

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

Original

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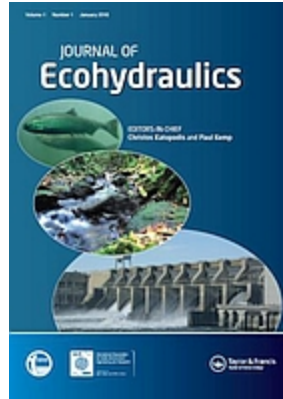
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Computational Fluid Dynamics in fishway research - a systematic review on upstream fish passage solutions

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Complete List of Authors:	Tarena, Fabio; Politecnico di Torino Comoglio, Claudio; Politecnico di Torino, DIATI Nyqvist, Daniel; Politecnico di Torino Katopodis, Christos; Katopodis Ecohydraulics Ltd.
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

11
12 4 Fabio Tarena^{1*}, Daniel Nyqvist¹, Christos Katopodis², and Claudio Comoglio¹
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17
18 6 ¹ Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Italy

19 7 ² Katopodis Ecohydraulics Ltd., Winnipeg, Canada

20
21 8 *Fabio Tarena, Politecnico di Torino – DIATI, Corso Duca degli Abruzzi, 24, 10129, Torino
22
23 9

24 25 10 **Emails and ORCID:**

26
27 11 Fabio Tarena: fabio.tarena@polito.it; 0009-0004-4465-3537
28

29 12 Daniel Nyqvist: daniel.nyqvist@polito.it; 0000-0002-3098-0594
30

31 13 Christos Katopodis: katopodisecohydraulics@live.ca; 0000-0001-7752-4409
32
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34 14 Claudio Comoglio : claudio.comoglio@polito.it; 0000-0002-7962-0653
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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.

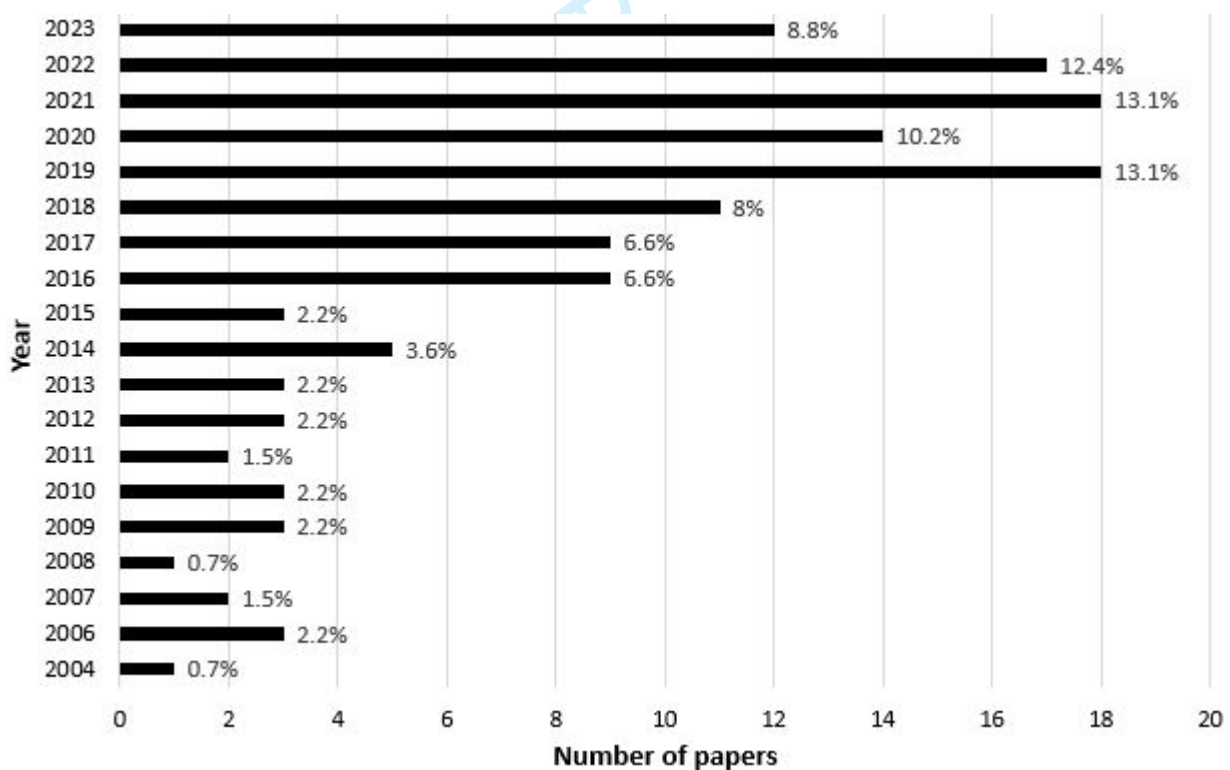


Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

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.

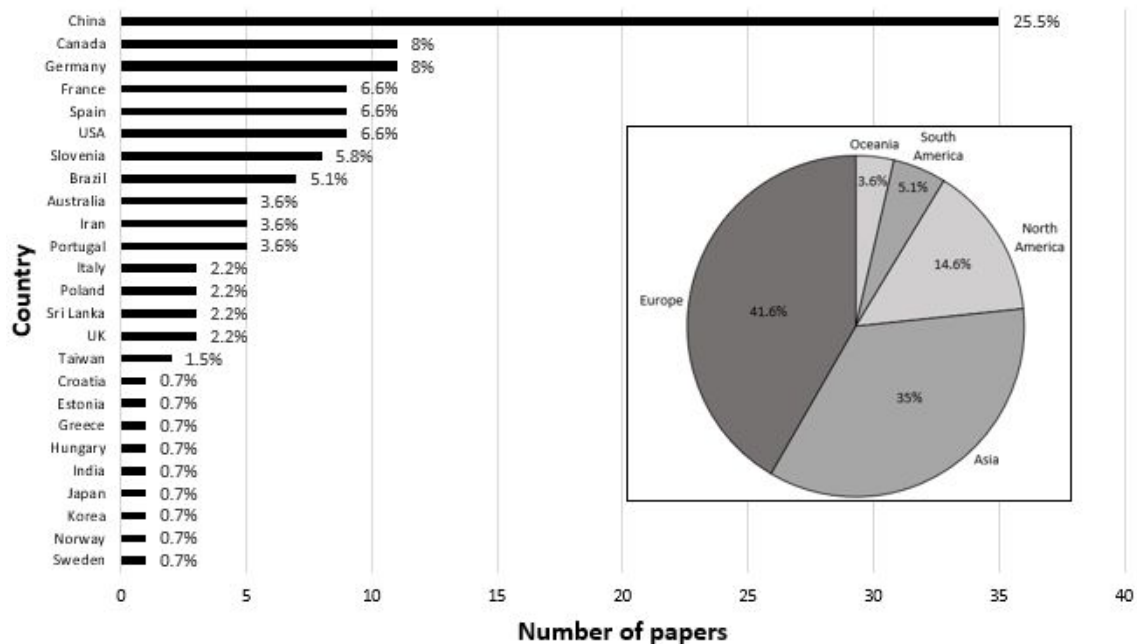


Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

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).

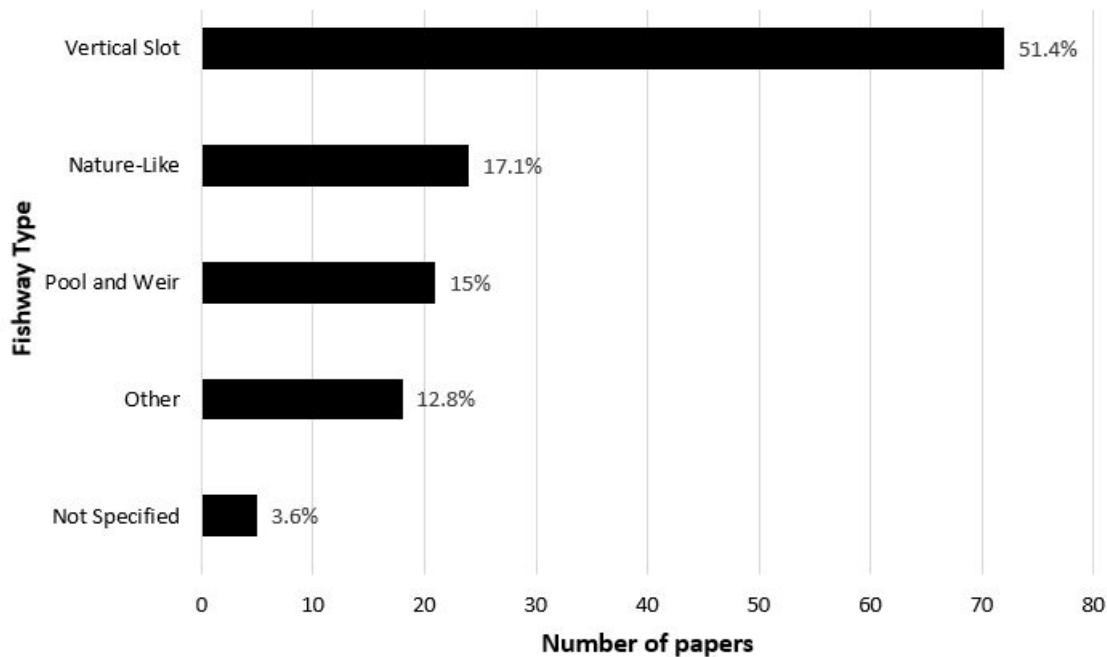


Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steep pass, eel pass, flat W-weir, island fishway, locks in dam,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

- 39 239 1. Application to theoretical fish passage geometries (experimental setups, inferences from
40 240 other studies) or to non-specified existing structures, studying the relationship between
41 241 modifications of the geometric layout and consequent changes in the flow field (32.8%): to
42 242 assess the impact of fishway geometry changes on hydrodynamics and describe the internal
43 243 hydraulic topology (e.g. Heimerl et al., 2008; Kim et al., 2012; Miranda et al., 2021).
- 44 244 2. Relationship between internal flow field and fish swimming ability (28.5%): to evaluate
45 245 suitability of flow structure and flow parameters with respect to target fish species
46 246 swimming abilities (e.g. Khan, 2006; Li M. et al., 2022; Mao et al., 2012).
- 47 247 3. Application to real structures (18.3%): to study the efficiency of an existing fishway (e.g.
48 248 Bombač et al., 2015), to improve the geometrical design of an existing one (e.g. Bung, 2018)
49 249 or to support the design phase of a new one (e.g. Song et al., 2019).
- 50 250 4. Suitability of different flow equations for internal fishway flow representation (7.3%): to
51 251 compare different equation systems and evaluate the best option (e.g. Stamou et al., 2018)
52 252 or to assess the suitability of the hydraulic model under determined hydrodynamic
53 253 conditions (e.g. Barton et al., 2009).
- 54 254 5. Comparison of different fish passage structures (5.1%): to evaluate which was the best
55 255 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).

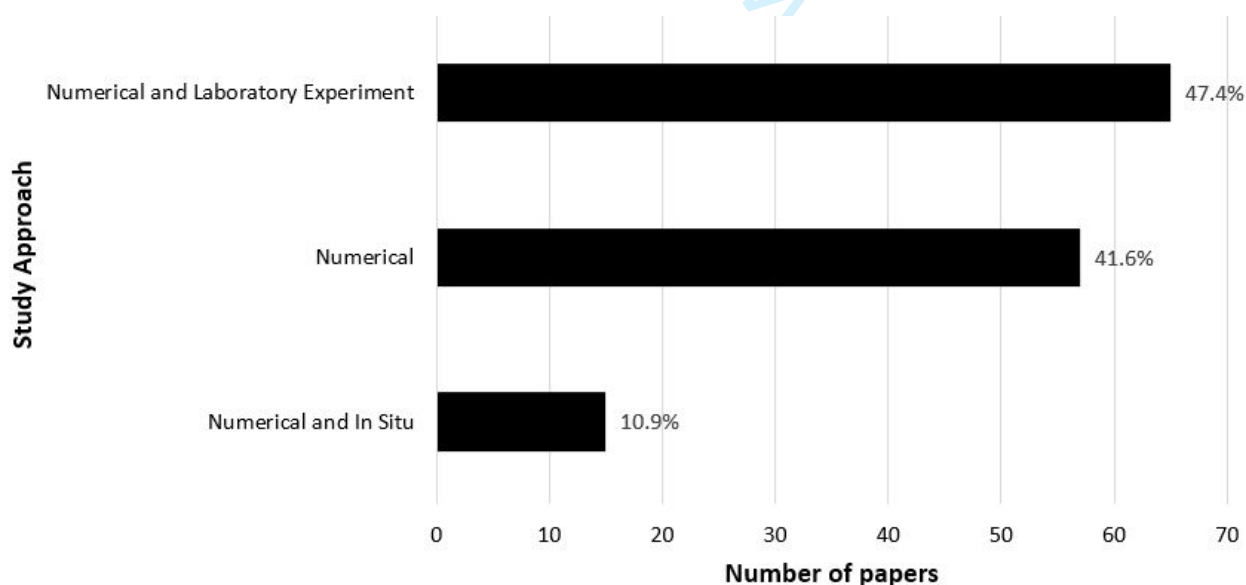


Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated 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.
- 17 341 2. Using as a reference the flow field from another paper’s case study, where a theoretical
18 342 model or fishway geometry was described but either not directly tested or missing some
19 343 information relative to flow parameters, and iteratively fine tuning the boundary conditions
20 344 or slightly tweaking the geometry in order to get the same flow distribution as the original
21 345 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).

15 382 While the internal flow of fishways is commonly recognized in CFD studies as a three-dimensional
16 383 phenomenon (Gong et al., 2021; Klein & Oertel, 2015), there are some particular cases in which a
17 384 2D approximation can help save time and resources. Actually, physical modeling demonstrated that
18 385 for VSFs with low slopes (< 5%), in a large area of internal pools, flow is approximately bidimensional
19 386 as the vertical component of velocity assumes significant values just in the narrow section of the
20 387 slot (Wu et al. 1999). Several numerical studies assumed 2D flow in VSF with gentle slopes (e.g.
21 388 Ballu et al., 2018; Bombač et al., 2017; Tran et al., 2016). In these conditions, the use of a 2D model
22 389 with Shallow Water Equations (SWE) approximation is justified and can provide useful results in
23 390 terms of identification of fish resting zones and flow topology (Bermúdez et al., 2010; Stamou et al.,
24 391 2018). However, the success of a fishway is highly related to the passage of fish through the slot
25 392 and, so, it is essential to verify the flow characteristics in that zone (Cea et al., 2007). The papers
26 393 that adopted a 2D model to study the flow field (8.8%) applied it to low slope VSF only (e.g.
27 394 Bermúdez et al., 2010; Bombač et al., 2015; Cea et al., 2007), as this approximation would be
28 395 inadequate for steeper VSFs and other types of fish passes with more pronounced three-
29 396 dimensional characteristics of the flow.

30 397 For most of the CFD applications analyzed, the need for three-dimensional models is widely
31 398 recognized (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2022; Maniecki, 2018). There are
32 399 certain zones (like in the proximity of the slot) and some ranges of discharge and bed slope for which
33 400 simplistic approximations fail to capture important features of flow topology (Cea et al., 2007;
34 401 Chorda et al., 2010). For example, neglecting the vertical component of velocity in 2D models, can
35 402 lead to an overestimation of turbulence parameters and water levels, in the presence of highly
36 403 turbulent flows (Lauchlan Arrowsmith & Zhu, 2014). Therefore, although being more complicated
37 404 and time consuming, 3D CFD is the irreplaceable way to reliably capture the flow numerically (Ballu
38 405 et al., 2018; Bombač et al., 2014). Moreover, the higher flexibility of the meshing algorithms used
39 406 by 3D CFD allows more dynamical changes in geometry and layout compared to 2D models
40 407 (Lauchlan Arrowsmith & Zhu, 2014). Three-dimensional CFD was used in 91.2% of the papers.

