INTERNATIONAL RIVER INTERFACE COOPERATIVE (IRIC) – A MULTITASKING SOFTWARE FOR HYDRODYNAMIC AND MORPHODYNAMICAL PROCESSES IN RIVERS: A REVIEW.

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Abstract: Rivers are sources of one of the natural resources indispensables to living beings: water. Studies about that topic are relevant for water resource management, disaster management, etc. River hydraulics modeling become essential tools for the proper management of these water resources. One recent tool, iRIC and its solvers, are able to represent a large range of rivers phenomena and their complexity. The objective of this work was to review information about research carried out with the iRIC software. Currently, iRIC has 22 solvers that are applicable to the most diverse problems related to rivers. To better understand the range and the spatial distribution of publications with iRIC, a systematic review of the bibliography was performed. In this search, a total of 104 publications were found. The solvers and the publications were separated in 3 topics: (i) sediment related; (ii) water related; and (iii) biology related. The spatial distribution and the topic distribution of the studies were assessed. Most publications originated in the United States and Japan, where the software's creators reside. Additionally, publications were found in 21 other countries, as well as publications that applied solvers in physical laboratory models or in hypothetical areas. The separation of articles into topics showed a balance between articles related to water and sediments, and a surprising number of publications related to biology. Publications with iRIC had a significant increase after 2016, the year in which the article presenting the tool and its solvers to the international community was published.

Keywords – iRIC software, computational model, river morphodynamics

INTRODUCTION

Rivers are sources of one of the natural resources indispensables to living beings: water. In addition, they have great importance in some fields such as culture, society, economy, and history. Although water is distributed in different ways in nature, it is in watercourses such as rivers that it offers the most rational and viable ways of using it (Vieira da Silva *et al*., 2003).

According to Shiklomanov (1998), the rivers' discharge is the most important component of the hydrological cycle. It has a pronounced effect on the ecology of the earth's surface and on human economic development. Thus, studies about this topic are relevant for managements of water resource, environment and disaster, and the functioning of the hydrological and geomorphic processes involved in the dynamics of rivers should be understood.

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Non-permanent flow is the most common pattern within natural rivers, being represented by hydrodynamic models, which provide the variation in time and space of flow variables in a river or channel (Vieira da Silva et al., 2003). Thus, river hydraulics modeling becomes an essential tool for the water resources management. In the 60s, Zanobetti and Lorgeré developed one of the first mathematical models for simulating floods in 2D. Later the authors published this study in the journal La Houille Blanche (1968). The model was developed for the Mekong River delta and had the principle of dividing the basin into storage cells and covering the entire flooded area of the delta, with around 50,000 km².

The flow in rivers and similar systems is characterized by complex processes. Thus, as computational capabilities increase, more complex models in 2D and 3D, with more features are available for use. Models that group more than one hydrological process at the same time, and can represent, to a certain degree, even the most complex phenomena. This is the case of the International River Interface Cooperative (iRIC) (Nelson *et al*., 2016) and its solvers, which are capable of interacting with each other, increasing the range of phenomena possible to represent and their complexity. These models increase opportunities for new steps in research on river hydraulics and geomorphology, providing a more complete understanding of the systems in which they are inserted. Thus, the objective of this work was to review researches carried out during the period 2009-2023, with the solvers available in the iRIC software.

THE INTERNATIONAL RIVER INTERFACE COOPERATIVE (IRIC)

The International River Interface Cooperative (iRIC) was started in 2007 by Professor Yasuyuki Shimizu (Hokkaido University, Japan) and Dr. Jonathan Nelson (USGS) with two purposes: (1) developing a software platform called iRIC for numerical simulation of flow and morphodynamics in rivers; and (2) providing seminars and educational material to support that software. The software is now in version 3.0, with version 4.0 due out soon.

