⁴⁷⁸ When the flow is highly turbulent, the LES method could be a valid option to improve modeling
39⁴⁷⁹ accuracy (Fuentes-Pérez et al., 2022), and it was applied in 20.9% of the cases. Filtering out the small
40⁴⁸⁰ but keeping the large turbulent scales from Navier-Stokes equations, the LES method offers a more
41⁴⁸¹ complete description of the instantaneous flow field, overcoming the limits of time-averaging that
42⁴⁸² characterize RANS (Chen & Tfwala, 2018). Actually, higher accuracy is linked to the direct simulation
43⁴⁸³ of large eddies, being more difficult to model due to their anisotropic nature, while small eddies can
44⁴⁸⁴ be considered closer to isotropy and thus approximated with subgrid stress models (Andersson,
45⁴⁸⁵ 2012). In the reviewed papers dealing with LES method, the turbulence closure model adopted for
46⁴⁸⁶ small scales was always the standard Smagorinsky one, where the isotropic stress is linked to the
47⁴⁸⁷ anisotropic one through an eddy-viscosity approximation (Andersson, 2012). However, the cost for
48⁴⁸⁸ improved modeling performance is a longer simulation time and a finer refinement of the
49⁴⁸⁹ computational mesh (Padgett et al., 2020; Pope, 2001). Since the correct assessment of flow
50⁴⁹⁰ suitability for fish passage is related to highly turbulent zones in the pools (e.g. near a slot, weir,
51⁴⁹¹ orifice or baffle), and fish responses depend on the instantaneous features of the flow field, the
52⁴⁹² increase in computational resources is often needed for a more accurate assessment on how well
53⁴⁹³ the structure functions (Silva et al., 2012). In addition, some specific hydrodynamic and biological
54⁴⁹⁴ applications, such as studying the impact of non-uniformity at flow boundaries (Fuentes-Pérez et
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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

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11⁵³⁶ result that does not significantly differ in modeling accuracy from the one produced by other known
12⁵³⁷ software (Stamou et al., 2018).

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15⁵³⁹ Commercial licensed codes were used in more than half (52.5%) of the paper collection, with FLOW-
16⁵⁴⁰ 3D and Ansys (Fluent and CFX) being the most common choices (Fig. 6). In addition to providing a
17⁵⁴¹ handy and straightforward modeling environment, they have the advantage of being widely applied,
18⁵⁴² tested and verified in a large number of different studies and applications (Khan, 2006). Despite an
19⁵⁴³ adequate quality in results is nowadays granted by both commercial and open-source software, the
20⁵⁴⁴ former bestow more user-friendliness to readily generate grids of different shapes and geometries,
21⁵⁴⁵ making them suitable for a wide range of applications and still often preferred over open-source
22⁵⁴⁶ ones (Fuentes-Pérez et al., 2022).

23⁵⁴⁷ ~~Despite advantages in terms of user friendly interfaces and adaptability to case studies in~~
24⁵⁴⁸ ~~commercial software, However,~~ the access to the source script is restricted ~~in commercial software,~~
25⁵⁴⁹ and licensing fees often represent a factor limiting use (Duguay et al., 2017). Open source codes
26⁵⁵⁰ overcome these issues with no license fees, and a complete and free access to the source code,
27⁵⁵¹ which can then be adjusted and modified according to the specific needs of the researcher. Several
28⁵⁵² studies (19%) showed the implementation of open source software, with OpenFOAM (12.4%) and
29⁵⁵³ DualSPHysics (4.4%) being the most used ones (Fig. 6). OpenFOAM was successfully applied to study
30⁵⁵⁴ the flow field within both vertical slot, pool and weir and nature-like fishways (e.g. Duguay et al.,
31⁵⁵⁵ 2017; Miranda et al., 2021; Santos et al., 2022). Also, DualSPHysics was applied to study the flow
32⁵⁵⁶ field in vertical slot and nature-like fishways, according to the SPH method, and it delivered suitable
33⁵⁵⁷ results in both cases (e.g. Gomes et al., 2022; Novak et al., 2021). The main drawback of open source
34⁵⁵⁸ codes, to date, is the computational mesh generation process. While in licensed codes the mesh
35⁵⁵⁹ construction is semi-automatic and handled directly within the modeling environment, in open
36⁵⁶⁰ source codes it often relies on external meshing programs with a manual and iterative procedure
37⁵⁶¹ (Fuentes-Pérez et al., 2022).