41 408 In addition, among 3D CFD papers, 4.8% adopted the so called Smoothed Particle Hydrodynamics
42 409 method (SPH), a 3D meshless approach in which the fluid domain is discretized in particles and the
43 410 equations of motion are solved with a Lagrangian point of view (e.g. Novak et al., 2019, 2021). In
44 411 contrast to traditional approaches (with Eulerian perspective), SPH grants more flexibility in the
45 412 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).

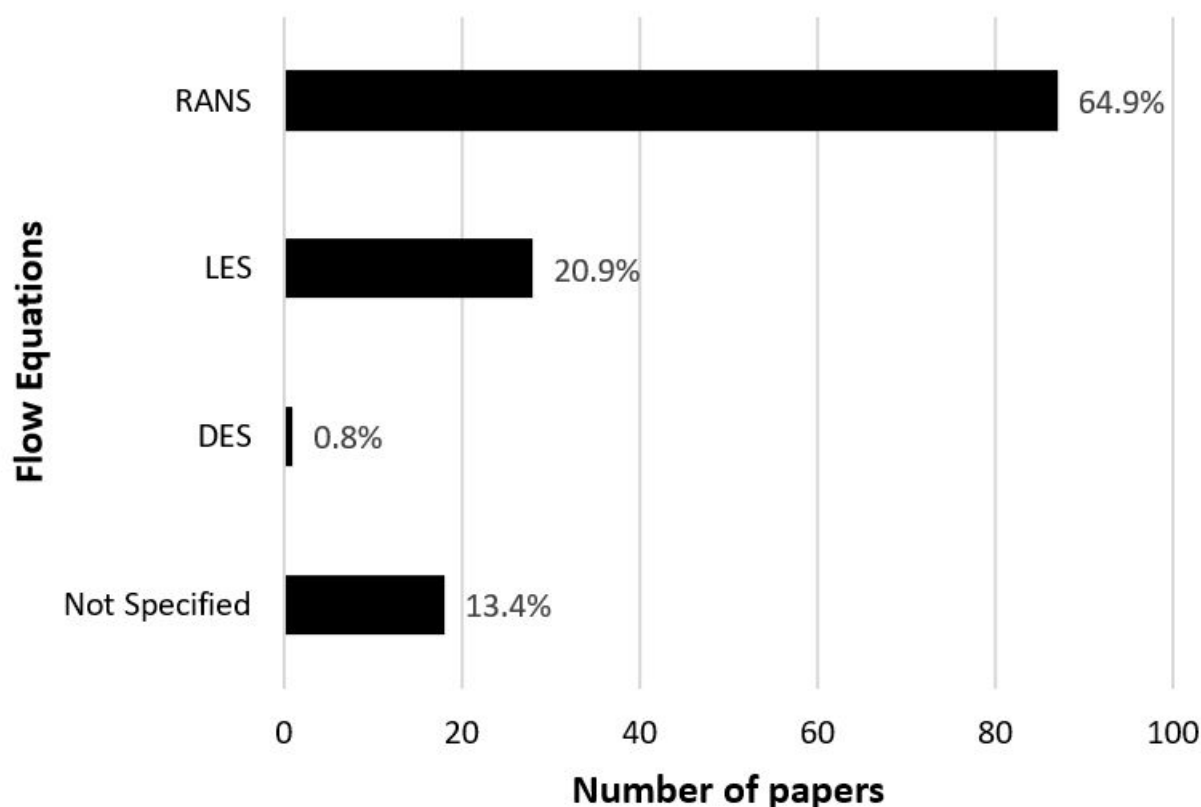


Fig. 5 - Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure models: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

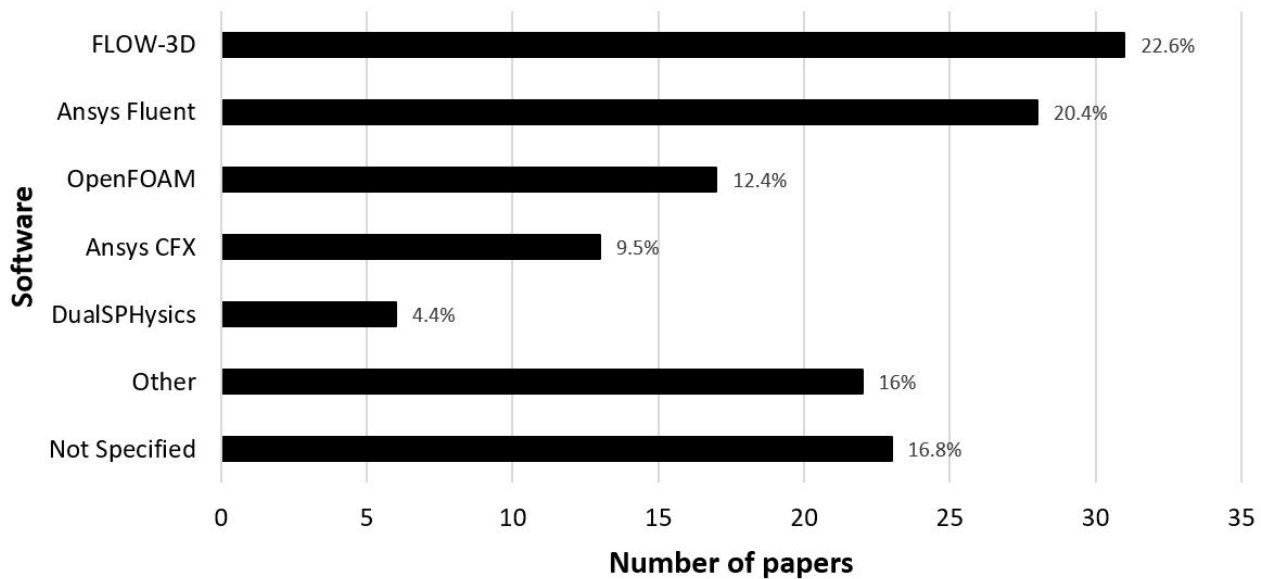


Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code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

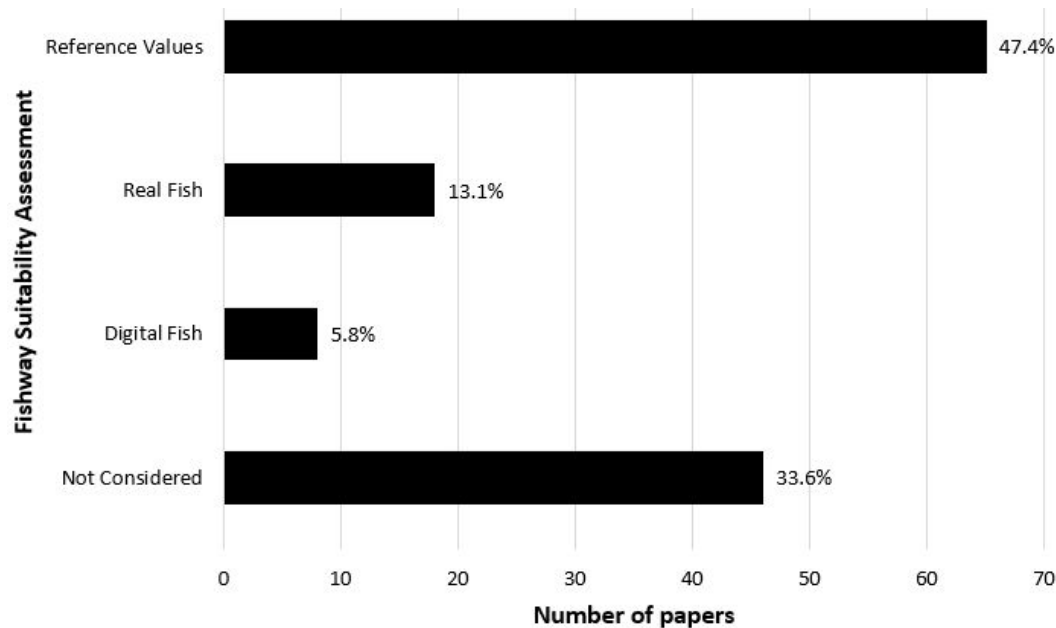


Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. *Digital Fish*: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; *Real Fish*: coupling numerical simulation with a parallel 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	
	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)
		White sucker (<i>Catostomus commersonii</i>)	TL = 29 ± 7cm		
P					
Eddy Size					

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
21 735 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
25 738 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
44 752 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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2
3 794 **REFERENCES**

- 5 795 Abdelaziz, S., Bui, M. D., Atsushi, N., & Rutschmann, P. (2013). *Numerical Simulation of Flow and Upstream Fish*
6 796 *Movement inside a Pool-and-Weir Fishway*. Proceedings of 2013 IAHR World Congress.
- 8 797 Abeyratne, W. M. L. K., Weerasinghe, P. S., & Weerakoon, S. B. (2021). Modeling of Flow in a Weir and Pool Fishway
9 798 With Orifices for Optimizing the Fishway Design. In L. Venkatakrisnan, S. Majumdar, G. Subramanian, G. S. Bhat, R.
10 799 Dasgupta, & J. Arakeri (Eds.), *Proceedings of 16th Asian Congress of Fluid Mechanics* (pp. 527–534). Springer Singapore.
11 800 https://doi.org/10.1007/978-981-15-5183-3_56
- 12
13 801 Amaral, S. D., Quaresma, A. L., Branco, P., Romão, F., Katopodis, C., Ferreira, M. T., Pinheiro, A. N., & Santos, J. M. (2019).
14 802 Assessment of Retrofitted Ramped Weirs to Improve Passage of Potamodromous Fish. *Water*, 11(12), 2441.
15 803 <https://doi.org/10.3390/w11122441>
- 16 804 An, R., Li, J., Liang, R., & Tuo, Y. (2016). Three-dimensional simulation and experimental study for optimising a vertical
17 805 slot fishway. *Journal of Hydro-Environment Research*, 12, 119–129. <https://doi.org/10.1016/j.jher.2016.05.005>
- 19 806 Andersson, A. G., Leonardsson, K., Lindberg, D.-E., Lundström, T. S., Hellström, J. G. I., & Lundqvist, H. (2016). *Describing*
20 807 *fish passage in a river confluence with telemetry and CFD*. 11th ISE 2016, Melbourne, Australia.
- 22 808 Andersson, B. (Ed.). (2012). *Computational fluid dynamics for engineers*. Cambridge University Press. The Edinburgh
23 809 Building, Cambridge CB2 8RU, UK.
- 24 810 Baki, A. B. M., Zhu, D. Z., & Rajaratnam, N. (2016). Flow Simulation in a Rock-Ramp Fish Pass. *Journal of Hydraulic*
25 811 *Engineering*, 142(10), 04016031. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001166](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001166)
- 27 812 Ballu, A., Pineau, G., Calluau, D., & David, L. (2018). *Influence of Macro-Roughnesses on Vertical Slot Fishways*. 7th
28 813 International Symposium on Hydraulic Structures, Aachen, Germany. <https://doi.org/10.15142/T39S7Q>
- 30 814 Barton, A. F., Keller, R. J., & Katopodis, C. (2009). Verification of a numerical model for the prediction of low slope vertical
31 815 slot fishway hydraulics. *Australasian Journal of Water Resources*, 13(1), 53–60.
32 816 <https://doi.org/10.1080/13241583.2009.11465360>
- 33
34 817 Bates, P. D., Lane, S. N., & Ferguson, R. I. (2005). *Computational fluid dynamics: Applications in environmental hydraulics*.
35 818 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.
- 36 819 Benchikh Le Hocine, A. E., Lacey, R. W. J., & Poncet, S. (2019). Turbulent flow over a D-section bluff body: A numerical
37 820 benchmark. *Environmental Fluid Mechanics*, 19(2), 435–456. <https://doi.org/10.1007/s10652-018-9634-4>
- 38
39 821 Bermúdez, M., Puertas, J., Cea, L., & Pena, L. (Eds.). (2010). Experimental and numerical evaluation of sixteen different
40 822 designs of vertical slot fishways. In *Environmental Hydraulics, Two Volume Set* (0 ed., pp. 1143–1148). CRC Press.
41 823 <https://doi.org/10.1201/b10553-194>
- 42
43 824 Bermúdez, M., Puertas, J., Cea, L., Pena, L., & Balairón, L. (2010). Influence of pool geometry on the biological efficiency
44 825 of vertical slot fishways. *Ecological Engineering*, 36(10), 1355–1364. <https://doi.org/10.1016/j.ecoleng.2010.06.013>
- 45 826 Bombač, M., Četina, M., & Novak, G. (2017). Study on flow characteristics in vertical slot fishways regarding slot layout
46 827 optimization. *Ecological Engineering*, 107, 126–136. <https://doi.org/10.1016/j.ecoleng.2017.07.008>
- 48 828 Bombač, M., Novak, G., Mlačnik, J., & Četina, M. (2015). Extensive field measurements of flow in vertical slot fishway as
49 829 data for validation of numerical simulations. *Ecological Engineering*, 84, 476–484.
50 830 <https://doi.org/10.1016/j.ecoleng.2015.09.030>
- 51
52 831 Bombač, M., Novak, G., Rodič, P., & Četina, M. (2014). Numerical and physical model study of a vertical slot fishway.
53 832 *Journal of Hydrology and Hydromechanics*, 62(2), 150–159. <https://doi.org/10.2478/johh-2014-0013>
- 54 833 Bravo-Córdoba, F. J., Fuentes-Pérez, J. F., Valbuena-Castro, J., Martínez de Azagra-Paredes, A., & Sanz-Ronda, F. J.
55 834 (2021). Turning Pools in Stepped Fishways: Biological Assessment via Fish Response and CFD Models. *Water*, 13(9),
56 835 1186. <https://doi.org/10.3390/w13091186>
- 58 836 Brown, A., Muller, S., & Dobrotkova, Z. (2011). Markets and Prospects by Technology. *RENEWABLE ENERGY*.
59 837 International Energy Agency, 9 rue de la Federation, 75739 Paris Cedex 15, France.
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42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 838 Bung, D., Valero D. & Hermens G. (2018). *Hybrid Investigation on the Hydraulic Performance of a New Trapezoidal Fishway*. 7th International Symposium on Hydraulic Structures, Aachen, Germany. <https://doi.org/10.15142/T3S06R>
- 840 Čada, G., Loar, J., Garrison, L., Fisher, R., & Neitzel, D. (2006). Efforts to Reduce Mortality to Hydroelectric Turbine-Passed Fish: Locating and Quantifying Damaging Shear Stresses. *Environmental Management*, 37(6), 898–906. <https://doi.org/10.1007/s00267-005-0061-1>
- 843 Calluad, D., Pineau, G., Texier, A., & David, L. (2014). Modification of vertical slot fishway flow with a supplementary cylinder. *Journal of Hydraulic Research*, 52(5), 614–629. <https://doi.org/10.1080/00221686.2014.906000>
- 845 Cao, P., Mu, X., Li, X., Baiyin, B., Wang, X., & Zhen, W. (2021). Relationship between Upstream Swimming Behaviors of Juvenile Grass Carp and Characteristic Hydraulic Conditions of a Vertical Slot Fishway. *Water*, 13(9), 1299. <https://doi.org/10.3390/w13091299>
- 848 Cea, L., Pena, L., Puertas, J., Vázquez-Cendón, M. E., & Peña, E. (2007). Application of Several Depth-Averaged Turbulence Models to Simulate Flow in Vertical Slot Fishways. *Journal of Hydraulic Engineering*, 133(2), 160–172. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:2\(160\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:2(160))
- 851 Chen, S. C., & Tfwala, S. S. (2018). *Performance Assessment of FLOW-3D and XFlow in the Numerical Modelling of Fishbone Type Fishway Hydraulics*. <https://doi.org/10.15142/T3HH1J>
- 853 Chorda, J., Cassan, L., & Laurens, P. (2019). Modeling Steep-Slope Flow across Staggered Emergent Cylinders: Application to Fish Passes. *Journal of Hydraulic Engineering*, 145(11), 04019038. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001630](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001630)
- 856 Chorda, J., Maubourguet, M. M., Roux, H., Larinier, M., Tarrade, L., & David, L. (2010). Two-dimensional free surface flow numerical model for vertical slot fishways. *Journal of Hydraulic Research*, 48(2), 141–151. <https://doi.org/10.1080/00221681003703956>
- 859 Clay, H.C. (1995). *Design of Fishways and Other Fish Facilities* (1st ed.). CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431. <https://doi.org/10.1201/9781315141046>
- 861 Ducrocq, T., Cassan, L., Chorda, J., & Roux, H. (2017). Flow and drag force around a free surface piercing cylinder for environmental applications. *Environmental Fluid Mechanics*, 17(4), 629–645. <https://doi.org/10.1007/s10652-016-9505-9>
- 864 Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., Naiman, R. J., Prieur-Richard, A.-H., Soto, D., Stiassny, M. L. J., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, 81(02), 163. <https://doi.org/10.1017/S1464793105006950>
- 867 Duguay, J., Foster, B., Lacey, J., & Castro-Santos, T. (2018). Sediment infilling benefits rainbow trout passage in a baffled channel. *Ecological Engineering*, 125, 38–49. <https://doi.org/10.1016/j.ecoleng.2018.10.003>
- 869 Duguay, J. M., Lacey, R. W. J., & Gaucher, J. (2017). A case study of a pool and weir fishway modeled with OpenFOAM and FLOW-3D. *Ecological Engineering*, 103, 31–42. <https://doi.org/10.1016/j.ecoleng.2017.01.042>
- 871 Ead, S. A., Katopodis, C., Sikora, G. J., & Rajaratnam, N. (2004). Flow regimes and structure in pool and weir fishways. *Journal of Environmental Engineering and Science*, 3(5), 379–390. <https://doi.org/10.1139/s03-073>
- 873 Feigenwinter, L., Vetsch, D., Kammerer, S., Kriewitz, C., & Boes, R. (2019). Conceptual Approach for Positioning of Fish Guidance Structures Using CFD and Expert Knowledge. *Sustainability*, 11(6), 1646. <https://doi.org/10.3390/su11061646>
- 875 Fuentes-Pérez, J. F., Quaresma, A. L., Pinheiro, A., & Sanz-Ronda, F. J. (2022). OpenFOAM vs FLOW-3D: A comparative study of vertical slot fishway modelling. *Ecological Engineering*, 174, 106446. <https://doi.org/10.1016/j.ecoleng.2021.106446>
- 878 Fuentes-Pérez, J. F., Silva, A. T., Tuhtan, J. A., García-Vega, A., Carbonell-Baeza, R., Musall, M., & Kruusmaa, M. (2018). 3D modelling of non-uniform and turbulent flow in vertical slot fishways. *Environmental Modelling & Software*, 99, 156–169. <https://doi.org/10.1016/j.envsoft.2017.09.011>
- 881 Gao, Z., Andersson, H. I., Dai, H., Jiang, F., & Zhao, L. (2016). A new Eulerian–Lagrangian agent method to model fish paths in a vertical slot fishway. *Ecological Engineering*, 88, 217–225. <https://doi.org/10.1016/j.ecoleng.2015.12.038>