The iRIC software can be described as an interface for public-domain tools for computing flow and morphodynamics in geophysical flows, with particular emphasis on rivers and other similar channels (Nelson *et al*., 2016). It was developed by an international group of scientists and engineers on an entirely voluntary basis. The software's creation as well as a library of instruction guides, tutorials, and other learning resources have been motivated by two different goals. First, the team of researchers that created the software believed that graduate and undergraduate students lacked enough access to state-of-the-art instruments for understanding and foreseeing river morphodynamics based on physical principles. Second, they believed that recently created methods for forecasting flow fields and morphodynamic channel modifications to change flow, sediment supply, or channel form resulting from natural or anthropogenic factors were sufficiently developed to leave the research area and get into the practical applications (Nelson *et al*., 2016).

According to Nelson *et al*. (2016), all these changes suggested that it was time for the model developers to make state-of-the-art research tools for river modeling available to students and other non-specialists so they could assimilate these tools into their own suite of capabilities.

SOLVERS

Currently, iRIC has 22 solvers that are applicable to the most diverse problems related to rivers. Table 1 presents the version 3.0 solvers and a brief description of their main function. More detailed information on each of the solvers presented in Table 1 can be encountered in the manuals and tutorials available on the iRIC website (https://i-ric.org/en/).

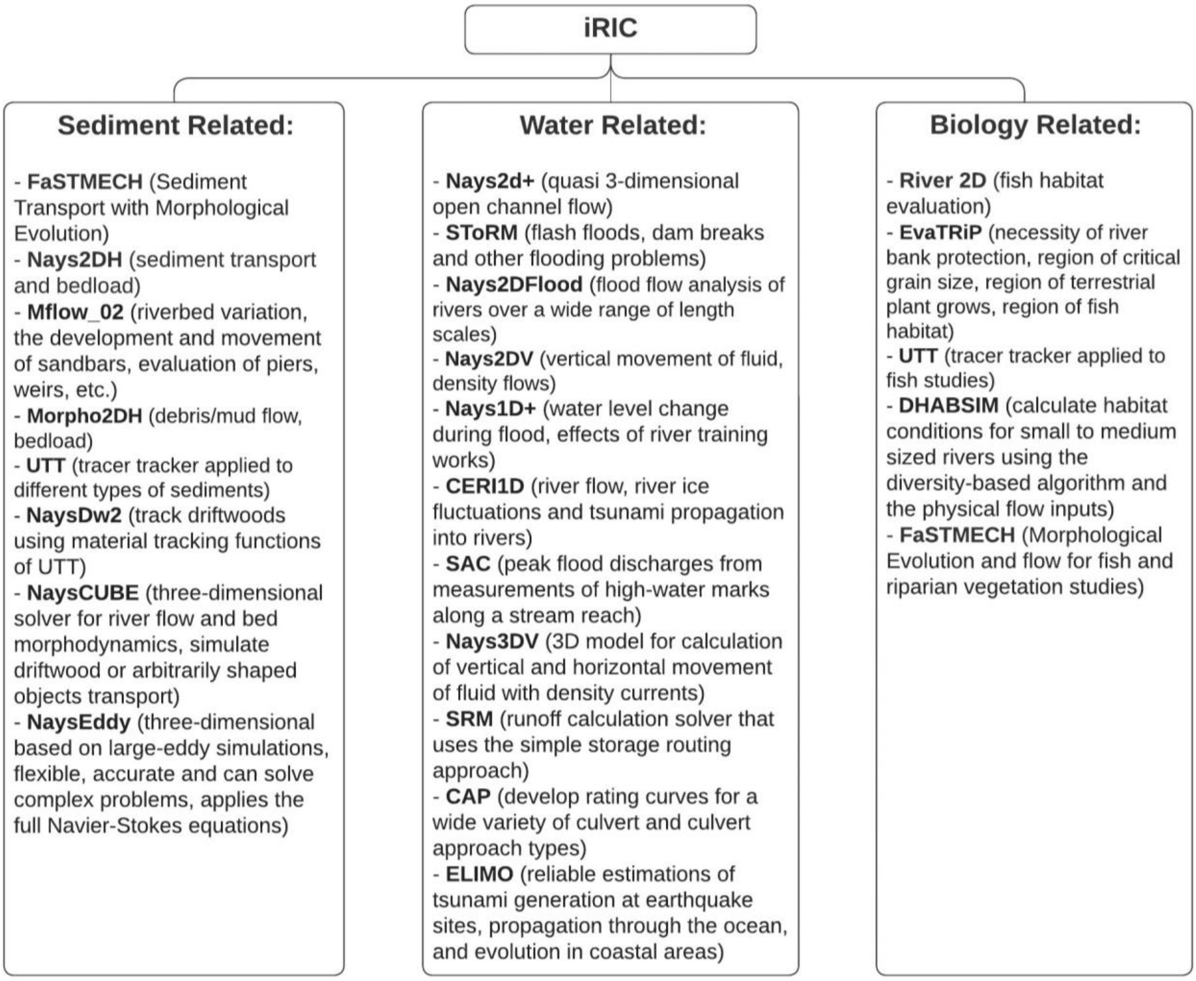
Table 1 - iRIC current solvers.

