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Integrating Downstream Ecological, Social and Economic Effects of Hydropower to Hydraulic Modeling: A Review

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Abstract

Hydropower gains increasing importance as a steerable and controllable power source in a renewable energy mix and deregulated markets. Although hydropower produces fossil-free energy, it has a significant impact on the local environment. This review investigates the effects of flow alterations by hydropower on the downstream river system and the possibilities to integrate these effects into hydraulic modeling. The results show that various effects of flow regulation on the ecosystem, but also social and economic effects on related communities were observed in the last decades. The application of hydraulic models for investigations of ecological effects is common. Especially hydraulic effects and effects on fish were extensively modeled with the help of hydraulic 1D- and 2D-simulations. Current applications to investigate social and economic effects integrated into hydraulic modeling are meanwhile limited. Approaches to realizing this integration are presented. Further research on the economic valuation of ecosystems and integration of social and economic effects to hydraulic models is necessary to develop holistic tools to support decision-making on sustainable hydropower.

Keywords

Sustainable Hydropower, Hydraulic Simulation, River Regulation, Downstream Effects, Integrated Modeling

1. Introduction

1.1. Hydropower and Its Impact on the Natural River Flow

Hydropower is the source of 16% of the produced electricity worldwide [1]. In the Nordic countries, hydropower even provides 56% of the electricity [2] and in Sweden, it accounts for 45% [3]. In the aspiration toward fossil-free energy production, hydropower will play an important role as regulation energy in deregulated markets [4] [5]. While the application of hydropower can secure the energy supply and help mitigate climate change [6], it has severe effects on the river ecosystem as well as social and economic impacts. To enable sustainable power production the adverse effects of hydropower need to be analyzed and compared with the benefits.

The effects of hydropower are various and can be directly caused by the construction of a plant, dam, and reservoir or indirectly by the operation of the plant [7] [8]. This review focuses on the downstream effects caused by the flow alteration as a consequence of the operation scheme. Hydropower operations can change the natural flow characteristics of a river in diverse ways. The flow characteristics named by Richter *et al.* [9] are the magnitude of flow, the frequency of occurrence of certain conditions, the duration of certain conditions, the timing of flow events, and the rate of change, also referred to as ramping rate [10]. All these flow characteristics can be altered by hydropower operation. Common phenomena of flow alteration at hydropower plants are hydropeaking, low base flow, or seasonal flow alteration. In combination with flow alteration other phenomena like thermal alteration (for example thermopeaking, [11]) or change in gas saturation (for example saturopeaking, [12]) occur, but are not within the scope of this review.

1.2. Application of (Eco-)Hydraulic Models in Decision Making

Many hydropower plants in Sweden were built before the implementation of advanced environmental law [13]. In 2014 the Swedish agencies for Marine and Water Management and Energy decided on a national action plan for relicensing the plants to evaluate the effects and implement appropriate measures [14]. To evaluate the effects of current and future plant operations suitable tools are required.

Many studies investigated the effects of implemented measures and described the observed impact of flow alteration [7] [10] [11]. While a-posteriori impact studies help in understanding the relations between flow parameters and impact, they have only limited advantages during the planning process. In such cases, hydraulic models could be used to simulate the flow and evaluate the effects of flow alteration based on the hydraulic conditions. These simulations enable predictions of future scenarios and the comparison of different alternatives of plant operation and mitigation measures without costly trial and error processes [15]. While the hydraulic simulation of rivers already became a standard process with often reliable results, the combination of hydraulic models and impact assessment is mostly limited to the discipline of ecohydraulics.