- 1
2
3 883 Gisen, D. C., Weichert, R. B., & Nestler, J. M. (2017). Optimizing attraction flow for upstream fish passage at a
4 884 hydropower dam employing 3D Detached-Eddy Simulation. *Ecological Engineering*, 100, 344–353.
5 885 <https://doi.org/10.1016/j.ecoleng.2016.10.065>
6
7 886 Golpira, A., Baki, A. B. M., Ghamry, H., Katopodis, C., Withers, J., & Minkoff, D. (2022). An experimental study: Effects of
8 887 boulder placement on hydraulic metrics of instream habitat complexity. *Scientific Reports*, 12(1), 13156.
9 888 <https://doi.org/10.1038/s41598-022-17281-1>
10
11 889 Gomes, D. dos S. da M., da Hora, M. de A. G. M., & Nascimento, G. de C. (2022). Application of recent SPH formulations
12 890 to simulate free-surface flow in a vertical slot fishway. *Computational Particle Mechanics*, 9(5), 941–951.
13 891 <https://doi.org/10.1007/s40571-021-00416-y>
14 892 Gong, Y., Mao, J., Dai, J., & Jiang, D. (2021). Large-eddy Simulation of Turbulent Flow in A Vertical Slot Fishway. *2021 7th*
15 893 *International Conference on Hydraulic and Civil Engineering & Smart Water Conservancy and Intelligent Disaster*
16 894 *Reduction Forum (ICHCE & SWIDR)*, 1302–1306. <https://doi.org/10.1109/ICHCESWIDR54323.2021.9656425>
17
18 895 Goodwin, R. A., Nestler, J. M., Anderson, J. J., Weber, L. J., & Loucks, D. P. (2006). Forecasting 3-D fish movement
19 896 behavior using a Eulerian–Lagrangian–agent method (ELAM). *Ecological Modelling*, 192(1–2), 197–223.
20 897 <https://doi.org/10.1016/j.ecolmodel.2005.08.004>
21
22 898 Haselbauer, M. A., & Martinez, C. B. (2007). Proposal of a sluice-type fish pass. *Neotropical Ichthyology*, 5(2), 223–228.
23 899 <https://doi.org/10.1590/S1679-62252007000200017>
24 900 Heimerl, S., Hagemeyer, M., & Ehteler, C. (2008). Numerical flow simulation of pool-type fishways: New ways with well-
25 901 known tools. *Hydrobiologia*, 609(1), 189–196. <https://doi.org/10.1007/s10750-008-9413-1>
26
27 902 Hershey, H. (2021). Updating the consensus on fishway efficiency: A meta-analysis. *Fish and Fisheries*, 22(4), 735–748.
28 903 <https://doi.org/10.1111/faf.12547>
29
30 904 Katopodis, C. (2005). Developing a toolkit for fish passage, ecological flow management and fish habitat works. *Journal*
31 905 *of Hydraulic Research*, 43(5), 451–467. <https://doi.org/10.1080/00221680509500144>
32
33 906 Katopodis, C. (1992). Introduction to fishway design. Working Document, Freshwater Institute, Fisheries and Oceans
34 907 Canada, Winnipeg, Manitoba.
35 908
36 909 Katopodis, C. and R. Gervais. 2016. Fish swimming performance database and analyses. DFO Can. Sci. Advis. Sec. Res.
37 910 Doc. 2016/002. vi + 550 p. [http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2016/2016_002-](http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2016/2016_002-eng.html)
38 911 [eng.html](http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2016/2016_002-eng.html)
39 912
40 913 Katopodis, C., Rajaratnam, N., Wu, S., & Tovell, D. (1997). Denil Fishways of Varying Geometry. *Journal of Hydraulic*
41 914 *Engineering*, 123(7), 624–631. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1997\)123:7\(624\)](https://doi.org/10.1061/(ASCE)0733-9429(1997)123:7(624))
42 915
43 916 Katopodis, C., & Williams, J. (2012). The development of fish passage research in a historical context. *Ecological*
44
45 917 Kelley, K., Gilbert, E. I., Pennock, C. A., McKinstry, M. C., Mackinnon, P. D., Durst, S. L., & Franssen, N. R. (2023). If you
46 918 build it, will they pass? A systematic evaluation of fish passage efficiency for three large-bodied warm-water fishes.
47 919 *Canadian Journal of Fisheries and Aquatic Sciences*, 80(10), 1631–1643. <https://doi.org/10.1139/cjfas-2023-0030>
48
49 920 Khan, L. A. (2006). A Three-Dimensional Computational Fluid Dynamics (CFD) Model Analysis of Free Surface
50 921 Hydrodynamics and Fish Passage Energetics in a Vertical-Slot Fishway. *North American Journal of Fisheries*
51 922 *Management*, 26(2), 255–267. <https://doi.org/10.1577/M05-014.1>
52 923
53 924 Kim, S., Yu, K., Yoon, B., & Lim, Y. (2012). A numerical study on hydraulic characteristics in the ice Harbor-type fishway.
54 *KSCE Journal of Civil Engineering*, 16(2), 265–272. <https://doi.org/10.1007/s12205-012-0010-5>
55 925
56 926 Klein, J., & Oertel, M. (2015). *Comparison between crossbar block ramp and vertical slot fish pass via numerical 3D CFD*
57 *simulation*. E-proceedings of the 36th IAHR World Congress, 28 June - 3 July 2015, The Hague, The Netherlands.
58 927
59 928 Kulic, T., Loncar, G., & Kovacevic, M. (2021). Application of agent-based modelling for selecting configuration of vertical
60 929 slot fishway. *Journal of the Croatian Association of Civil Engineers*, 73(03), 235–247.
<https://doi.org/10.14256/JCE.3150.2021>

- 1
2
3 930 Lacey, R. W. J., Neary, V. S., Liao, J. C., Enders, E. C., & Tritico, H. M. (2012). The Ipos Framework: Linking Fish Swimming
4 931 Performance in Altered Flows from Laboratory Experiments to Rivers. *River Research and Applications*, 28(4), 429–443.
5 932 <https://doi.org/10.1002/rra.1584>
6
7 933 Larinier, M. (2002). Pool fishways, pre-barrages and natural bypass channels. *Bulletin Français de La Pêche et de La*
8 934 *Pisciculture*, 364 supplément, 54–82. <https://doi.org/10.1051/kmae/2002108>
9
10 935 Lauchlan Arrowsmith, C. S., & Zhu, Y. (2014). Comparison between 2D and 3D hydraulic modelling approaches for
11 936 simulation of vertical slot fishways. *Hydraulic Structures and Society - Engineering Challenges and Extremes*, 1–9.
12 937 <https://doi.org/10.14264/uql.2014.49>
13 938 Leng, X., & Chanson, H. (2020a). Hybrid modelling of low velocity zones in box culverts to assist fish passage: Why simple
14 939 is better! *River Research and Applications*, 36(9), 1765–1777. <https://doi.org/10.1002/rra.3710>
15
16 940 Leng, X., & Chanson, H. (2020b). Hybrid modelling of low velocity zones in box culverts to assist upstream fish passage.
17 941 *Environmental Fluid Mechanics*, 20(2), 415–432. <https://doi.org/10.1007/s10652-019-09700-1>
18
19 942 Leng, X., & Chanson, H. (2020c). “Vegan” culvert: Application of hybrid modelling in modern hydraulic structures.
20 943 *Proceedings of the 8th IAHR International Symposium on Hydraulic Structures ISHS2020*, Santiago, Chile.
21 944 <https://doi.org/10.14264/uql.2020.516>
22
23 945 Leroy, A., Bourqui, P., Dumond, L., & De Cesare, G. (2018). Physical and 3D Numerical Simulations of the Flow in the
24 946 Tailrace of a Hydroelectric Power Plant to Design Fishway Entries. In P. Gourbesville, J. Cunge, & G. Caignaert (Eds.),
25 947 *Advances in Hydroinformatics* (pp. 855–868). Springer Singapore. https://doi.org/10.1007/978-981-10-7218-5_61
26 948 Lewandoski, S. A., Hrodey, P., Miehl, S., Piszczek, P. P., & Zielinski, D. P. (2021). Behavioral responses of sea lamprey (*Petromyzon marinus*) and white sucker (*Catostomus commersonii*) to turbulent flow during fishway passage attempts. *Canadian Journal of Fisheries and Aquatic Sciences*, 78(4), 409–421. <https://doi.org/10.1139/cjfas-2020-0223>
27 949
28 950
29
30 951 Li, G., Sun, S., Liu, H., & Zheng, T. (2021). Schizothorax prenanti swimming behavior in response to different flow patterns
31 952 in vertical slot fishways with different slot positions. *Science of The Total Environment*, 754, 142142.
32 953 <https://doi.org/10.1016/j.scitotenv.2020.142142>
33
34 954 Li, M., An, R., Chen, M., & Li, J. (2022). Evaluation of Volitional Swimming Behavior of Schizothorax prenanti Using an
35 955 Open-Channel Flume with Spatially Heterogeneous Turbulent Flow. *Animals*, 12(6), Article 6.
36 956 <https://doi.org/10.3390/ani12060752>
37 957 Li, P., Zhang, W., Burnett, N. J., Zhu, D. Z., Casselman, M., & Hinch, S. G. (2021). Evaluating Dam Water Release Strategies
38 958 for Migrating Adult Salmon Using Computational Fluid Dynamic Modeling and Biotelemetry. *Water Resources Research*,
39 959 57(8), e2020WR028981. <https://doi.org/10.1029/2020WR028981>
40
41 960 Li, S., Yang, J., & Ansell, A. (2022). Evaluation of Pool-Type Fish Passage with Labyrinth Weirs. *Sustainability*, 14(3), 1098.
42 961 <https://doi.org/10.3390/su14031098>
43
44 962 Lindberg, D.-E., Leonardsson, K., Andersson, A. G., Lundström, T. S., & Lundqvist, H. (2013). Methods for locating the
45 963 proper position of a planned fishway entrance near a hydropower tailrace. *Limnologica*, 43(5), 339–347.
46 964 <https://doi.org/10.1016/j.limno.2013.05.007>
47
48 965 Liu, M., Rajaratnam, N., & Zhu, D. Z. (2006). Mean Flow and Turbulence Structure in Vertical Slot Fishways. *Journal of*
49 966 *Hydraulic Engineering*, 132(8), 765–777. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2006\)132:8\(765\)](https://doi.org/10.1061/(ASCE)0733-9429(2006)132:8(765))
50 967 Lomax, H., T. H. Pulliam, and D. W. Zingg. (2001). Fundamentals of computational fluid dynamics. *Springer-Verlag*, Berlin.
51 968
52 969 Lucas, M. C., & Baras, E. (2001). *Migration of Freshwater Fishes*. Blackwell Science Ltd, Osney Mead, Oxford OX2 0EL 25,
53 970 UK.
54
55 971 Mahl, L., Heneka, P., Henning, M., & Weichert, R. B. (2021). Numerical Study of Three-Dimensional Surface Jets Emerging
56 972 from a Fishway Entrance Slot. *Water*, 13(8), 1079. <https://doi.org/10.3390/w13081079>
57
58 973 Maniecki, Ł. (2018). Numerical Modelling of Fish Passage with Turning Pools. *Archives of Hydro-Engineering and*
59 974 *Environmental Mechanics*, 65(1), 41–65. <https://doi.org/10.1515/heem-2018-0004>
60 975 Mao, X., Fu, J., Tuo, Y., An, R., & Li, J. (2012). Influence of Structure on Hydraulic Characteristics of T Shape Fishway.
976 *Journal of Hydrodynamics*, 24(5), 684–691. [https://doi.org/10.1016/S1001-6058\(11\)60292-8](https://doi.org/10.1016/S1001-6058(11)60292-8)