SOLVER	DESCRIPTION
NAYS2DH	Nays2DH is a computational model for simulating unsteady horizontal two-dimensional (2D) flow, sediment transport, and morphological changes of bed and banks in rivers.
NAYS1D+	Nays1D+ is a one-dimensional (1D) solver for river flows and bed level deformations in the iRIC platform. Nays1D+ can simulate not only steady/unsteady flows but also bed level change considering bedload transport.
NAYS2D+	Nays2d+ is a quasi-3-dimensional open channel flow solver, which combines the results of a horizontal 2-dimensional shallow water flow model and a theoretical solution of velocity profiles of the main flow and secondary flow profiles in the vertical direction.
NAYS2DFLOOD	Nays2DFlood is a flood flow solver that treats unsteady 2-dimensional plane flow using general curvilinear coordinates. Nay2dFlood has been applied for flood flow analysis of rivers over a wide range of length scales, from small streams to the Mississippi.
NAYS2DV	Nays2DV is a computational model for simulating two-dimensional vertical plane flow. Model was developed for calculation of vertical movement of fluid (density flow).
NAYS3DV	Nays3DV is 3-Dimensional model developed for calculation of vertical and horizontal movement of fluid with density currents.
NAYSCUBE	NaysCUBE is an unsteady fully three-dimensional solver for river flow and bed morphodynamics. The approach solves the basic equations of three-dimensional flow incorporate the nonhydrostatic water pressure associated with strong vertical accelerations and velocities.
NAYSEDDY	NaysEddy is a three-dimensional solver based on large-eddy simulations (LES). It solves the flow in more detail using Cartesian grids with ghost-cell immersed boundary methods. NaysEddy is flexible, accurate and can solve complex problems with a great success. This solver applies the full Navier-Stokes equations without approximation and without temporal averaging.
NAYSDW2	NaysDw2 is a solver in iRIC for tracking driftwoods using material tracking functions of UTT. The method used in NaysDw2 is the same as UTT, which is the Lagrangian method of tracing materials. NaysDw2 also has a function of hitting and rotating materials to each other as the DEM method.
UTT	UTT (Universal Tracer Tracker) is a tool to track and visualize the trajectory of various materials specified by the user using the calculation result of various flow calculation solvers implemented in iRIC. The target-transported substance is not only completely following the flow, but also the substance itself has a cruising ability; a typical example is a fish, by specifying its ability and characteristics to express its movement.
FASTMECH	FaSTMECH (Flow and Sediment Transport with Morphological Evolution of Channels) is a quasi-steady two and three-dimensional river flow and morphodynamics solver. The solver has no Courant condition and can perform spatially detailed calculations over relatively long-time scales extremely quickly.
RIVER2D	River2D is an unsteady two-dimensional depth averaged finite element hydrodynamic model. This model is very good for certain kinds of complex domains that cannot be well treated with finite difference models. River2d has been customized for evaluation of fish habitat and used extensively for that purpose all around the world.
STORM	SToRM (System for Transport and River Modeling) is an unsteady two-dimensional unstructured-grid flow solver and can provide suitable analysis even under the most complex boundary conditions. SToRM incorporates higher-order shock capturing schemes and accurate moving boundary methods, this approach is very good for handling strong spatial and temporal variability such as that associated with flash floods, dam breaks, etc.