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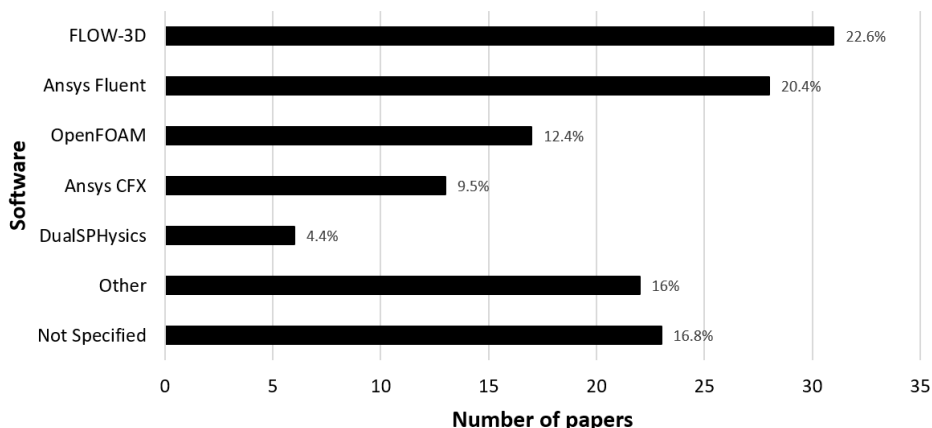


Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code (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).

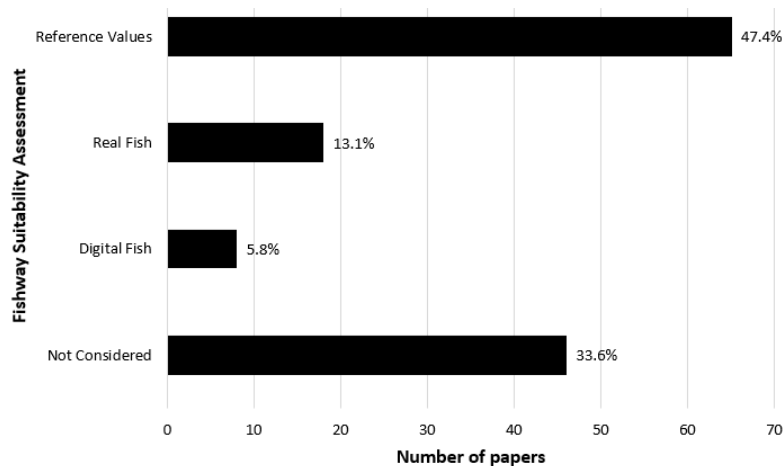


Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. *Digital Fish*: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; *Real Fish*: coupling numerical simulation with a parallel 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 (<i>Luciobarbus bocagei</i>)	21.3%
Grass carp (<i>Ctenopharyngodon idella</i>)	16.7%
Japanese eel (<i>Anguilla japonica</i>)	6.3%
Algae shrimp (<i>Macrobrachium japonicum</i>), Bighead carp (<i>Hypophthalmichthys nobilis</i>), Brown trout (<i>Salmo trutta</i>), Cebacek (<i>Pseudorasbora parva</i>), Common galaxias (<i>Galaxias maculatus</i>), Gitterorfe (<i>Acrossocheilus paradoxus</i>), Gobiobotia intermedia, Iberian straightmouth nase (<i>Pseudochondrostoma polylepis</i>), Lambari (<i>Astyanax bimaculatus</i>), Piau (<i>Leporinus reinhardtii</i>), sea lamprey (<i>Petromyzon marinus</i>), silver carp (<i>Hypophthalmichthys molitrix</i>), south Iberian barbel (<i>Luciobarbus sclateri</i>), south Iberian chub (<i>Squalius pyrenaicus</i>), <i>Spinibarbus hollandi</i> , Stone loach (three species: <i>Triplophysa leptosome</i> , <i>Triplophysa wuweiensis</i> , <i>Triplophysa yarkandensis</i>), Taiwanese freshwater goby (<i>Rhinogobius candidus</i>), white sucker (<i>Catostomus commersonii</i>), Ya-fish (<i>Schizothorax prenanti</i>), <i>Zacco pachycephalus</i>	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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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).