- 1
2
3 977 Marriner, B. A., Baki, A. B. M., Zhu, D. Z., Cooke, S. J., & Katopodis, C. (2016). The hydraulics of a vertical slot fishway: A
4 978 case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. *Ecological Engineering*, *90*, 190–202.
5 979 <https://doi.org/10.1016/j.ecoleng.2016.01.032>
6
7 980 Marriner, B. A., Baki, A. B. M., Zhu, D. Z., Thiem, J. D., Cooke, S. J., & Katopodis, C. (2014). Field and numerical assessment
8 981 of turning pool hydraulics in a vertical slot fishway. *Ecological Engineering*, *63*, 88–101.
9 982 <https://doi.org/10.1016/j.ecoleng.2013.12.010>
10
11 983 Mawer, R., Pauwels, I. S., Bruneel, S. P., Goethals, P. L. M., Kopecki, I., Elings, J., Coeck, J., & Schneider, M. (2023).
12 984 Individual based models for the simulation of fish movement near barriers: Current work and future directions. *Journal*
13 985 *of Environmental Management*, *335*, 117538. <https://doi.org/10.1016/j.jenvman.2023.117538>
14 986 Miranda, F. C., Cassan, L., Laurens, P., & Tran, T. D. (2021). *Study of a Rock-Ramp Fish Pass with Staggered Emergent*
15 987 *Square Obstacles*. *Water* 2021, *13*, 1175. <https://doi.org/10.3390/w13091175>
16
17 988 Nilsson, C., & Berggren, K. (2000). Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have
18 989 caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of
19 990 rivers remains one of the most important questions of our time. *BioScience*, *50*(9), 783–792.
20 991 [https://doi.org/10.1641/0006-3568\(2000\)050\[0783:AORECB\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2)
21
22 992 Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and Flow Regulation of the World's Large
23 993 River Systems. *Science*, *308*(5720), 405–408. <https://doi.org/10.1126/science.1107887>
24 994 Novak, G., Domínguez, J. M., Tafuni, A., Silva, A. T., Pengal, P., Četina, M., & Žagar, D. (2021). 3-D Numerical Study of a
25 995 Bottom Ramp Fish Passage Using Smoothed Particle Hydrodynamics. *Water*, *13*(11), 1595.
26 996 <https://doi.org/10.3390/w13111595>
27
28 997 Novak, G., Tafuni, A., Domínguez, J. M., Četina, M., & Žagar, D. (2019). A Numerical Study of Fluid Flow in a Vertical Slot
29 998 Fishway with the Smoothed Particle Hydrodynamics Method. *Water*, *11*(9), 1928. <https://doi.org/10.3390/w11091928>
30
31 999 Oertel, M., & Schlenkhoff, A. (2012). Crossbar Block Ramps: Flow Regimes, Energy Dissipation, Friction Factors, and Drag
32 1000 Forces. *Journal of Hydraulic Engineering*, *138*(5), 440–448. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0000522](https://doi.org/10.1061/(ASCE)HY.1943-7900.0000522)
33
34 1001 Olden, J.D., Closs G.P. & Krkosek M.(2015). Conservation of Freshwater Fishes: Cambridge: Cambridge University Press,
35 1002 pp. 107–148.
36 1003
37 1004 Padgett, T. E., Thomas, R. E., Borman, D. J., & Mould, D. C. (2020). Individual-based model of juvenile eel movement
38 1005 parametrized with computational fluid dynamics-derived flow fields informs improved fish pass design. *Royal Society*
39 1006 *Open Science*, *7*(1), 191505. <https://doi.org/10.1098/rsos.191505>
40 1007 Plymessenger, K., & Cahoon, J. (2017). Pressure gradients in a steep pass fishway using a computational fluid dynamics
41 1008 model. *Ecological Engineering*, *108*, 277–283. <https://doi.org/10.1016/j.ecoleng.2017.08.035>
42
43 1009 Pope, S. B. (2001). Turbulent Flows. *Measurement Science and Technology*, *12*(11), 2020. [https://doi.org/10.1088/0957-](https://doi.org/10.1088/0957-0233/12/11/705)
44 1010 [0233/12/11/705](https://doi.org/10.1088/0957-0233/12/11/705)
45
46 1011 Quaranta, E., Comoglio, C., Katopodis, C., & Revelli, R. (2016). *Numerical simulations of flow field in vertical slot fishways*,
47 1012 *Proceedings, XXXV Convegno Nazionale di Idraulica e Costruzioni Idrauliche Bologna, 14-16 Settembre 2016*.
48 1013 Quaranta, E., Katopodis, C., & Comoglio, C. (2019). Effects of bed slope on the flow field of vertical slot fishways. *River*
49 1014 *Research and Applications*, *rra.3428*. <https://doi.org/10.1002/rra.3428>
50
51 1015 Quaranta, E., Katopodis, C., Revelli, R., & Comoglio, C. (2017). Turbulent flow field comparison and related suitability for
52 1016 fish passage of a standard and a simplified low-gradient vertical slot fishway. *River Research and Applications*, *33*(8),
53 1017 1295–1305. <https://doi.org/10.1002/rra.3193>
54
55 1018 Quaresma, A. L., Romão, F., Branco, P., Ferreira, M. T., & Pinheiro, A. N. (2018). Multi slot versus single slot pool-type
56 1019 fishways: A modelling approach to compare hydrodynamics. *Ecological Engineering*, *122*, 197–206.
57 1020 <https://doi.org/10.1016/j.ecoleng.2018.08.006>
58
59 1021 Rajaratnam, N., Katopodis, C., & Solanki, S. (1992). New designs for vertical slot fishways. *Canadian Journal of Civil*
60 1022 *Engineering*, *19*(3), 402–414. <https://doi.org/10.1139/l92-049>

1

2

3 1023 Romão, F., Quaresma, A. L., Branco, P., Santos, J. M., Amaral, S., Ferreira, M. T., Katopodis, C., & Pinheiro, A. N. (2017).
4 1024 Passage performance of two cyprinids with different ecological traits in a fishway with distinct vertical slot
5 1025 configurations. *Ecological Engineering*, 105, 180–188. <https://doi.org/10.1016/j.ecoleng.2017.04.031>

6

7 1026 Romão, F., Quaresma, A. L., Santos, J. M., Amaral, S. D., Branco, P., & Pinheiro, A. N. (2021). Multislot Fishway Improves
8 1027 Entrance Performance and Fish Transit Time over Vertical Slots. *Water*, 13(3), 275. <https://doi.org/10.3390/w13030275>

9

10 1028 Roth, M. S., Jähnel, C., Stamm, J., & Schneider, L. K. (2022). Turbulent eddy identification of a meander and vertical-slot
11 1029 fishways in numerical models applying the IPOS-framework. *Journal of Ecohydraulics*, 7(2), 124–143.
12 1030 <https://doi.org/10.1080/24705357.2020.1869916>

13

14 1031 Sanagiotto, D. G., Rossi, J. B., Lauffer, L. L., & Bravo, J. M. (2019). Three-dimensional numerical simulation of flow in
15 1032 vertical slot fishways: Validation of the model and characterization of the flow. *RBRH*, 24, e20.
16 1033 <https://doi.org/10.1590/2318-0331.241920180174>

17

18 1034 Santos, H. A., Pinheiro, A. P., Mendes, L. M. M., & Junho, R. A. C. (2022). Turbulent Flow in a Central Vertical Slot Fishway:
19 1035 Numerical Assessment with RANS and LES Schemes. *Journal of Irrigation and Drainage Engineering*, 148(7), 04022025.
20 1036 [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001682](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001682)

21

22 1037 Santos, J. M., Silva, A., Katopodis, C., Pinheiro, P., Pinheiro, A., Bochechas, J., & Ferreira, M. T. (2012). Ecohydraulics of
23 1038 pool-type fishways: Getting past the barriers. *Ecological Engineering*, 48, 38–50.
24 1039 <https://doi.org/10.1016/j.ecoleng.2011.03.006>

25

26 1040 Schmutz, S., & Mielach, C. (2013). Measures for ensuring fish migration at transversal structures. *ICPDR – International
27 1041 Commission for the Protection of the Danube River*. ICPDR Secretariat, Vienna International Centre / D0412 P.O. Box 500
28 1042 / 1400 Vienna / Austria.

29

30 1043 Shahabi, M., Ahadiyan, J., Ghomeshi, M., Narimousa, M., Katopodis, C., & Azizi Nadian, H. (2023). Numerical study of
31 1044 the effect of a V-shaped weir on turbulence characteristics and velocity in V-weir fishways. *River Research and
32 1045 Applications*, 39(1), 21–34. <https://doi.org/10.1002/rra.4064>

33

34 1046 Shahabi, M., Ghomeshi, M., Ahadiyan, J., Mohammadian, T., & Katopodis, C. (2021). Do fishways stress fish? Assessment
35 1047 of physiological and hydraulic parameters of rainbow trout navigating a novel W-weir fishway. *Ecological Engineering*,
36 1048 169, 106330. <https://doi.org/10.1016/j.ecoleng.2021.106330>

37

38 1049 Shamloo, H., Rajaratnam, N., & Katopodis, C. (2001). Hydraulics of simple habitat structures. *Journal of Hydraulic
39 1050 Research*, 39(4), 351–366. <https://doi.org/10.1080/00221680109499840>

40

41 1051 Silva, A. T., Hatry, C., Thiem, J. D., Gutowsky, L. F. G., Hatin, D., Zhu, D. Z., Dawson, J. W., Katopodis, C., & Cooke, S. J.
42 1052 (2015). Behaviour and Locomotor Activity of a Migratory Catostomid during Fishway Passage. *PLOS ONE*, 10(4),
43 1053 e0123051. <https://doi.org/10.1371/journal.pone.0123051>

44

45 1054 Silva, A. T., Katopodis, C., Santos, J. M., Ferreira, M. T., & Pinheiro, A. N. (2012). Cyprinid swimming behaviour in response
46 1055 to turbulent flow. *Ecological Engineering*, 44, 314–328. <https://doi.org/10.1016/j.ecoleng.2012.04.015>

47

48 1056 Silva, A. T., Bærum, K. M., Hedger, R. D., Baktoft, H., Fjeldstad, H.-P., Gjelland, K. Ø., Økland, F., & Forseth, T. (2020). The
49 1057 effects of hydrodynamics on the three-dimensional downstream migratory movement of Atlantic salmon. *Science of
50 1058 The Total Environment*, 705, 135773. <https://doi.org/10.1016/j.scitotenv.2019.135773>

51

52 1059 Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., Aarestrup, K., Pompeu, P. S.,
53 1060 O'Brien, G. C., Braun, D. C., Burnett, N. J., Zhu, D. Z., Fjeldstad, H.-P., Forseth, T., Rajaratnam, N., Williams, J. G., & Cooke,
54 1061 S. J. (2018). The future of fish passage science, engineering, and practice. *Fish and Fisheries*, 19(2), 340–362.
55 1062 <https://doi.org/10.1111/faf.12258>

56

57 1063 Song, W., Xu, Q., Fu, X., Wang, C., Pang, Y., & Song, D. (2019). EFDC simulation of fishway in the Diversion Dahaerteng
58 1064 River to Danghe Reservoir, China. *Ecological Indicators*, 102, 704–715. <https://doi.org/10.1016/j.ecolind.2019.03.025>

59

60 1065 Sparks, R. E. (1995). Need for ecosystem management of large rivers and their floodplains. *BioScience*, 45(3), 168–182.

61

62 1066 Stamou, A. I., Mitsopoulos, G., Rutschmann, P., & Bui, M. D. (2018). Verification of a 3D CFD model for vertical slot fish-
63 1067 passes. *Environmental Fluid Mechanics*, 18(6), 1435–1461. <https://doi.org/10.1007/s10652-018-9602-z>

64

65 1068 Tan, J., Tao, L., Gao, Z., Dai, H., & Shi, X. (2018). Modeling Fish Movement Trajectories in Relation to Hydraulic Response
66 1069 Relationships in an Experimental Fishway. *Water*, 10(11), 1511. <https://doi.org/10.3390/w10111511>

- 1
2
3 1070 Tran, T. D., Chorda, J., Laurens, P., & Cassan, L. (2016). Modelling nature-like fishway flow around unsubmerged
4 1071 obstacles using a 2D shallow water model. *Environmental Fluid Mechanics*, 16(2), 413–428.
5 1072 <https://doi.org/10.1007/s10652-015-9430-3>
6
7 1073 Tritico, H. M., & Cotel, A. J. (2010). The effects of turbulent eddies on the stability and critical swimming speed of creek
8 1074 chub (*Semotilus atromaculatus*). *Journal of Experimental Biology*, 213(13), 2284–2293.
9 1075 <https://doi.org/10.1242/jeb.041806>
10
11 1076 Umeda C., de Lima G., Janzen J.G., Salla M.R. (2017). One and three-dimensional modeling of a vertical-slot fishway.
12 1077 *Journal of Urban and Environmental Engineering*, v.11, n.1, p.99-107. <https://doi.org/10.4090/juee.2017.v11n1.099107>
13 1078
14 1079 Vezza, P., Parasiewicz, P., Calles, O., Spairani, M., & Comoglio, C. (2014). Modelling habitat requirements of bullhead
15 1080 (Cottus gobio) in Alpine streams. *Aquatic Sciences*, 76, 1–15. DOI 10.1007/s00027-013-0306-7
16 1081 Williams, J. G., Armstrong, G., Katopodis, C., Larinier, M., & Travade, F. (2012). Thinking like a fish: a key ingredient for
17 1082 development of effective fish passage facilities at river obstructions: fish behaviour related fish passage at dams. *River*
18 1083 *Research and Applications*, 28(4), 407–417. <https://doi.org/10.1002/rra.1551>
19
20 1084 Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q., Yin, Z., Dai, J., Yin, D., Liang, J., & Ye, S. (2019). Effects of dam
21 1085 construction on biodiversity: A review. *Journal of Cleaner Production*, 221, 480–489.
22 1086 <https://doi.org/10.1016/j.jclepro.2019.03.001>
23
24 1087 Wu, S., Rajaratnam, N., & Katopodis, C. (1999). Structure of Flow in Vertical Slot Fishway. *Journal of Hydraulic*
25 1088 *Engineering*, 125(4), 351–360. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1999\)125:4\(351\)](https://doi.org/10.1061/(ASCE)0733-9429(1999)125:4(351))
26 1089
27 1090 Zeng, G., Xu, M., Mou, J., Hua, C., & Fan, C. (2022). Application of Tesla Valve’s Obstruction Characteristics to Reverse
28 1091 Fluid in Fish Migration. *Water*, 15(1), 40. <https://doi.org/10.3390/w15010040>
29 1091
30 1092 Zhang, D., Bian, X., Shi, X., Deng, J., & Liu, Y. (2023). Design of a bilateral-symmetric multi-slot fishway and its
31 1093 comparison with vertical slot fishway in terms of hydraulic properties. *River Research and Applications*, 39(5), 954–
32 1094 969. <https://doi.org/10.1002/rra.4125>
33 1094
34 1095 Zhao, H., Xu, Y., Lu, Y., Lu, S., Dai, J., & Meng, D. (2022). Numerical Study of Vertical Slot Fishway Flow with
35 1096 Supplementary Cylinders. *Water*, 14(11), 1772. <https://doi.org/10.3390/w14111772>
36 1096
37 1097 Zhong, Z., Ruan, T., Hu, Y., Liu, J., Liu, B., & Xu, W. (2021). Experimental and numerical assessment of hydraulic
38 1098 characteristic of a new semi-frustum weir in the pool-weir fishway. *Ecological Engineering*, 170, 106362.
39 1099 <https://doi.org/10.1016/j.ecoleng.2021.106362>
40 1100
41 1101 Zhou, S., Xu, G., Hu, J., Bao, Z., Tu, X., Wang, Y., & Wang, Z. (2020). Numerical Simulation Study On Flows In Natural-like
42 1102 Fishway Of Low-head Junction. *IOP Conference Series: Earth and Environmental Science*, 510(4), 042019.
43 1102 <https://doi.org/10.1088/1755-1315/510/4/042019>
44 1103
45 1104 Zhu, G., Zhou, Z., & Andersson, H. I. (2020). Role of Transient Characteristics in Fish Trajectory Modeling. *Sustainability*,
46 1105 12(17), 6765. <https://doi.org/10.3390/su12176765>
47 1105
48 1106 Zielinski, D. P., Voller, Vr., & Sorensen, P. W. (2018). A physiologically inspired agent-based approach to model upstream
49 1107 passage of invasive fish at a lock-and-dam. *Ecological Modelling*, 382, 18–32.
50 1108 <https://doi.org/10.1016/j.ecolmodel.2018.05.004>
51 1109
52 1109 Zöschg, H., Dobler, W., Aufleger, M., & Zeiringer, B. (2023). *Evaluation of Hydraulics and Downstream Fish Migration at*
53 1110 *Run-of-River Hydropower Plants with Horizontal Bar Rack Bypass Systems by Using CFD*. *Water* 2023, 15, 1042.
54 1110 <https://doi.org/10.3390/w15061042>
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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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18 4 Fabio Tarena^{1*}, Daniel Nyqvist¹, Christos Katopodis², and Claudio Comoglio¹
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21 6 ¹ Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Italy
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23 7 ² Katopodis Ecohydraulics Ltd., Winnipeg, Canada
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25 8 *Fabio Tarena, Politecnico di Torino – DIATI, Corso Duca degli Abruzzi, 24, 10129, Torino
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27 9