MFLOW_02	Mflow_02 is a solver for calculating unsteady two-dimensional plane flow and riverbed morphodynamics using unstructured meshes and the finite element method in an orthogonal Cartesian coordinate system. This solver can calculate unsteady flow in structures like piers, weirs, etc., or to calculate flooding in complicated area, such as floodplain areas.
MORPHO2DH	Morpho2DH is the horizontal two-dimensional debris/mud flow solver. The model can reproduce the transport and erosion/deposition processes of debris/mud flow due to landslides. Structures (e.g., SABO dam, weir, buildings and so on) and the horizontal distribution of maximum erosion depth can be incorporated in the analysis. Additionally, the unsteady horizontal two-dimensional flow and bed deformation analysis for clear-water flows can be performed using Morpho2DH as in the original version of Morpho2D.
EVATRIP	EvaTRiP (Evaluation Tools for River environmental Planning) is a solver to provide outcome of existing research for river environmental planning. This tool can evaluate the necessity of river bank protection, the region of critical grain size, the region of terrestrial plant grows, the region of fish habitat, etc.
SRM	The Storage Routing Model (SRM) is a runoff calculation solver that uses the simple storage routing approach. The solver consists of two types of storage routing models: a synthetic storage routing model and a two-cascade storage routing model. The solver can calculate runoff amount from rainfall, while he optimizes parameters of the storage routing model.
ELIMO	ELIMO was a solver that is capable of reliable estimations of tsunami generation at earthquake sites, propagation through the ocean, and evolution in coastal areas. ELIMO has been developed with a motto of “simple and easy tsunami computation” to make such calculation accessible to non-specialists using PC computers and Window operating systems along with the freely available iRIC software interface.
DHABSIM	DHABSIM (Diversity based HABitat SIMulation) is an easy-to-use two-dimensional habitat calculator. The solver calculates habitat conditions for small to medium sized rivers without using Habitat Suitability Indices for specific fish species. Based on the diversity-based algorithm and the physical flow inputs, the solver outputs a habitat distribution map.
CERI1D	CERI1D is a solver for one-dimensional (1D) unsteady flows. CERI1D is capable of calculating river flow, river ice fluctuations and tsunami propagation into rivers. CERI1D provides supporting data for the drafting of flood control measures and disaster prevention measures in cold regions.
SAC	The Slope-Area Computation (SAC) is a solver used to compute peak flood discharges from measurements of high-water marks along a stream reach. The solver uses a general version of the slope-area method to estimate flows based on high-water marks and prescribed roughness values.
CAP	The Culvert Analysis Program (CAP) is a solver for developing rating curves for a wide variety of culvert and culvert approach types. Given a suite of information about culvert geometry, approach details and more, the solver produces a culvert rating that predicts culvert flow rates as function of water-surface elevations.

The solvers presented in Table 1 can be separated primarily into 3 categories (Figure 1): (i) sediment related (whose main function of the solver is to evaluate some process of the hydrosedimetological cycle); (ii) water related (whose main function is to evaluate some hydrological/hydrodynamic phenomenon, such as floods); and (iii) biology related (which have as main function to evaluate ideal habitat conditions and other biological parameters).

Figure 1 - Separation of solvers according to their main function.



IRIC REVIEW

In order to better understand the range and the spatial distribution of the applications of iRIC and its solvers, a brief systematic review of the bibliography was performed. The criteria used in the search will be described in this section.