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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.

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 (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm TL = 15.6 ± 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	Marinier et al. (2016)
	Passage preference in zones close to the side walls with $0.1 < V < 0.3$ m/s.	Ya-fish (<i>Schizothorax premeritzi</i>)	$30 < TL < 50$ cm	Experimental VSF	Li G. et al. (2021)
	Avoidance of dam tailrace areas with velocities higher than $V > 2.4$ m/s.	Sockeye salmon (<i>Oncorhynchus nerka</i>)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	L.P. et al. (2021)
	Preference for areas (close to the flume bottom) with $TKE < 0.06$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm TL = 15.6 ± 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	Marinier et al. (2016)
	Baffled performed better also for $0.061 < TKE < 0.021$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	$17.2 < TL < 26$ cm	Experimental VSF with two different slot configurations (lateral and central baffles)	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 (<i>Squalius pyrenaicus</i>)	$11.1 < TL < 15.4$ cm	Experimental VSF	Dugay et al. (2018)
	Preference for the substrate configuration with $TKE < 0.25$ m ² /s ² .	Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.5 ± 0.6cm	Baffled experimental flume	Dugay et al. (2018)
	Preference for the substrate configuration with $TKE < 0.25$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 17.4 ± 2cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
TKE	Preference for $TKE < 0.09$ m ² /s ² (inhibited at $TKE = 0.24$ m ² /s ²).	Atlantic salmon smolts (<i>Salmo salar</i>)	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 (<i>Schizothorax premeritzi</i>)	$30 < TL < 50$ cm	Experimental VSF	Li G. et al. (2021)
	Preference for pool resting zones with $TKE < 0.063$ m ² /s ² .	Rainbow trout (<i>Oncorhynchus mykiss</i>)	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 (<i>Oncorhynchus nerka</i>)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	L.P. et al. (2021)
	Injuries/Mortality for $RSS > 700$ N/m ² .	Juvenile Coho salmon (<i>Oncorhynchus kisutch</i>)	/	CFD and In Situ study of turbine mortality	Čadež et al. (2006)
	Experimental range: $0.02 < RSS < 73.4$ N/m ² . No damage observed within the range but displacement/displacements occurred.	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 15-25cm, 25-35cm	Experimental Pool and Office fishway	Shiva 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 (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm TL = 15.6 ± 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 (<i>Oncorhynchus nerka</i>)	FL = 59.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	L.P. et al. (2021)
	$P = 150-200$ W/m ³ $P = 100-150$ W/m ³ $P < 100$ W/m ³	Salmónids Cyprinids Weak swimmers	/	Pool-type fishways	Larimer (2002)
	Instability when Eddy Size > 76% fish body length.	Creek chub (<i>Bemotilus altonacutus</i>)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Trifeco & Cole (2010)
Eddy Size	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 15-25cm, 25-35cm	Experimental Pool and Office fishway	Shiva et al. (2012)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.5 ± 0.6cm	Baffled experimental flume	Dugay et al. (2018)
	Spatially averaged turbulent length scale magnitude > 0.43 times the average with zero barony (total length) affecting stability in the flow.	Sea lamprey (<i>Petromyzon marinus</i>) White sucker (<i>Catostomus commersoni</i>)	TL = 47 ± 4cm TL = 29 ± 7cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)

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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.