28 10 **Emails and ORCID:**

29
30 11 Fabio Tarena: fabio.tarena@polito.it; 0009-0004-4465-3537
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32 12 Daniel Nyqvist: daniel.nyqvist@polito.it; 0000-0002-3098-0594
33

34 13 Christos Katopodis: katopodisecohydraulics@live.ca; 0000-0001-7752-4409
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37 14 Claudio Comoglio : claudio.comoglio@polito.it; 0000-0002-7962-0653
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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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11 94 environmental contexts (Bates et al., 2005). The model consists of the definition and discretization
12 95 of a computational geometry in elementary particles (meshless methods) or cells (meshed method),
13 96 the application of boundary conditions at the inlet and outlet of the model, and the solution of the
14 97 equations of motion within the discretized volume (Andersson, 2012). By using CFD-models, the
15 98 flow can be described, and its hydrodynamic characteristics may be analyzed with only the known
16 99 discharge, water levels and the geometry of the fishway (Andersson, 2012).

17 00 The application of CFD for fishways allows testing of different geometrical configurations and flow
18 01 conditions with flexibility and at low cost (An et al., 2016; Bates et al., 2005). There is no widely
19 02 recognized standard procedure to simulate the flow inside fishways with CFD. Each study makes
20 03 particular modeling choices based on the expertise of the software user (Andersson, 2012; Leng &
21 04 Chanson, 2020b), and a systematic overview of methods applied is lacking. In this context, the main
22 05 objective of this paper is to elucidate the current state-of-the-art relative to the application of
23 06 ~~computational fluid dynamics~~CFD related to fishways by identifying, analyzing and critically
24 07 reviewing available primary literature. Specifically, we summarize spatial-temporal parameters,
25 08 scope and application fields, modeling procedures and approximations related to the use of CFD in
26 09 fishways. We limited the review to upstream migration solutions and internal flow field analysis, as
27 10 numerical modeling applications for fishway entrance positioning (e.g. Andersson et al., 2016;
28 11 Lindberg et al., 2013) and downstream passage (e.g. Feigenwinter et al., 2019; Zöschg et al., 2023)
29 12 are still few, more site-specific, and not easily classifiable.

30 13 31 32 14 **2. METHODS**

33 15 A complete search of the available primary scientific literature on CFD and fishways was conducted
34 16 on *Scopus* and *Web of Science* databases. The collection encompassed all the literature available in
35 17 the two engines up until the end of 2023. The initial search and identification of papers were
36 18 performed through the definition of a series of keywords, including general terms relating to
37 19 numerical modeling, hydrodynamics and fishways: ~~fishway~~, ~~CFD~~, ~~computational fluid dynamics~~, ~~fish~~
38 20 ~~ladder~~, ~~fish pass~~, ~~fish passage~~, ~~computational fluid dynamics~~, ~~CFD~~, ~~hydrodynamics~~, ~~fishway~~,
39 21 ~~hydrodynamic modeling~~, ~~hydrodynamics~~, ~~numerical simulation~~. All the possible (meaningful)
40 22 permutations of these words were explored, and the abstract of each paper was read to identify
41 23 those that were suitable for this study. A paper was considered relevant only if dealing with a
42 24 numerical model used to study the hydrodynamics within an upstream fish passage solution, and in
43 25 that case the full manuscript was then read for further analysis. Papers unavailable online or not
44 26 written in English were excluded from the study. When reading the selected full manuscripts, if
45 27 referenced relevant papers that had not emerged in the search query were found, they were also
46 28 included in the collection of papers.

47 29 The analysis of the full manuscripts included an initial critical reading of the paper followed by the
48 30 collection of selected information to fill a summary database. The database was devised to assess
49 31 the different ways computational fluid dynamics was applied in analyzing the upstream fishway
50 32 from different perspectives. The database included the following classification/analysis parameters:

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52 33 • Year of publication of the paper
- 53 34 • Country (and continent) in which the study was carried out;

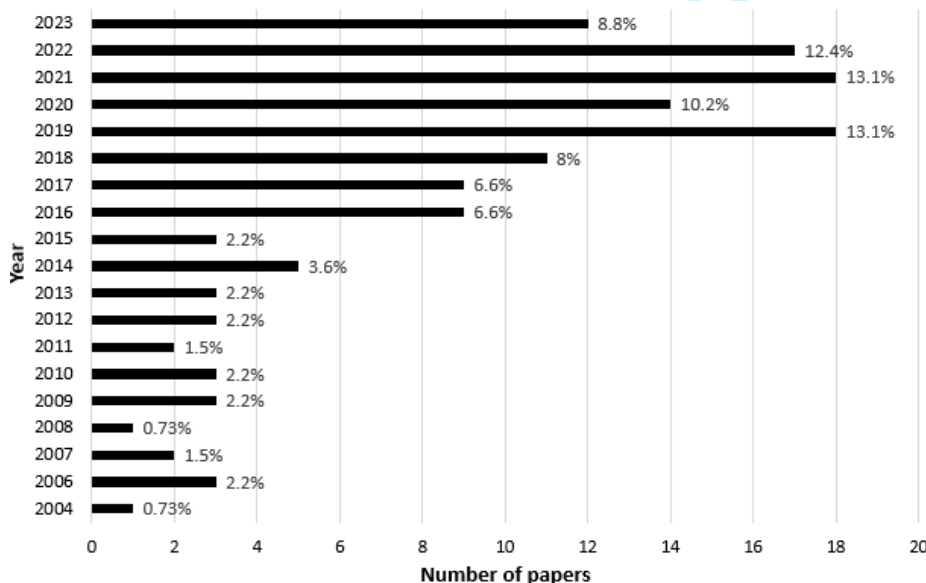
- Type of fishway studied and modeled (e.g. vertical slot, pool and weir, nature-like, etc.);
- Aim of the paper (the reason why a numerical model was used for the analysis of a fishway);
- Approach type (if the numerical model was coupled with physical experiments or applied alone);
- Equations of flow,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



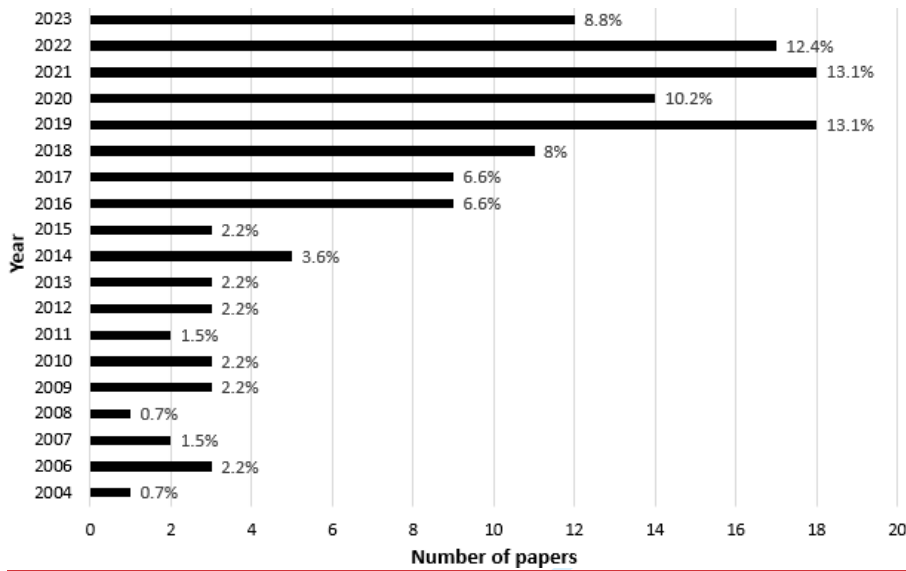


Fig. 1 – Trend over time of published scientific papers on CFD applications to study fishways. Percentages of contribution to the collection are indicated in the figure.

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.

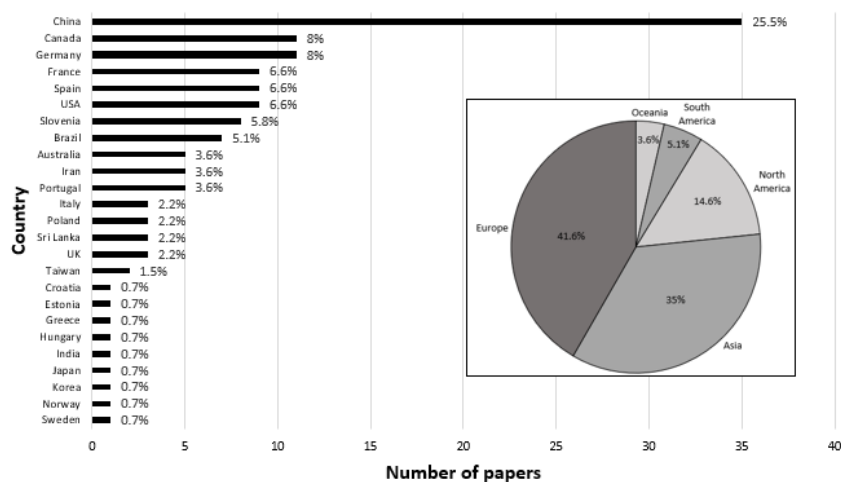


Fig. 2 - Geographical distribution of papers included in the systematic review. Number of papers by country (bar plot) and contribution by continent (pie chart). Percentages of contribution to the collection are indicated in the figure.

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. Calluau 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).

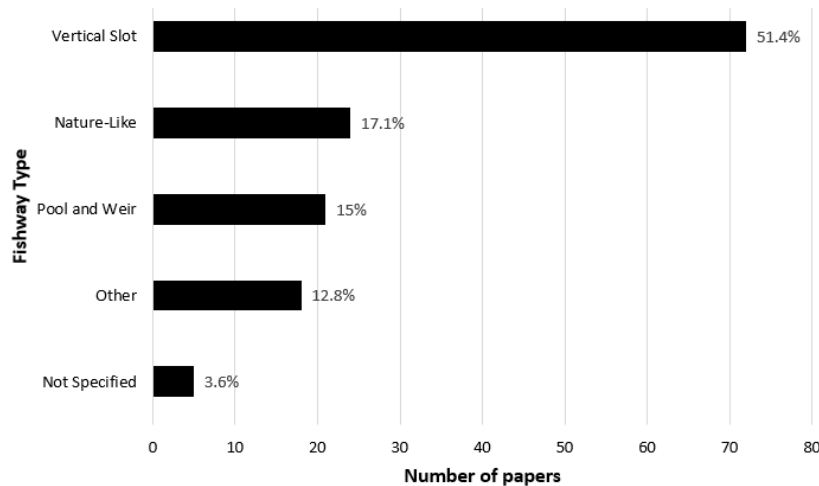


Fig. 3 - Different fishway structures considered in the collection: Nature-Like (NLF), Pool and Weir (PW), Vertical Slot (VSF). The category Other includes fishway typologies not represented in the general previous categories (i.e. Denil steep pass, eel pass, flat Weir, island fishway, Locks in dam, 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. Bombač et al., 2015), to improve the geometrical design of an existing one (e.g. Bung, 2018) or to support the design phase of a new one (e.g. Song et al., 2019).
4. Suitability of different flow equations for internal fishway flow representation (7.3%): to compare different equation systems and evaluate the best option (e.g. Stamou et al., 2018) or to assess the suitability of the hydraulic model under determined hydrodynamic conditions (e.g. Barton et al., 2009).
5. Comparison of different fish passage structures (5.1%): to evaluate which was the best option for a specific location or fish reference zone (e.g. Klein & Oertel, 2015; Quaresma et al., 2018).
6. Choice of the appropriate turbulence closure model (5.8%): application of different turbulence approximation equations with respect to the same structure and evaluation of the best option (e.g. Cea et al., 2007; Santos et al., 2022).
7. Software performance comparisons (2.2%): application of different computational software (commercial and open source) to simulate the flow inside the same fishway and evaluate the most suitable choice (e.g. Duguay et al., 2017; Fuentes-Pérez et al., 2022).

3.3 MODELING APPROACHES

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

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

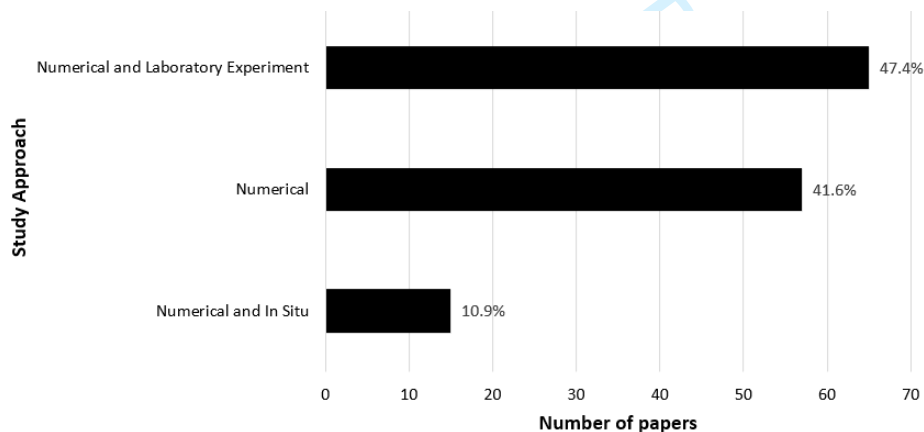


Fig. 4 - Frequency of study approaches identified in the analysed papers: Numerical, Numerical and In Situ, Numerical and Laboratory Experiment. The category Numerical and Laboratory Experiment includes the sub-categories Flume and Physical Model. Percentages of contribution to the collection are indicated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

In more than half of the collection of papers (58.3%) numerical models were coupled with laboratory, either flume or physical model, or field experiment. This process, commonly called hybrid modeling, is mutually beneficial to both physical and numerical approaches (Bung, 2018; Leng & Chanson, 2020b). Results from physical experiments are based on the reconstruction of the flow field features through the interpolation of a finite number of sampling velocity points and are, therefore, limited by the maximum resolution obtainable in the interpolated raster (Roth et al.,

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

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

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

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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).