Firstly, we used the publications database of *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES) (https://www.periodicos.capes.gov.br/), a Brazilian government institution to promote research. To perform the search on this platform, a function of Boolean search algorithms was used. The used function was:

"(iRIC OR "System for Transport and River Modeling" OR Nays2DH OR Nays1D+ OR Nays2d+ OR Nays2DFlood OR Nays2DV OR Nays3DV OR NaysCUBE OR NaysEddy OR NaysDw2 OR "Universal Tracer Tracker" OR FaSTMECH OR River2D OR Mflow_02 OR Morpho2DH OR EvaTRiP OR "Storage Routing Model" OR ELIMO OR DHABSIM OR CERI1D OR "Culvert Analysis Program") NOT (Health OR Medicine) NOT (Irice)"

In addition to this function, some filters were applied in the search: (i) language, only articles in English, Portuguese and Spanish were analyzed; (ii) all articles with subjects related to medicine and health were removed; (iii) all articles with subjects related to mathematics, theorems, metric space and fixed points were removed; (iv) the type of publication, only peer-reviewed articles and thesis were displayed in the search result.

This search turned up 153 publications. Their titles and abstracts were examined to determine whether they were relevant to the topic under discussion. Some models such as River 2D already had a version prior to their implementation on the iRIC platform, the articles that used the previous version of these models were also discarded. This procedure resulted in 43 articles, 2 of which were publications on the development and advancement of research with the software (Nelson *et al*., 2016; Shimizu *et al*., 2020).

Additionally, an analysis of the articles that cited the publication that described the development of the iRIC software (Nelson *et al*., 2016) was performed. This list is available on the publisher's website (https://www.scopus.com/results/citedbyresults.uri?sort=plf-f&cite=2-s2.0-84949988017&src=s&imp=t&sid=636243fab860aba30c63d1c8cd468742&sot=cite&sdt=a&sl=0&origin=inward&editSaveSearch=&txGid=533daa4aab083121ce696e6e8c6442f9). The studies that used an iRIC solver and weren't yet found by the first search were selected from this list. It resulted in the identification of 61 additional articles, reaching a total of 104 publications.

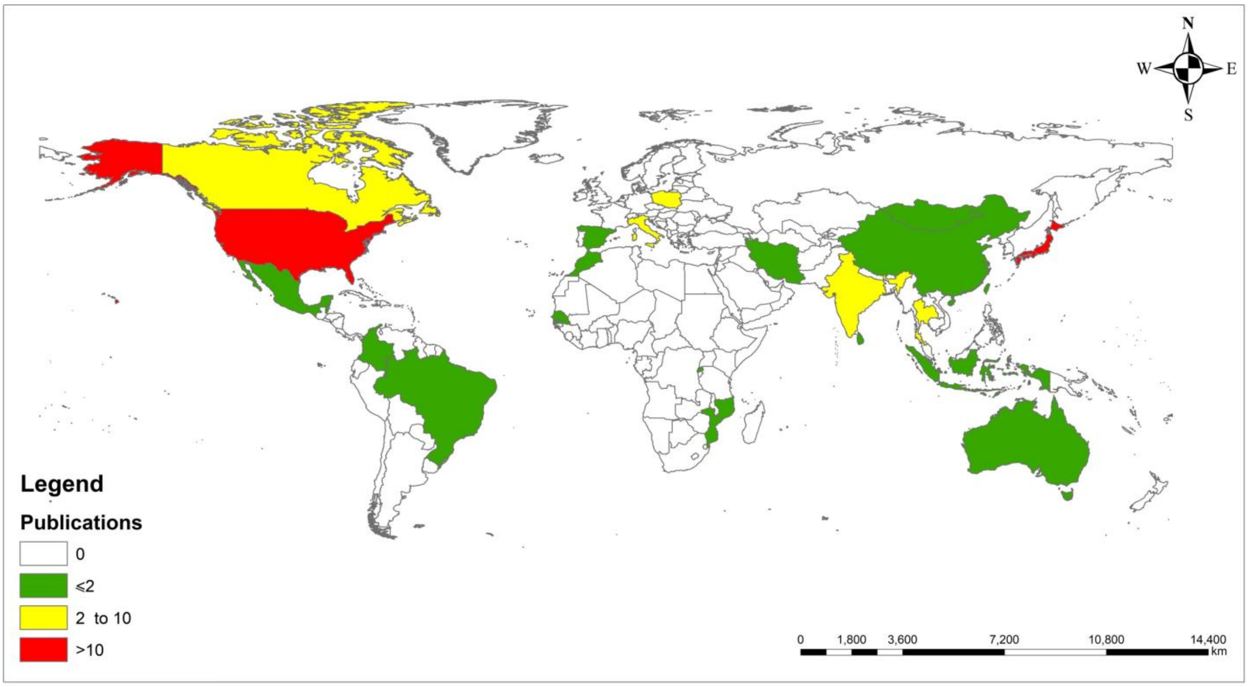
The 102 articles were analyzed (disregarding the two related to the tool's development and advancement) in order to comprehend the geographic distribution of the iRIC application and the main topics of each study. The topics assessed in each article were: country where the application area is located; main topic of the article (based on the three categories shown in Figure 1).