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 (<i>Luciobarbus bocagei</i>)	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.	Ys-fish (<i>Schizothorax prenanti</i>)	/	CFD model of VSF with turning pools	Marriner et al. (2016)
TKE	Passage preference in zones close to the side walls with $0.1 < V < 0.3$ m/s.	Sockeye salmon (<i>Oncorhynchus nerka</i>)	$30 < TL < 50$ cm	Experimental VSF	Li G. et al. (2021)
	Avoidance of dam tailrace areas with velocities higher than $V > 2.4$ m/s.	Iberian barbel (<i>Luciobarbus bocagei</i>)	FL = 50.3 ± 4.0cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
	Preference for areas close to the flume bottom with $TKE < 0.05$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	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 dam tailrace.	/	/	CFD model of VSF with turning pools	Marriner et al. (2016)
	Barbel performed better also for $0.061 < TKE < 0.074$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	$17.2 < TL < 25$ cm	Experimental VSF with two different slot configurations (lateral and central baffles)	Romão et al. (2017)
	Chub performed an higher number of upstream movements in the lateral baffle configuration with $TKE < 0.09$ m ² /s ² .	South Iberian chub (<i>Squalius pyrenaicus</i>)	$11.1 < TL < 15.4$ cm	Experimental VSF with two different slot configurations (lateral and central baffles)	Romão et al. (2017)
	Preference for TKE < 0.05 m ² /s ² .	Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.6 ± 0.8cm	Buffered experimental flume	Dugay et al. (2018)
	Preference for the substrate configuration with $TKE < 0.05$ m ² /s ² .	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 17.4 ± 2.5cm	Experimental and CFD analysis of different bottom substrates for a low ramped weir	Amaral et al. (2019)
	Preference for TKE < 0.09 m ² /s ² (limited at TKE = 0.24 m ² /s ²).	Atlantic salmon smolt (<i>Salmo salar</i>)	TL = 14.70 ± 1.05cm	In Situ and CFD study of an Hydropower plant intake race	Siva et al. (2020)
	Passage preference in zones close to the side walls with $TKE < 0.015$ m ² /s ² .	Ys-fish (<i>Schizothorax prenanti</i>)	$30 < TL < 50$ cm	Experimental VSF	Li G. et al. (2021)
Preference for pool resting zones with $TKE < 0.065$ m ² /s ² .	Rainbow trout (<i>Oncorhynchus mykiss</i>)	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 (<i>Oncorhynchus nerka</i>)	FL = 50.3 ± 4.0cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)	
Injuries/mortality for RSS > 700 N/m ² .	Juvenile Coho salmon (<i>Oncorhynchus kisutch</i>)	/	CFD and In Situ study of turbine mortality	Choi et al. (2006)	
RSS	Experimental range: $0.02 < RSS < 73.4$ N/m ² . No damage observed within the range but disorientation/displacements occurred.	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Siva 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 (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm TL = 19.6 ± 3.1cm TL = 20.7 ± 2.4cm	Experimental Pool-type fishway	Santos et al. (2012)
P	Avoidance of dam tailrace areas with $PSS > 21$ W/m ² .	Sockeye salmon (<i>Oncorhynchus nerka</i>)	FL = 50.3 ± 0.6cm	CFD model and In Situ measurements in a dam tailrace with two water release scenarios	Li P. et al. (2021)
	$P = 150-200$ W/m ² $P = 100-150$ W/m ² $P < 100$ W/m ²	Salmoids Carabids Weak swimmers	/	Pool-type fishways Post-type fishways	Larimer (2003) Larimer (2002)
Eddy Size	Instability when Eddy Size > 76% fish body length.	Creek chub (<i>Semotilus atromaculatus</i>)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Trillo & Colet (2010)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 15-25cm, 25-35cm	Experimental Pool and Orifice fishway	Siva et al. (2012)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.6 ± 0.8cm	Buffered experimental flume	Dugay 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 (<i>Petromyzon marinus</i>)	TL = 47 ± 4cm	Experimental VSF and CFD simulation	Lewandowski et al. (2021)
	White sucker (<i>Catostomus commersoni</i>)	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, owing 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

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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.