Ecohydraulics emerged as a discipline in the 1990s and early 2000s with the 1st International Symposium on Habitat Hydraulics (Trondheim 1994 [16], from

1999 named International Symposia on Ecohydraulics) and the appearance of the term "ecohydraulics" in the scientific literature [17] [18]. The discipline is formed at the interface between the physical and biological sciences and includes applied as well as fundamental work. It combines the hydraulic properties of water with their influence on the ecosystem in interdisciplinary approaches to solve modern river management problems [19]. Already decades before the emergence of the term ecohydraulics multidisciplinary research in this field was conducted. Statzner *et al.* [20] for example, conducted research on the response of lotic organisms to flow characteristics under the term "hydraulic stream ecology". Already in the 1970s and 1980s Bovee, Milhous, and colleagues at the U. S. Fish and Wildlife Services laid the foundation for habitat modeling with the Instream Flow Incremental Method (IFIM) and the Physical Habitat Simulation (PHABSIM) system [21] [22] [23] [24]. These methods are used to model the fish habitat as weighted usable area (WUA) depending on the hydraulic parameters depth and velocity as well as data on substrate and cover. Nowadays conceptual and numeric models are standard tools in the field of ecohydraulics [25].

In contrast to the widely known discipline of ecohydraulics, there are only a few studies combining social and economic effects of flow alteration with hydraulic models. A holistic evaluation of effects based on hydraulic simulations is not realized. This literature review aims to accumulate research on the effects of hydropower integrated into hydraulic modeling and identify research gaps to serve as a basis for further research. To fulfill this aim, the work was divided into three particular objectives:

- First, we want to summarize the effects of river regulation related to hydropower on the downstream river. In contrast to works like Hayes *et al.* [26] and Poff and Zimmermann [27], this review will not only focus on the ecological aspects of flow alteration but also include social and economic effects.
- In a second step, we will identify the current state of research in integrating these effects to hydraulic models and the methods used for this purpose. Thereby, we will identify which effects have not been integrated into hydraulic models yet.
- At the end, we want to form ideas on how to use the ecohydraulic methods to include social and economic effects to hydraulic modeling and develop a concept for an integrated modeling approach. Such an approach will help to support decision-making on sustainable hydropower.

2. Methods

In this work, a literature review is performed to synthesize the existing research within the field. From the review, research gaps are identified and a concept for integrated modeling based on existing methods is developed. To address the different research objectives the literature review was performed in two parts, see **Figure 1**. In the first part, the literature on the effects of river regulation related to hydropower was extensively reviewed. The search was conducted unstructured