In some articles, there was an overlap between categories, because to achieve the objective of the study, analyzes that fit into 2 or more of the categories proposed in Figure 1 were necessary. For example, for an analysis of the ideal habitat for a species of fish, the river hydraulic parameters and morphological variations were to be evaluated. In cases like this, the topic proposed by the primary objective of the article was prioritized. In the example mentioned above, the category of the article would be related to biology, because the primary objective of the article is to evaluate the habitat conditions for the studied species.

SPATIAL DISTRIBUTION

For a better visualization of the spatial distribution of the studies, Figure 2 was created, which presents the number of articles that applied the iRIC in each country in 4 classes: (i) 0; (ii) less than or equal to 2; (iii) from 2 to 10 and; (iv) more than 10.

Figure 2 – Spatial distribution of the found publications.



Publications were identified in 23 countries (Table 2), of which only 2 had more than 10 (Japan and the United States), this is mainly since the main developers of this software (Professor Yasuyuki Shimizu and Dr. Jonathan Nelson) work in these countries. Thus, it is expected that most of the studies will be elaborated by the research groups to which both belong.

Figure 2 and Table 2 show how the use of this tool is still very concentrated in its creation environment and nearby countries (with some exceptions), however, the studies already carried out demonstrate the great potential of solvers and the platform in solving engineering problems and even in the study of complex phenomena. Thus, when analyzing this spatial distribution, the need to test the potential of this tool in different environments becomes clear, which has been implemented, but slowly.

In addition to the 23 countries, applications of solvers for comparisons and validation of laboratory studies with physical models were identified. This was more common in studies of phenomena in 3 dimensions, where the studied phenomena becomes more complex and the amount of input data and detail needed to apply the model sometimes makes it difficult to apply it in natural environments. Therefore, it is more common that these studies of 3D phenomena are conducted with experiments in the laboratory.

Table 2 - Number of publications by application site.

Application sites	*Number of publications*	*Application sites*	*Number of publications*
United Estates	27	Spain	1
Japan	21	Iran	1
India	5	Colombia	1
Canada	4	Belize	1
Italy	3	Mongolia	1
Poland	3	Rwanda	1
Thailand	3	Morocco	1
Mexico	2	Brazil	1
Sri Lanka	2	Senegal	1
China	1	Indonesia	1
Taiwan	1	Laboratory	14
Mozambique	1	Hypothetical Area	4
Australia	1		