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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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For Peer Review Only

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

	Preference for pool resting zones with $TKE < 0.063 \text{ m}^2/\text{s}^2$.
	Avoidance of dam tailrace areas with $TKE > 0.12 \text{ m}^2/\text{s}^2$.
RSS	Injuries/Mortality for $RSS > 700 \text{ N/m}^2$.
	Experimental range: $0.02 < RSS < 73.4 \text{ N/m}^2$. No damage observed within the range but disorientation/displacements occurred.
	Fish spent less time in areas close to $RSS = 60 \text{ N/m}^2$ (experiment range: $20 < RSS < 60 \text{ N/m}^2$).
	Avoidance of dam tailrace areas with $RSS > 21 \text{ N/m}^2$.
P	$P = 150\text{-}200 \text{ W/m}^3$
	$P = 100\text{-}150 \text{ W/m}^3$
	$P < 100 \text{ W/m}^3$
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 (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm
	TL = 19.6 ± 3.1cm
	TL = 20.7 ± 2.4cm
/	/
Ya-fish (<i>Schizothorax prenanti</i>)	30 < TL < 50cm
Sockeye salmon (<i>Oncorhynchus nerka</i>)	FL = 59.3 ± 0.6cm
Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 18.6 ± 3.1cm
	TL = 19.6 ± 3.1cm
	TL = 20.7 ± 2.4cm
/	/
Iberian barbel (<i>Luciobarbus bocagei</i>)	17.2 < TL < 26cm
South iberian chub (<i>Squalius pyrenaicus</i>)	11.1 < TL < 15.4cm
Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	FL = 8.6 ± 0.6cm
Iberian barbel (<i>Luciobarbus bocagei</i>)	TL = 17.4 ± 2cm
Atlantic salmon smolts (<i>Salmo salar</i>)	TL = 14.70 ± 1.05cm
Ya-fish (<i>Schizothorax prenanti</i>)	30 < TL < 50cm

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

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3	Pool and Weir fishway (with W-	Shahabi et al. (2021)
4	weirs)	
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6	CFD model and In Situ	
7	measurements in a dam tailrace with	Li P. et al. (2021)
8	two water release scenarios	
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12	CFD and In Situ study of turbine	
13	mortality	Čada et al. (2006)
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16	Experimental Pool and Orifice	
17	fishway	Silva et al. (2012)
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21	Experimental Pool-type fishway	Santos et al. (2012)
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25	CFD model and In Situ	
26	measurements in a dam tailrace with	Li P. et al. (2021)
27	two water release scenarios	
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31	Pool-type fishways	Larinier (2002)
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33	Pool-type fishways	Larinier (2002)
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35	Pool-type fishways	Larinier (2002)
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37	Flume experiment with different	
38	cylinders arrays	Tritico & Cotel (2010)
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41	Experimental Pool and Orifice	
42	fishway	Silva et al. (2012)
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45	Baffled experimental flume	Duguay et al. (2018)
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50	Experimental VSF and CFD	
51	simulation	Lewandowski et al. (2021)
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Species
Iberian barbel (<i>Luciobarbus bocagei</i>)
Grass carp (<i>Ctenopharyngodon idella</i>)
Japanese eel (<i>Anguilla japonica</i>)
Algae shrimp (<i>Macrobrachium japonicum</i>), Bighead carp (<i>Hypophthalmichthys nobilis</i>), Brown trout (<i>Salmo trutta</i>), Cebacek (<i>Pseudorasbora parva</i>), Common galaxias (<i>Galaxias maculatus</i>), Gitterorfe (<i>Acrossochelys paradoxus</i>), <i>Gobiobotia intermedia</i> , Iberian straightmouth nase (<i>Pseudochondrostoma polylepis</i>), Lambari (<i>Astyanax bimaculatus</i>), Piau (<i>Leporinus reinhardti</i>), sea lamprey (<i>Petromyzon marinus</i>), silver carp (<i>Hypophthalmichthys molitrix</i>), south Iberian barbel (<i>Luciobarbus sclateri</i>), south Iberian chub (<i>Squalius pyrenaicus</i>), <i>Spinibarbus hollandi</i> , Stone loach (three species: <i>Triplophysa leptosome</i> , <i>Triplophysa wuweiensis</i> , <i>Triplophysa yarkandensis</i>), Taiwanese freshwater goby (<i>Rhinogobius candidus</i>), white sucker (<i>Catostomus commersonii</i>), Ya-fish (<i>Schizothorax prenanti</i>), <i>Zacco pachycephalus</i>

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