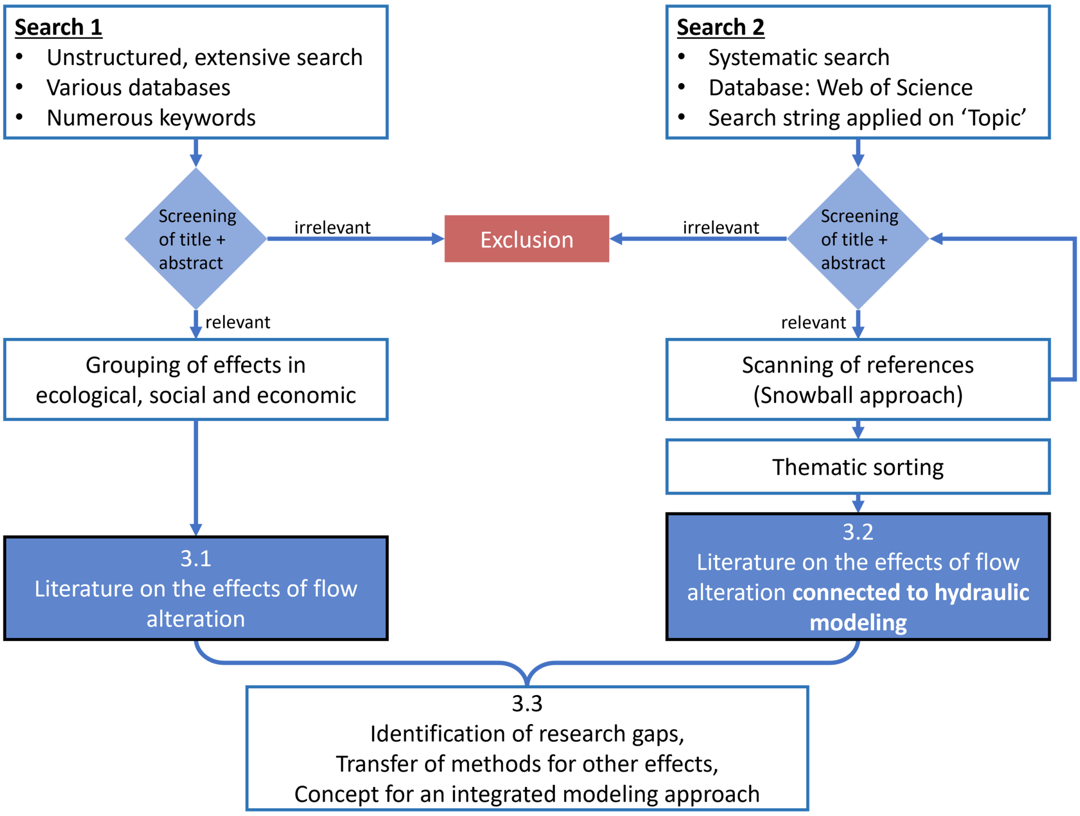


Figure 1. Illustration of the study methodology used and the structure of the article.

with various search terms in different databases. The resulting literature was screened regarding the title and abstract. Articles not relevant to the research question were excluded. In the following, the effects were grouped as ecological, economic, and social effects, although a clear distinction is sometimes impossible.

The second part was a systematic review of the effects of hydropower which have already been assessed with the help of hydraulic modeling. The database Web of Science (www.webofscience.com) was used for the search. The search was conducted by using search strings on the "topic", which combines the title, keywords, and abstract of resources.

As the focus was on studies conducting hydraulic simulations to reproduce or evaluate the effects of hydropower on the river reach, the terms "hydraulic model*" and "hydraulic simulat*" were included as concepts in the string. The kind of effects (environmental, social, economic, etc.) investigated should not be limited in the search but analyzed afterward so the general concepts "effect*", "affect*", and "impact*" were added to the string.

Regarding the context of these concepts, the literature study should concentrate on the effects connected to flow alteration due to hydropower production and new production schemes. "Hydropower" as a term would be too general. The context was therefore defined by "flow alteration" and "river regulation" to address the anthropogenic changed discharge as well as "hydropeaking" as the most common, most researched concept of future hydropower operation schemes.

These reflections resulted in the search string (Hydropeaking OR “flow alteration” OR “river regulation”) AND (impact* OR effect* OR affect*) AND (“hydraulic model*” OR “hydraulic simulat*”).

The search in September 2023 resulted in 40 articles. After scanning the titles and abstracts, 15 results were excluded as they did not cover river regulation by hydropower, did not apply hydraulic models, or were not relevant for the review for other reasons. The references of the remaining 25 articles were scanned in a snowball approach and 20 more relevant articles were detected, resulting in a total of 45 studies. A thematic analysis of the literature was performed and the articles were sorted thematically by the focus of the studies. We are aware that a lot more studies using ecohydraulic modeling to investigate the environmental effects of hydropower exist. Nevertheless, a more extensive review of literature on ecohydraulic and habitat modeling was not seen as beneficial for the aims of this review.

Finally, the findings from the two literature searches are combined to reveal research gaps when it comes to hydraulic modeling of the effects of flow alteration. The transfer of applied methods for the investigation of other effects and a concept for an integrated modeling approach will be discussed.

3. Results and Discussion

3.1. Flow-Related Effects of Hydropower

The effects of hydropower caused by flow alteration are numerous. In the following, the findings from the extensive literature review are presented. The effects are distinguished into ecological, social, and economic effects, although they are often interrelated. Figure 2 gives an overview of the effects with a tendency of their impact based on the characterization in the literature. On the ecological side, the literature review by Poff and Zimmermann [27] showed that