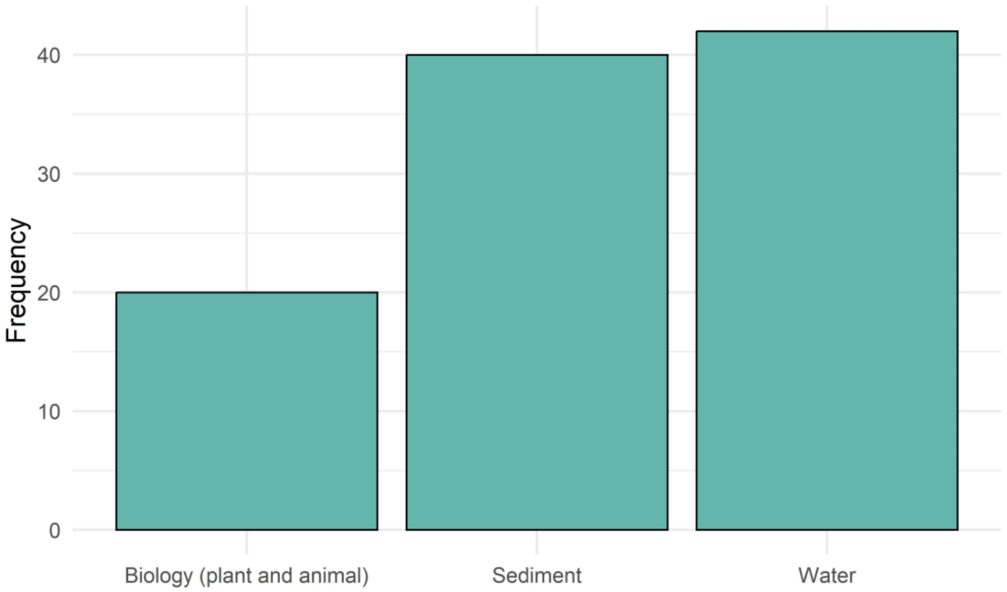
Another environment that is not identified in Figure 2 are the hypothetical rivers. Some studies aimed at parameters for designing structures, thresholds for certain phenomena or studying phenomena under different conditions used hypothetical rivers with different configurations. This favors the research development, because measured data are not necessary for simulations.

TOPIC DISTRIBUTION

When analyzing the distribution of the main topics of each study (Figure 3), it is observed a balance between studies about sediments and about water. This demonstrates that the authors' initial objective has been reached, according to Nelson *et al*. (2016), the initial focus of the software was to provide a tool capable of carrying out studies on the flow and morphodynamics of rivers, in this sense this result was expected.

However, the number of studies related to biology should be highlighted, despite being the category with the fewest articles found, approximately 20% of the publications had the main objective of evaluating biological parameters. This significant quantity demonstrates the high potential and versatility of the tool, which was initially not developed for such purposes but due to these studies, today already has its own solvers for these assessments.

Figure 3 - Separation of solvers according to their main function.

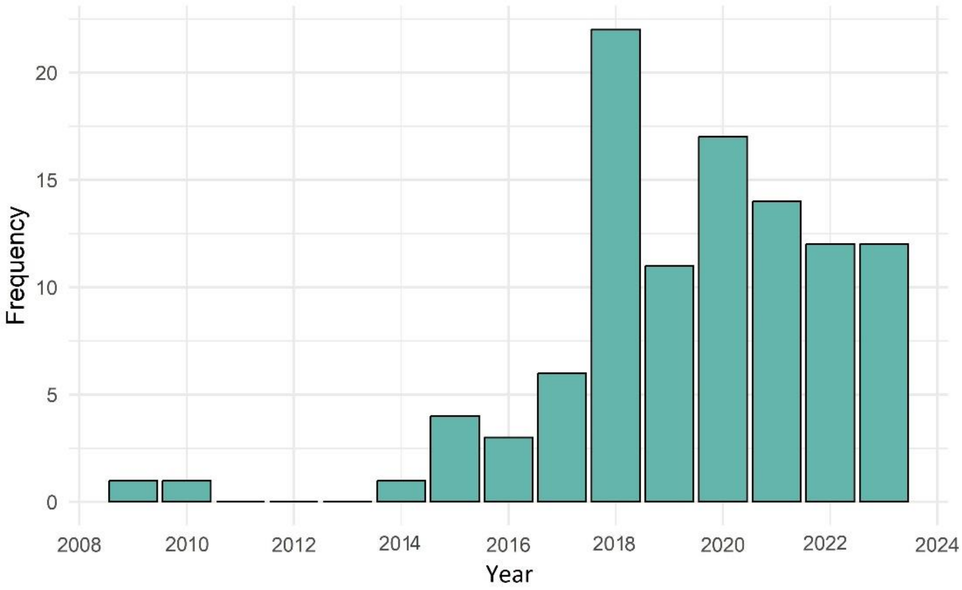


Another interesting analysis concerns the evolution of the number of publications over the years. In Figure 4, we have a significant increase in publications after 2016, the year in which the iRIC disclosure article was published. This fact, together with the group's strong investment in offering training in several countries, with classes given by the model developers themselves, has had a strong impact on the increase in the use of iRIC in recent years.