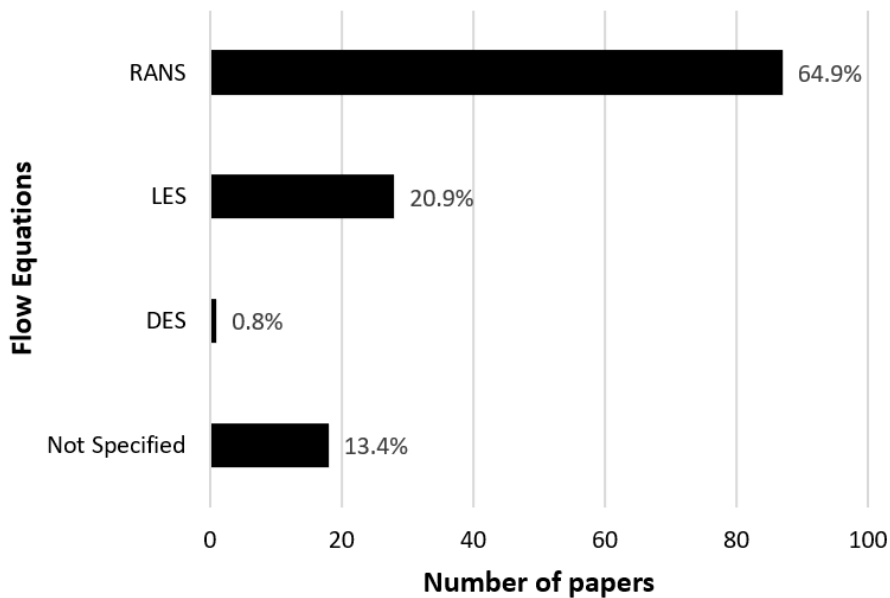


Fig. 5 - ~~Flow~~ Three-dimensional flow equations and turbulence approximations adopted in the paper collection: Reynolds-averaged Navier-Stokes equations (RANS), Large-Eddy Simulation (LES) and Detached Eddy Simulations (DES). RANS category, where specified, includes two different turbulent closure 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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11 and computational cost (Bravo-Córdoba et al., 2021; Fuentes-Pérez et al., 2018). Since RANS are
12 based on time averaging of the dynamic variables of the Navier-Stokes equations, they perform well
13 in capturing the average flow field, yet are weaker in assessing the turbulent parameters, as they
14 depend on the unsteady and time varying features of the flow (Chorda et al., 2010; Fuentes-Pérez
15 et al., 2018). For example, several studies outlined the over- or underestimation of turbulent kinetic
16 energy from RANS (e.g. Baki et al., 2016; Sanagiotto et al., 2019; Tran et al., 2016). In general, the
17 precision of turbulence parameters estimation depends on the type of closure model adopted for a
18 specific problem. In RANS, the approaches used mainly consist of the so called two-equation models,
19 solving a pair of additional transport equations to obtain a characteristic length and velocity of the
20 turbulence process (Andersson, 2012). According to our review, the most used approach was the
21 k- ϵ model, implemented in 83.1% of the RANS applications, while the k- ω model was adopted only
22 in 10.1% of the cases. In the remaining 6.7% of the RANS applications the equation model used was
23 not specified. Even if both equation models are recognized as adequate for general-purpose
24 applications of RANS (Andersson, 2012), the disproportionally high use of the k- ϵ model emerging
25 from our search, is related to the higher computational time associated with the k- ω model.
26 Nevertheless, the performance of k- ω is higher in zones close to solid boundaries and in contexts
27 with separating or swirling flows (Ducrocq et al., 2017). In particular, within the k- ω model
28 applications, the improved Shear-Stress Transport (SST) k- ω model was adopted in the majority of
29 the cases (90%), combining the benefits of both k- ϵ and k- ω approximations and allowing a
30 strengthened performance in representing adverse pressure gradient and separating flows (Padgett
31 et al., 2020; Zhang et al., 2023). However, since both equation models depend on the Boussinesq
32 eddy viscosity approach, RANS suffer from inherent deficiencies deriving from the approximation
33 that considers turbulence as an isotropic phenomenon (Andersson, 2012). This contributes to
34 limiting the precision of RANS in fishways, where, inside the pools, turbulence is considered strongly
35 anisotropic (Duguay et al., 2017). However, fishways are still considered a suitable field of
36 application for RANS, as the inner flow topology is represented well overall, despite the limits in
37 wakes zones and complex flows (Mahl et al., 2021; Sanagiotto et al., 2019).

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39 When the flow is highly turbulent, the LES method could be a valid option to improve modeling
40 accuracy (Fuentes-Pérez et al., 2022), and it was applied in 20.9% of the cases. Filtering out the small
41 but keeping the large turbulent scales from Navier-Stokes equations, the LES method offers a more
42 complete description of the instantaneous flow field, overcoming the limits of time-averaging that
43 characterize RANS (Chen & Tfwala, 2018). Actually, higher accuracy is linked to the direct simulation
44 of large eddies, being more difficult to model due to their anisotropic nature, while small eddies can
45 be considered closer to isotropy and thus approximated with subgrid stress models (Andersson,
46 2012). In the reviewed papers dealing with LES method, the turbulence closure model adopted for
47 small scales was always the standard Smagorinsky one, where the isotropic stress is linked to the
48 anisotropic one through an eddy-viscosity approximation (Andersson, 2012). However, the cost for
49 improved modeling performance is a longer simulation time and a finer refinement of the
50 computational mesh (Padgett et al., 2020; Pope, 2001). Since the correct assessment of flow
51 suitability for fish passage is related to highly turbulent zones in the pools (e.g. near a slot, weir,
52 orifice or baffle), and fish responses depend on the instantaneous features of the flow field, the
53 increase in computational resources is often needed for a more accurate assessment on how well
54 the structure functions (Silva et al., 2012). In addition, some specific hydrodynamic and biological
55 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 & Schlenkoff, 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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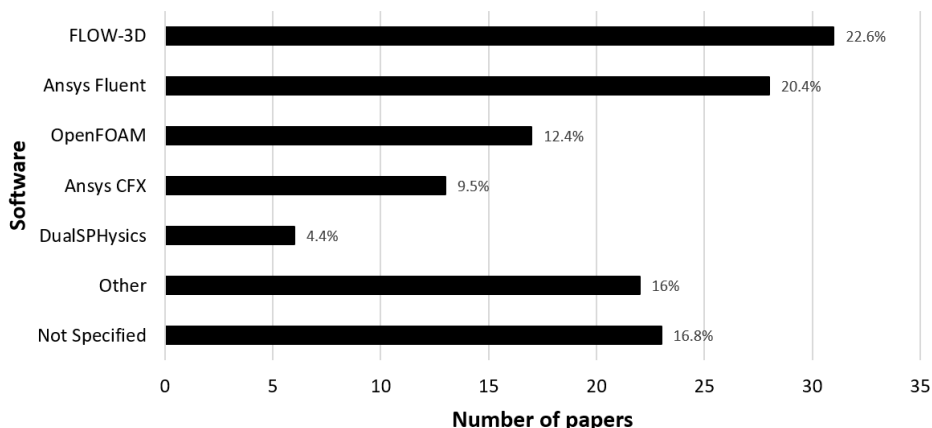


Fig. 6 - Frequency of use of the main different CFD software: Ansys CFX, Ansys Fluent, DualSPHysics, Flow-3D and OpenFOAM. The category Other groups together papers where the number of software applications was not high enough to be a standalone category (< 3): CCHE2D, Environmental Fluid Dynamic Code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

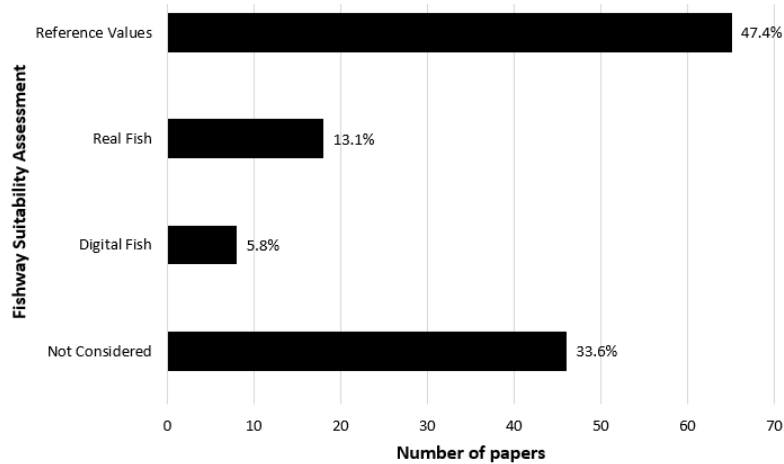


Fig. 7 - Approaches adopted to include fish swimming features in the suitability analysis of the flow in the paper collection. *Digital Fish*: reproduction of fish behavior through mathematical algorithms in a numerically generated flow field; *Real Fish*: coupling numerical simulation with a parallel 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>), Spinibarbus hollandi, 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 pachycephalus	2.4%

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

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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 premeri</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	Duguy 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	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 (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)
TKE	Passage preference in zones close to the side walls with $TKE < 0.015$ m ² /s ² .	Ya-fish (<i>Schizothorax premeri</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	Salmoids Cyprinids Weak swimmers	/	Pool-type fishways	Larimer (2002) Larimer (2002) Larimer (2002)
	Instability when Eddy Size > 76% fish body length.	Creek chub (<i>Ictalurus atropalensis</i>)	TL = 12.2 ± 0.9cm	Flume experiment with different cylinders arrays	Trifoco & Cole (2010)
	Fish exhibited disorientation/displacement when Eddy Size was similar to fish length. Fish exhibited disorientation/displacement when Eddy Size was similar to fish length.	Iberian barbel (<i>Luciobarbus bocagei</i>) Juvenile Rainbow trout (<i>Oncorhynchus mykiss</i>)	TL = 15-25cm, 25-35cm FL = 8.5 ± 0.6cm	Experimental Pool and Office fishway	Shiva et al. (2012) Duguy et al. (2018)
Eddy Size	Spatially averaged turbulent length scale range is $0.43 < L_{turb} < 0.45$ cm comparable with zeta 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	Baffled experimental flume 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 m²/s² 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 ± 2cm	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	Salmonids Carabids Weak swimmers	/	Pool-type fishways Post-type fishways	Leinber (2003) Larmer (2002) Larmer (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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REFERENCES

- Abdelaziz, S., Bui, M. D., Atsushi, N., & Rutschmann, P. (2013). *Numerical Simulation of Flow and Upstream Fish Movement inside a Pool-and-Weir Fishway*. Proceedings of 2013 IAHR World Congress.
- Abeyratne, W. M. L. K., Weerasinghe, P. S., & Weerakoon, S. B. (2021). Modeling of Flow in a Weir and Pool Fishway With Orifices for Optimizing the Fishway Design. In L. Venkatakrishnan, S. Majumdar, G. Subramanian, G. S. Bhat, R. Dasgupta, & J. Arakeri (Eds.), *Proceedings of 16th Asian Congress of Fluid Mechanics* (pp. 527–534). Springer Singapore. https://doi.org/10.1007/978-981-15-5183-3_56
- Amaral, S. D., Quaresma, A. L., Branco, P., Romão, F., Katopodis, C., Ferreira, M. T., Pinheiro, A. N., & Santos, J. M. (2019). Assessment of Retrofitted Ramped Weirs to Improve Passage of Potamodromous Fish. *Water*, *11*(12), 2441. <https://doi.org/10.3390/w11122441>
- An, R., Li, J., Liang, R., & Tuo, Y. (2016). Three-dimensional simulation and experimental study for optimising a vertical slot fishway. *Journal of Hydro-Environment Research*, *12*, 119–129. <https://doi.org/10.1016/j.jher.2016.05.005>
- Andersson, A. G., Leonardsson, K., Lindberg, D.-E., Lundström, T. S., Hellström, J. G. I., & Lundqvist, H. (2016). *Describing fish passage in a river confluence with telemetry and CFD*. 11th ISE 2016, Melbourne, Australia.
- Andersson, B. (Ed.). (2012). *Computational fluid dynamics for engineers*. Cambridge University Press. The Edinburgh Building, Cambridge CB2 8RU, UK.
- Baki, A. B. M., Zhu, D. Z., & Rajaratnam, N. (2016). Flow Simulation in a Rock-Ramp Fish Pass. *Journal of Hydraulic Engineering*, *142*(10), 04016031. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001166](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001166)
- Ballu, A., Pineau, G., Calluad, D., & David, L. (2018). *Influence of Macro-Roughnesses on Vertical Slot Fishways*. 7th International Symposium on Hydraulic Structures, Aachen, Germany. <https://doi.org/10.15142/T39S7Q>
- Barton, A. F., Keller, R. J., & Katopodis, C. (2009). Verification of a numerical model for the prediction of low slope vertical slot fishway hydraulics. *Australasian Journal of Water Resources*, *13*(1), 53–60. <https://doi.org/10.1080/13241583.2009.11465360>
- Bates, P. D., Lane, S. N., & Ferguson, R. I. (2005). *Computational fluid dynamics: Applications in environmental hydraulics*. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.
- Benchikh Le Hocine, A. E., Lacey, R. W. J., & Poncet, S. (2019). Turbulent flow over a D-section bluff body: A numerical benchmark. *Environmental Fluid Mechanics*, *19*(2), 435–456. <https://doi.org/10.1007/s10652-018-9634-4>
- Bermúdez, M., Puertas, J., Cea, L., & Pena, L. (Eds.). (2010). Experimental and numerical evaluation of sixteen different designs of vertical slot fishways. In *Environmental Hydraulics, Two Volume Set* (0 ed., pp. 1143–1148). CRC Press. <https://doi.org/10.1201/b10553-194>