Regarding the solvers, the most frequently used were FaSTECH and Nays2DH (Table 3). FaSTECH is very versatile, and requires little computational power and performs the simulation of relatively large areas in a short time (due to its quasi-2D and quasi-3D approximations), it has been used in a wide variety of subjects and sizes of study sites, and in all the 3 categories. Some studies stand out, such as the Tonina *et al*. (2022), who assessed the fragmentation of salmon habitat in snow-dependent regions due to climate change, Bywater-Reyes *et al*. (2018), who evaluated the influence of a vegetated bar on channel-bend flow dynamics, and Nelson *et al*. (2018), who developed a new method for predicting and measuring dispersion in rivers with FaSTMECH.

Nays2DH, on the other hand, uses RANS equations (Reynolds-averaged Navier–Stokes equations), which demands more computational cost, however it is able to simulate the phenomena in a more detailed way. This solver was used in most of the laboratory studies found to validate physical models. Another very common application of Nays2DH was to evaluate sediment engineering problems, such as the formation of bars and erosion in structures in rivers. However, it was also used to evaluate the behavior of certain phenomena, as in Uchiyama *et al.* (2022) who evaluated the nearshore dispersal of suspended 137Cs in a storm-induced flood, and Bair *et al.* (2019) that quantified the restoration success of wood introductions to increase coho salmon winter habitat.

Figure 4 - Number of publications by year.



Another solver that stood out in a number of publications was Nays2DFlood. Developed more recently, it is a modification of Nays2DH more focused on the evaluation of floods. Among interesting studies developed with these solvers, exists Ogawa *et al*. (2023) who proposed a route search system to avoid the danger to life in dynamic flood and Guirro and Michel (2023) who made a hydrological and hydrodynamic reconstruction of a flood event in a poorly monitored basin in southern Brazil.

Table 3 - Number of publications found for each solver.

Solver	*Publications*	*Solver*	*Publications*
Nays2DH	37	Morpho2DH	2
FaSTECH	24	SToRM	2
Nays2DFlood	19	Nays2DV	1
River 2D	8	EvaTrip	1
Mflow_02	5	UTT	1
NaysCUBE	3		

FINAL CONSIDERATIONS

The present work introduces the IRIC, a software that performs numerical simulations of flow and analyzes the morphodynamic changes that occur in a river based on the simulation of various situations. This package at this moment includes 22 solvers that can be used to do simulations in three main areas: biology (plant and animal), sediment, and water. Being free and open software with a comprehensive English manual is one of its primary advantages.

When analyzing the spatial distribution of publications involving this software, it is noticed that the countries with the highest number of published articles were the United States and Japan. However, there has been an increase in the number of publications in other countries in recent years. Regarding the topics of the publications, it is important to note that while though the program was created to model water and sediments, there are a considerable number of articles published with a biological focus.

Publications with iRIC had a significant increase after 2016, the year in which the article by Nelson et al. (2016) presenting the tool and its solvers to the international community. The most used solvers were Nays2DH, FaSTMECH and Nays2DFlood, with 37, 24 and 19 publications respectively.

Through this brief review we recognize that this software with a few publications (in English) has a high potential to be explored. There are some solvers capable of evaluating phenomena and considering unusual parameters such as the vegetation density, which brings some interesting results. There are also solvers capable of simulating complex phenomena in 3D that have been little explored. This is probably due to the large amount of data required to perform this type of simulation. Thus, still exist gaps to be accessed. Since there is a considerable number of publications in other languages like Japanese, Thai and Chinese, a next step would be to expand this review to other languages.

Due to the immense number of references used in the bibliographic review, which would overload the references section, here we chose to generate a file of the RIS type (publication library that can be read in a reference manager software) with all the publications analyzed. It can be downloaded from the link:
<https://drive.google.com/file/d/13tRQxAOo8gxTGed09V11FpjBdrzxJA1Q/view?usp=sharing>

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