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11 871 Bermúdez, M., Puertas, J., Cea, L., Pena, L., & Balairón, L. (2010). Influence of pool geometry on the biological efficiency
12 872 of vertical slot fishways. *Ecological Engineering*, 36(10), 1355–1364. <https://doi.org/10.1016/j.ecoleng.2010.06.013>
- 13 873 Bombač, M., Četina, M., & Novak, G. (2017). Study on flow characteristics in vertical slot fishways regarding slot layout
14 874 optimization. *Ecological Engineering*, 107, 126–136. <https://doi.org/10.1016/j.ecoleng.2017.07.008>
- 15 875 Bombač, M., Novak, G., Mlačnik, J., & Četina, M. (2015). Extensive field measurements of flow in vertical slot fishway as
16 876 data for validation of numerical simulations. *Ecological Engineering*, 84, 476–484.
17 877 <https://doi.org/10.1016/j.ecoleng.2015.09.030>
- 18 878 Bombač, M., Novak, G., Rodič, P., & Četina, M. (2014). Numerical and physical model study of a vertical slot fishway.
19 879 *Journal of Hydrology and Hydromechanics*, 62(2), 150–159. <https://doi.org/10.2478/johh-2014-0013>
- 20 880 Bravo-Córdoba, F. J., Fuentes-Pérez, J. F., Valbuena-Castro, J., Martínez de Azagra-Paredes, A., & Sanz-Ronda, F. J.
21 881 (2021). Turning Pools in Stepped Fishways: Biological Assessment via Fish Response and CFD Models. *Water*, 13(9),
22 882 1186. <https://doi.org/10.3390/w13091186>
- 23 883 Brown, A., Muller, S., & Dobrotkova, Z. (2011). Markets and Prospects by Technology. *RENEWABLE ENERGY*.
24 884 International Energy Agency, 9 rue de la Federation, 75739 Paris Cedex 15, France.
- 25 885 Bung, D., Valero D. & Hermens G. (2018). *Hybrid Investigation on the Hydraulic Performance of a New Trapezoidal*
26 886 *Fishway*. 7th International Symposium on Hydraulic Structures, Aachen, Germany. <https://doi.org/10.15142/T3S06R>
- 27 887 Čada, G., Loar, J., Garrison, L., Fisher, R., & Neitzel, D. (2006). Efforts to Reduce Mortality to Hydroelectric Turbine-
28 888 Passed Fish: Locating and Quantifying Damaging Shear Stresses. *Environmental Management*, 37(6), 898–906.
29 889 <https://doi.org/10.1007/s00267-005-0061-1>
- 30 890 Calluad, D., Pineau, G., Texier, A., & David, L. (2014). Modification of vertical slot fishway flow with a supplementary
31 891 cylinder. *Journal of Hydraulic Research*, 52(5), 614–629. <https://doi.org/10.1080/00221686.2014.906000>
- 32 892 Cao, P., Mu, X., Li, X., Baiyin, B., Wang, X., & Zhen, W. (2021). Relationship between Upstream Swimming Behaviors of
33 893 Juvenile Grass Carp and Characteristic Hydraulic Conditions of a Vertical Slot Fishway. *Water*, 13(9), 1299.
34 894 <https://doi.org/10.3390/w13091299>
- 35 895 Cea, L., Pena, L., Puertas, J., Vázquez-Cendón, M. E., & Peña, E. (2007). Application of Several Depth-Averaged
36 896 Turbulence Models to Simulate Flow in Vertical Slot Fishways. *Journal of Hydraulic Engineering*, 133(2), 160–172.
37 897 [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:2\(160\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:2(160))
- 38 898 Chen, S. C., & Tfwala, S. S. (2018). *Performance Assessment of FLOW-3D and XFlow in the Numerical Modelling of Fish-*
39 899 *bone Type Fishway Hydraulics*. <https://doi.org/10.15142/T3HH1J>
- 40 900 Chorda, J., Cassan, L., & Laurens, P. (2019). Modeling Steep-Slope Flow across Staggered Emergent Cylinders: Application
41 901 to Fish Passes. *Journal of Hydraulic Engineering*, 145(11), 04019038. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001630](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001630)
- 42 902 Chorda, J., Maubourguet, M. M., Roux, H., Larinier, M., Tarrade, L., & David, L. (2010). Two-dimensional free surface
43 903 flow numerical model for vertical slot fishways. *Journal of Hydraulic Research*, 48(2), 141–151.
44 904 <https://doi.org/10.1080/00221681003703956>
- 45 905 Clay, H.C. (1995). *Design of Fishways and Other Fish Facilities* (1st ed.). CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca
46 906 Raton, Florida 33431. <https://doi.org/10.1201/9781315141046>
- 47 907 Ducrocq, T., Cassan, L., Chorda, J., & Roux, H. (2017). Flow and drag force around a free surface piercing cylinder for
48 908 environmental applications. *Environmental Fluid Mechanics*, 17(4), 629–645. <https://doi.org/10.1007/s10652-016-9505-9>
- 49 909 Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., Naiman, R. J., Prieur-Richard,
50 910 A.-H., Soto, D., Stiassny, M. L. J., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and
51 911 conservation challenges. *Biological Reviews*, 81(02), 163. <https://doi.org/10.1017/S1464793105006950>
- 52 912 Duguay, J., Foster, B., Lacey, J., & Castro-Santos, T. (2018). Sediment infilling benefits rainbow trout passage in a baffled
53 913 channel. *Ecological Engineering*, 125, 38–49. <https://doi.org/10.1016/j.ecoleng.2018.10.003>

ha formattato: Svedese (Svezia)

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- Duguay, J. M., Lacey, R. W. J., & Gaucher, J. (2017). A case study of a pool and weir fishway modeled with OpenFOAM and FLOW-3D. *Ecological Engineering*, 103, 31–42. <https://doi.org/10.1016/j.ecoleng.2017.01.042>
- Ead, S. A., Katopodis, C., Sikora, G. J., & Rajaratnam, N. (2004). Flow regimes and structure in pool and weir fishways. *Journal of Environmental Engineering and Science*, 3(5), 379–390. <https://doi.org/10.1139/s03-073>
- Feigenwinter, L., Vetsch, D., Kammerer, S., Kriewitz, C., & Boes, R. (2019). Conceptual Approach for Positioning of Fish Guidance Structures Using CFD and Expert Knowledge. *Sustainability*, 11(6), 1646. <https://doi.org/10.3390/su11061646>
- Fuentes-Pérez, J. F., Quaresma, A. L., Pinheiro, A., & Sanz-Ronda, F. J. (2022). OpenFOAM vs FLOW-3D: A comparative study of vertical slot fishway modelling. *Ecological Engineering*, 174, 106446. <https://doi.org/10.1016/j.ecoleng.2021.106446>
- Fuentes-Pérez, J. F., Silva, A. T., Tuhtan, J. A., García-Vega, A., Carbonell-Baeza, R., Musall, M., & Kruusmaa, M. (2018). 3D modelling of non-uniform and turbulent flow in vertical slot fishways. *Environmental Modelling & Software*, 99, 156–169. <https://doi.org/10.1016/j.envsoft.2017.09.011>
- Gao, Z., Andersson, H. I., Dai, H., Jiang, F., & Zhao, L. (2016). A new Eulerian–Lagrangian agent method to model fish paths in a vertical slot fishway. *Ecological Engineering*, 88, 217–225. <https://doi.org/10.1016/j.ecoleng.2015.12.038>
- Gisen, D. C., Weichert, R. B., & Nestler, J. M. (2017). Optimizing attraction flow for upstream fish passage at a hydropower dam employing 3D Detached-Eddy Simulation. *Ecological Engineering*, 100, 344–353. <https://doi.org/10.1016/j.ecoleng.2016.10.065>
- Golpira, A., Baki, A. B. M., Ghamry, H., Katopodis, C., Withers, J., & Minkoff, D. (2022). An experimental study: Effects of boulder placement on hydraulic metrics of instream habitat complexity. *Scientific Reports*, 12(1), 13156. <https://doi.org/10.1038/s41598-022-17281-1>
- Gomes, D. dos S. da M., da Hora, M. de A. G. M., & Nascimento, G. de C. (2022). Application of recent SPH formulations to simulate free-surface flow in a vertical slot fishway. *Computational Particle Mechanics*, 9(5), 941–951. <https://doi.org/10.1007/s40571-021-00416-y>
- Gong, Y., Mao, J., Dai, J., & Jiang, D. (2021). Large-eddy Simulation of Turbulent Flow in A Vertical Slot Fishway. *2021 7th International Conference on Hydraulic and Civil Engineering & Smart Water Conservancy and Intelligent Disaster Reduction Forum (ICHCE & SWIDR)*, 1302–1306. <https://doi.org/10.1109/ICHCESWIDR54323.2021.9656425>
- Goodwin, R. A., Nestler, J. M., Anderson, J. J., Weber, L. J., & Loucks, D. P. (2006). Forecasting 3-D fish movement behavior using a Eulerian–Lagrangian–agent method (ELAM). *Ecological Modelling*, 192(1–2), 197–223. <https://doi.org/10.1016/j.ecolmodel.2005.08.004>
- Haselbauer, M. A., & Martinez, C. B. (2007). Proposal of a sluice-type fish pass. *Neotropical Ichthyology*, 5(2), 223–228. <https://doi.org/10.1590/S1679-62252007000200017>
- Heimerl, S., Hagemeyer, M., & Ehteler, C. (2008). Numerical flow simulation of pool-type fishways: New ways with well-known tools. *Hydrobiologia*, 609(1), 189–196. <https://doi.org/10.1007/s10750-008-9413-1>
- Hershey, H. (2021). Updating the consensus on fishway efficiency: A meta-analysis. *Fish and Fisheries*, 22(4), 735–748. <https://doi.org/10.1111/faf.12547>
- Katopodis, C. (2005). Developing a toolkit for fish passage, ecological flow management and fish habitat works. *Journal of Hydraulic Research*, 43(5), 451–467. <https://doi.org/10.1080/00221680509500144>
- Katopodis, C. (1992). Introduction to fishway design. Working Document, Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, Manitoba.
- Katopodis, C. and R. Gervais. 2016. Fish swimming performance database and analyses. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/002. vi + 550 p. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2016/2016_002-eng.html
- Katopodis, C., Rajaratnam, N., Wu, S., & Tovell, D. (1997). Denil Fishways of Varying Geometry. *Journal of Hydraulic Engineering*, 123(7), 624–631. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1997\)123:7\(624\)](https://doi.org/10.1061/(ASCE)0733-9429(1997)123:7(624))
- Katopodis, C., & Williams, J. (2012). The development of fish passage research in a historical context. *Ecological Engineering*, 48. <https://doi.org/10.1016/j.ecoleng.2011.07.004>

ha formattato: Tedesco (Germania)

ha formattato: Tedesco (Germania)

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- Kelley, K., Gilbert, E. I., Pennock, C. A., McKinstry, M. C., Mackinnon, P. D., Durst, S. L., & Franssen, N. R. (2023). If you build it, will they pass? A systematic evaluation of fish passage efficiency for three large-bodied warm-water fishes. *Canadian Journal of Fisheries and Aquatic Sciences*, 80(10), 1631–1643. <https://doi.org/10.1139/cjfas-2023-0030>
- Khan, L. A. (2006). A Three-Dimensional Computational Fluid Dynamics (CFD) Model Analysis of Free Surface Hydrodynamics and Fish Passage Energetics in a Vertical-Slot Fishway. *North American Journal of Fisheries Management*, 26(2), 255–267. <https://doi.org/10.1577/M05-014.1>
- Kim, S., Yu, K., Yoon, B., & Lim, Y. (2012). A numerical study on hydraulic characteristics in the ice Harbor-type fishway. *KSCE Journal of Civil Engineering*, 16(2), 265–272. <https://doi.org/10.1007/s12205-012-0010-5>
- Klein, J., & Oertel, M. (2015). *Comparison between crossbar block ramp and vertical slot fish pass via numerical 3D CFD simulation*. E-proceedings of the 36th IAHR World Congress, 28 June - 3 July 2015, The Hague, The Netherlands.
- Kulic, T., Loncar, G., & Kovacevic, M. (2021). Application of agent-based modelling for selecting configuration of vertical slot fishway. *Journal of the Croatian Association of Civil Engineers*, 73(03), 235–247. <https://doi.org/10.14256/JCE.3150.2021>
- Lacey, R. W. J., Neary, V. S., Liao, J. C., Enders, E. C., & Tritico, H. M. (2012). The Ipos Framework: Linking Fish Swimming Performance in Altered Flows from Laboratory Experiments to Rivers. *River Research and Applications*, 28(4), 429–443. <https://doi.org/10.1002/rra.1584>
- Larinier, M. (2002). Pool fishways, pre-barrages and natural bypass channels. *Bulletin Français de La Pêche et de La Pisciculture*, 364 supplément, 54–82. <https://doi.org/10.1051/kmae/2002108>
- Lauchlan Arrowsmith, C. S., & Zhu, Y. (2014). Comparison between 2D and 3D hydraulic modelling approaches for simulation of vertical slot fishways. *Hydraulic Structures and Society - Engineering Challenges and Extremes*, 1–9. <https://doi.org/10.14264/uql.2014.49>
- Leng, X., & Chanson, H. (2020a). Hybrid modelling of low velocity zones in box culverts to assist fish passage: Why simple is better! *River Research and Applications*, 36(9), 1765–1777. <https://doi.org/10.1002/rra.3710>
- Leng, X., & Chanson, H. (2020b). Hybrid modelling of low velocity zones in box culverts to assist upstream fish passage. *Environmental Fluid Mechanics*, 20(2), 415–432. <https://doi.org/10.1007/s10652-019-09700-1>
- Leng, X., & Chanson, H. (2020c). “Vegan” culvert: Application of hybrid modelling in modern hydraulic structures. *Proceedings of the 8th IAHR International Symposium on Hydraulic Structures ISHS2020*, Santiago, Chile. <https://doi.org/10.14264/uql.2020.516>
- Leroy, A., Bourqui, P., Dumond, L., & De Cesare, G. (2018). Physical and 3D Numerical Simulations of the Flow in the Tailrace of a Hydroelectric Power Plant to Design Fishway Entries. In P. Gourbesville, J. Cunge, & G. Caignaert (Eds.), *Advances in Hydroinformatics* (pp. 855–868). Springer Singapore. https://doi.org/10.1007/978-981-10-7218-5_61
- Lewandoski, S. A., Hrodey, P., Miehs, S., Piszczek, P. P., & Zielinski, D. P. (2021). Behavioral responses of sea lamprey (*Petromyzon marinus*) and white sucker (*Catostomus commersonii*) to turbulent flow during fishway passage attempts. *Canadian Journal of Fisheries and Aquatic Sciences*, 78(4), 409–421. <https://doi.org/10.1139/cjfas-2020-0223>
- Li, G., Sun, S., Liu, H., & Zheng, T. (2021). Schizothorax prenanti swimming behavior in response to different flow patterns in vertical slot fishways with different slot positions. *Science of The Total Environment*, 754, 142142. <https://doi.org/10.1016/j.scitotenv.2020.142142>
- Li, M., An, R., Chen, M., & Li, J. (2022). Evaluation of Volitional Swimming Behavior of Schizothorax prenanti Using an Open-Channel Flume with Spatially Heterogeneous Turbulent Flow. *Animals*, 12(6), Article 6. <https://doi.org/10.3390/ani12060752>
- Li, P., Zhang, W., Burnett, N. J., Zhu, D. Z., Casselman, M., & Hinch, S. G. (2021). Evaluating Dam Water Release Strategies for Migrating Adult Salmon Using Computational Fluid Dynamic Modeling and Biotelemetry. *Water Resources Research*, 57(8), e2020WR028981. <https://doi.org/10.1029/2020WR028981>
- Li, S., Yang, J., & Ansell, A. (2022). Evaluation of Pool-Type Fish Passage with Labyrinth Weirs. *Sustainability*, 14(3), 1098. <https://doi.org/10.3390/su14031098>

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60

- Lindberg, D.-E., Leonardsson, K., Andersson, A. G., Lundström, T. S., & Lundqvist, H. (2013). Methods for locating the proper position of a planned fishway entrance near a hydropower tailrace. *Limnologica*, 43(5), 339–347. <https://doi.org/10.1016/j.limno.2013.05.007>
- Liu, M., Rajaratnam, N., & Zhu, D. Z. (2006). Mean Flow and Turbulence Structure in Vertical Slot Fishways. *Journal of Hydraulic Engineering*, 132(8), 765–777. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2006\)132:8\(765\)](https://doi.org/10.1061/(ASCE)0733-9429(2006)132:8(765))
- Lomax, H., T. H. Pulliam, and D. W. Zingg. (2001). Fundamentals of computational fluid dynamics. *Springer-Verlag*, Berlin.
- Lucas, M. C., & Baras, E. (2001). *Migration of Freshwater Fishes*. Blackwell Science Ltd, Osney Mead, Oxford OX2 0EL 25, UK.
- Mahl, L., Heneka, P., Henning, M., & Weichert, R. B. (2021). Numerical Study of Three-Dimensional Surface Jets Emerging from a Fishway Entrance Slot. *Water*, 13(8), 1079. <https://doi.org/10.3390/w13081079>
- Maniecki, Ł. (2018). Numerical Modelling of Fish Passage with Turning Pools. *Archives of Hydro-Engineering and Environmental Mechanics*, 65(1), 41–65. <https://doi.org/10.1515/heem-2018-0004>
- Mao, X., Fu, J., Tuo, Y., An, R., & Li, J. (2012). Influence of Structure on Hydraulic Characteristics of T Shape Fishway. *Journal of Hydrodynamics*, 24(5), 684–691. [https://doi.org/10.1016/S1001-6058\(11\)60292-8](https://doi.org/10.1016/S1001-6058(11)60292-8)
- Marriner, B. A., Baki, A. B. M., Zhu, D. Z., Cooke, S. J., & Katopodis, C. (2016). The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. *Ecological Engineering*, 90, 190–202. <https://doi.org/10.1016/j.ecoleng.2016.01.032>
- Marriner, B. A., Baki, A. B. M., Zhu, D. Z., Thiem, J. D., Cooke, S. J., & Katopodis, C. (2014). Field and numerical assessment of turning pool hydraulics in a vertical slot fishway. *Ecological Engineering*, 63, 88–101. <https://doi.org/10.1016/j.ecoleng.2013.12.010>
- Mawer, R., Pauwels, I. S., Bruneel, S. P., Goethals, P. L. M., Kopecki, I., Elings, J., Coeck, J., & Schneider, M. (2023). Individual based models for the simulation of fish movement near barriers: Current work and future directions. *Journal of Environmental Management*, 335, 117538. <https://doi.org/10.1016/j.jenvman.2023.117538>
- Miranda, F. C., Cassan, L., Laurens, P., & Tran, T. D. (2021). *Study of a Rock-Ramp Fish Pass with Staggered Emergent Square Obstacles*. *Water* 2021, 13, 1175. <https://doi.org/10.3390/w13091175>
- Nilsson, C., & Berggren, K. (2000). Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time. *BioScience*, 50(9), 783–792. [https://doi.org/10.1641/0006-3568\(2000\)050\[0783:AORECB\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2)
- Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and Flow Regulation of the World's Large River Systems. *Science*, 308(5720), 405–408. <https://doi.org/10.1126/science.1107887>
- Novak, G., Domínguez, J. M., Tafuni, A., Silva, A. T., Pengal, P., Četina, M., & Žagar, D. (2021). 3-D Numerical Study of a Bottom Ramp Fish Passage Using Smoothed Particle Hydrodynamics. *Water*, 13(11), 1595. <https://doi.org/10.3390/w13111595>
- Novak, G., Tafuni, A., Domínguez, J. M., Četina, M., & Žagar, D. (2019). A Numerical Study of Fluid Flow in a Vertical Slot Fishway with the Smoothed Particle Hydrodynamics Method. *Water*, 11(9), 1928. <https://doi.org/10.3390/w11091928>
- Oertel, M., & Schlenkoff, A. (2012). Crossbar Block Ramps: Flow Regimes, Energy Dissipation, Friction Factors, and Drag Forces. *Journal of Hydraulic Engineering*, 138(5), 440–448. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0000522](https://doi.org/10.1061/(ASCE)HY.1943-7900.0000522)
- Olden, J.D., Closs G.P. & Krkosek M. (2015). *Conservation of Freshwater Fishes*: Cambridge: Cambridge University Press, pp. 107–148.
- Padgett, T. E., Thomas, R. E., Borman, D. J., & Mould, D. C. (2020). Individual-based model of juvenile eel movement parametrized with computational fluid dynamics-derived flow fields informs improved fish pass design. *Royal Society Open Science*, 7(1), 191505. <https://doi.org/10.1098/rsos.191505>
- Plymnesser, K., & Cahoon, J. (2017). Pressure gradients in a steep pass fishway using a computational fluid dynamics model. *Ecological Engineering*, 108, 277–283. <https://doi.org/10.1016/j.ecoleng.2017.08.035>

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47
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50
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57
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59
60

- Pope, S. B. (2001). Turbulent Flows. *Measurement Science and Technology*, 12(11), 2020. <https://doi.org/10.1088/0957-0233/12/11/705>
- Quaranta, E., Comoglio, C., Katopodis, C., & Revelli, R. (2016). *Numerical simulations of flow field in vertical slot fishways*, Proceedings, XXXV Convegno Nazionale di Idraulica e Costruzioni Idrauliche Bologna, 14-16 Settembre 2016.
- Quaranta, E., Katopodis, C., & Comoglio, C. (2019). Effects of bed slope on the flow field of vertical slot fishways. *River Research and Applications*, rra.3428. <https://doi.org/10.1002/rra.3428>
- Quaranta, E., Katopodis, C., Revelli, R., & Comoglio, C. (2017). Turbulent flow field comparison and related suitability for fish passage of a standard and a simplified low-gradient vertical slot fishway. *River Research and Applications*, 33(8), 1295–1305. <https://doi.org/10.1002/rra.3193>
- Quaresma, A. L., Romão, F., Branco, P., Ferreira, M. T., & Pinheiro, A. N. (2018). Multi slot versus single slot pool-type fishways: A modelling approach to compare hydrodynamics. *Ecological Engineering*, 122, 197–206. <https://doi.org/10.1016/j.ecoleng.2018.08.006>
- Rajaratnam, N., Katopodis, C., & Solanki, S. (1992). New designs for vertical slot fishways. *Canadian Journal of Civil Engineering*, 19(3), 402–414. <https://doi.org/10.1139/92-049>
- Romão, F., Quaresma, A. L., Branco, P., Santos, J. M., Amaral, S., Ferreira, M. T., Katopodis, C., & Pinheiro, A. N. (2017). Passage performance of two cyprinids with different ecological traits in a fishway with distinct vertical slot configurations. *Ecological Engineering*, 105, 180–188. <https://doi.org/10.1016/j.ecoleng.2017.04.031>
- Romão, F., Quaresma, A. L., Santos, J. M., Amaral, S. D., Branco, P., & Pinheiro, A. N. (2021). Multislot Fishway Improves Entrance Performance and Fish Transit Time over Vertical Slots. *Water*, 13(3), 275. <https://doi.org/10.3390/w13030275>
- Roth, M. S., Jähnel, C., Stamm, J., & Schneider, L. K. (2022). Turbulent eddy identification of a meander and vertical-slot fishways in numerical models applying the IPOS-framework. *Journal of Ecohydraulics*, 7(2), 124–143. <https://doi.org/10.1080/24705357.2020.1869916>
- Sanagiotto, D. G., Rossi, J. B., Lauffer, L. L., & Bravo, J. M. (2019). Three-dimensional numerical simulation of flow in vertical slot fishways: Validation of the model and characterization of the flow. *RBRH*, 24, e20. <https://doi.org/10.1590/2318-0331.241920180174>
- Santos, H. A., Pinheiro, A. P., Mendes, L. M. M., & Junho, R. A. C. (2022). Turbulent Flow in a Central Vertical Slot Fishway: Numerical Assessment with RANS and LES Schemes. *Journal of Irrigation and Drainage Engineering*, 148(7), 04022025. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001682](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001682)
- Santos, J. M., Silva, A., Katopodis, C., Pinheiro, P., Pinheiro, A., Bochechas, J., & Ferreira, M. T. (2012). Ecohydraulics of pool-type fishways: Getting past the barriers. *Ecological Engineering*, 48, 38–50. <https://doi.org/10.1016/j.ecoleng.2011.03.006>
- Schmutz, S., & Mielach, C. (2013). Measures for ensuring fish migration at transversal structures. *ICPDR – International Commission for the Protection of the Danube River*. ICPDR Secretariat, Vienna International Centre / D0412 P.O. Box 500 / 1400 Vienna / Austria.
- Shahabi, M., Ahadiyan, J., Ghomeshi, M., Narimousa, M., Katopodis, C., & Azizi Nadian, H. (2023). Numerical study of the effect of a V-shaped weir on turbulence characteristics and velocity in V-WEIR fishways. *River Research and Applications*, 39(1), 21–34. <https://doi.org/10.1002/rra.4064>
- Shahabi, M., Ghomeshi, M., Ahadiyan, J., Mohammadian, T., & Katopodis, C. (2021). Do fishways stress fish? Assessment of physiological and hydraulic parameters of rainbow trout navigating a novel W-weir fishway. *Ecological Engineering*, 169, 106330. <https://doi.org/10.1016/j.ecoleng.2021.106330>
- Shamloo, H., Rajaratnam, N., & Katopodis, C. (2001). Hydraulics of simple habitat structures. *Journal of Hydraulic Research*, 39(4), 351–366. <https://doi.org/10.1080/00221680109499840>
- Silva, A. T., Hatry, C., Thiem, J. D., Gutowsky, L. F. G., Hatin, D., Zhu, D. Z., Dawson, J. W., Katopodis, C., & Cooke, S. J. (2015). Behaviour and Locomotor Activity of a Migratory Catostomid during Fishway Passage. *PLOS ONE*, 10(4), e0123051. <https://doi.org/10.1371/journal.pone.0123051>
- Silva, A. T., Katopodis, C., Santos, J. M., Ferreira, M. T., & Pinheiro, A. N. (2012). Cyprinid swimming behaviour in response to turbulent flow. *Ecological Engineering*, 44, 314–328. <https://doi.org/10.1016/j.ecoleng.2012.04.015>

ha formattato: Tedesco (Germania)

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Silva, A. T., Bærum, K. M., Hedger, R. D., Baktoft, H., Fjeldstad, H.-P., Gjelland, K. Ø., Økland, F., & Forseth, T. (2020). The effects of hydrodynamics on the three-dimensional downstream migratory movement of Atlantic salmon. *Science of The Total Environment*, 705, 135773. <https://doi.org/10.1016/j.scitotenv.2019.135773>

ha formattato: Svedese (Svezia)

Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., Aarestrup, K., Pompeu, P. S., O'Brien, G. C., Braun, D. C., Burnett, N. J., Zhu, D. Z., Fjeldstad, H.-P., Forseth, T., Rajaratnam, N., Williams, J. G., & Cooke, S. J. (2018). The future of fish passage science, engineering, and practice. *Fish and Fisheries*, 19(2), 340–362. <https://doi.org/10.1111/faf.12258>

Song, W., Xu, Q., Fu, X., Wang, C., Pang, Y., & Song, D. (2019). EFDC simulation of fishway in the Diversion Dahaerteng River to Danghe Reservoir, China. *Ecological Indicators*, 102, 704–715. <https://doi.org/10.1016/j.ecolind.2019.03.025>

ha formattato: Tedesco (Germania)

Sparks, R. E. (1995). Need for ecosystem management of large rivers and their floodplains. *BioScience*, 45(3), 168–182.

Stamou, A. I., Mitsopoulos, G., Rutschmann, P., & Bui, M. D. (2018). Verification of a 3D CFD model for vertical slot fish-passes. *Environmental Fluid Mechanics*, 18(6), 1435–1461. <https://doi.org/10.1007/s10652-018-9602-z>

Tan, J., Tao, L., Gao, Z., Dai, H., & Shi, X. (2018). Modeling Fish Movement Trajectories in Relation to Hydraulic Response Relationships in an Experimental Fishway. *Water*, 10(11), 1511. <https://doi.org/10.3390/w10111511>

Tran, T. D., Chorda, J., Laurens, P., & Cassan, L. (2016). Modelling nature-like fishway flow around unsubmerged obstacles using a 2D shallow water model. *Environmental Fluid Mechanics*, 16(2), 413–428. <https://doi.org/10.1007/s10652-015-9430-3>

Tritico, H. M., & Cotel, A. J. (2010). The effects of turbulent eddies on the stability and critical swimming speed of creek chub (*Semotilus atromaculatus*). *Journal of Experimental Biology*, 213(13), 2284–2293. <https://doi.org/10.1242/jeb.041806>

Umeda C., de Lima G., Janzen J.G., Salla M.R. (2017). One and three-dimensional modeling of a vertical-slot fishway. *Journal of Urban and Environmental Engineering*, v.11, n.1, p.99-107. <https://doi.org/10.4090/juee.2017.v11n1.099107>

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Vezza, P., Parasiewicz, P., Calles, O., Spairani, M., & Comoglio, C. (2014). Modelling habitat requirements of bullhead (*Cottus gobio*) in Alpine streams. *Aquatic Sciences*, 76, 1–15. DOI 10.1007/s00027-013-0306-7

Williams, J. G., Armstrong, G., Katopodis, C., Larinier, M., & Travade, F. (2012). Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions: fish behaviour related fish passage at dams. *River Research and Applications*, 28(4), 407–417. <https://doi.org/10.1002/rra.1551>

Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q., Yin, Z., Dai, J., Yin, D., Liang, J., & Ye, S. (2019). Effects of dam construction on biodiversity: A review. *Journal of Cleaner Production*, 221, 480–489. <https://doi.org/10.1016/j.jclepro.2019.03.001>

Wu, S., Rajaratnam, N., & Katopodis, C. (1999). Structure of Flow in Vertical Slot Fishway. *Journal of Hydraulic Engineering*, 125(4), 351–360. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1999\)125:4\(351\)](https://doi.org/10.1061/(ASCE)0733-9429(1999)125:4(351))

Zeng, G., Xu, M., Mou, J., Hua, C., & Fan, C. (2022). Application of Tesla Valve's Obstruction Characteristics to Reverse Fluid in Fish Migration. *Water*, 15(1), 40. <https://doi.org/10.3390/w15010040>

Zhang, D., Bian, X., Shi, X., Deng, J., & Liu, Y. (2023). Design of a bilateral-symmetric multi-slot fishway and its comparison with vertical slot fishway in terms of hydraulic properties. *River Research and Applications*, 39(5), 954–969. <https://doi.org/10.1002/rra.4125>

Zhao, H., Xu, Y., Lu, Y., Lu, S., Dai, J., & Meng, D. (2022). Numerical Study of Vertical Slot Fishway Flow with Supplementary Cylinders. *Water*, 14(11), 1772. <https://doi.org/10.3390/w14111772>

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

ha formattato: Tipo di carattere: 11 pt

Zhong, Z., Ruan, T., Hu, Y., Liu, J., Liu, B., & Xu, W. (2021). Experimental and numerical assessment of hydraulic characteristic of a new semi-frustum weir in the pool-weir fishway. *Ecological Engineering*, 170, 106362. <https://doi.org/10.1016/j.ecoleng.2021.106362>

Zhou, S., Xu, G., Hu, J., Bao, Z., Tu, X., Wang, Y., & Wang, Z. (2020). Numerical Simulation Study On Flows In Natural-like Fishway Of Low-head Junction. *IOP Conference Series: Earth and Environmental Science*, 510(4), 042019. <https://doi.org/10.1088/1755-1315/510/4/042019>

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Zhu, G., Zhou, Z., & Andersson, H. I. (2020). Role of Transient Characteristics in Fish Trajectory Modeling. *Sustainability*, 12(17), 6765. <https://doi.org/10.3390/su12176765>

Zielinski, D. P., Voller, Vr., & Sorensen, P. W. (2018). A physiologically inspired agent-based approach to model upstream passage of invasive fish at a lock-and-dam. *Ecological Modelling*, 382, 18–32. <https://doi.org/10.1016/j.ecolmodel.2018.05.004>

Zöschg, H., Dobler, W., Aufleger, M., & Zeiringer, B. (2023). Evaluation of Hydraulics and Downstream Fish Migration at Run-of-River Hydropower Plants with Horizontal Bar Rack Bypass Systems by Using CFD. *Water* 2023, 15, 1042. <https://doi.org/10.3390/w15061042>

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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>Acrossochelius 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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