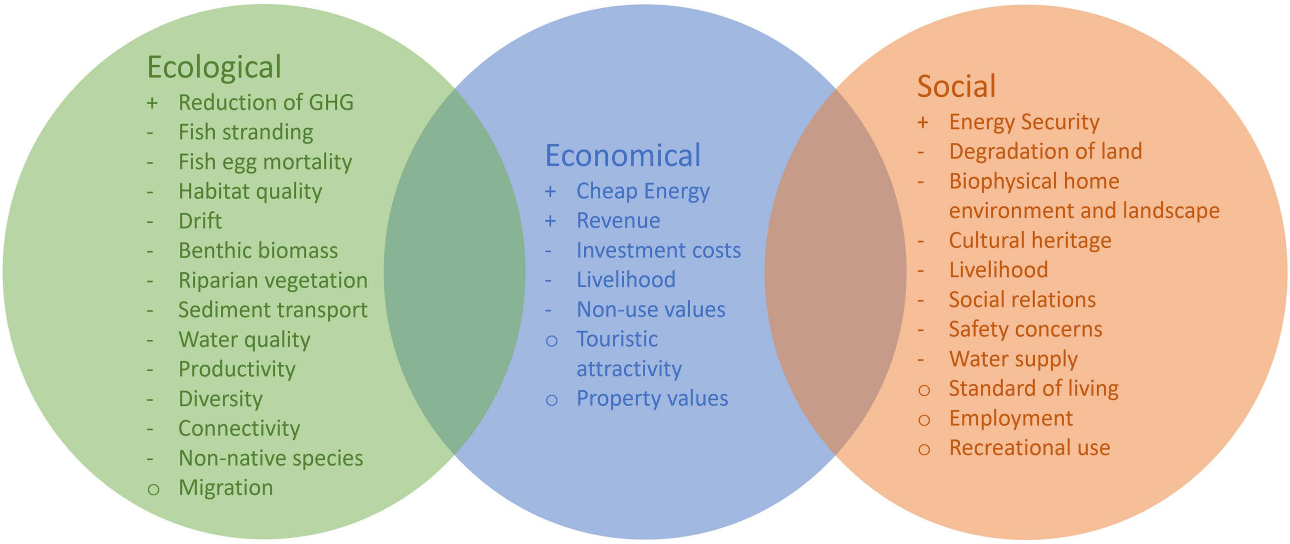


Figure 2. Overview of ecological, social, and economic factors impacted by flow alteration and the tendency of impact (+ positive, – negative, o neutral/unclear).

the impact on the river system is mostly adverse. In general, the effects of flow alteration are species-specific but often favor non-native or exotic species of plants, fish, insects, or other animals [28]. Regarding fish, changes in frequency and ramping rate can lead to an increased risk of stranding [29] [30] [31]. Due to high peak floods and high ramping rates drift of fish can occur [29] [32]. The likeliness of both, stranding and drifting, is also dependent on the seasonal and sub-daily timing of flow changes [28]. The frequencies of flow changes influence the spawning area [31], can impact fish egg mortality [33], and can reduce the spawning and rearing success [32]. Low or fluctuating flows reduce the habitat availability and quality [29] [34]. Hydropeaking can also impact the migration of salmonids [35] and thereby reduce the longitudinal connectivity of the river additional to the physical barrier of the dam. An indirect adverse effect of flow alteration on fish can be the effect of sediment movement due to flow alteration in the form of moving bed or increased sediment transport [10]. These increased sediment as well as bank erosions in the river can be caused by peak floods [36] [37]. On the other hand, the peaks maintain the habitat by flushing fine sediments. More uniform flows or cutting of the spring floods would prevent this natural flushing and could lead to colmation of the substrate, degrading the habitats [7] [32] [38]. Similar to fish macroinvertebrates can also be subject to drift or even scouring due to peak floods or high ramping rates [39] [40]. The drift especially in combination with habitat alterations can lead to alteration of food webs [10] [26]. Hydropeaking usually leads to reduced macroinvertebrate biomass and a change in community structures [10]. Furthermore, a decrease in benthic biomass can be caused by intermittent or low flows [41] [42].

With regard to the flora, low flows or elimination of the seasonal peak floods can either cause an extensive growth of aquatic plants [28] or when causing the above-mentioned substrate colmation indirectly depress the periphyton growth [10]. In contrast, increased flow velocities can decrease the periphytic biomass due to increased cell abrasion [10]. Hydropeaking would decrease the germination success and survival of riparian vegetation [36]. The riparian zone is often influenced due to the cut-off of seasonal peaks. The lack of frequent flood events disrupts the lateral connectivity between river and riparian areas and floodplains [43]. The decreased lateral connectivity implies an alteration in floodplain habitats. This can for example lead to a shift in riparian vegetation from hydric to xeric guilds [44] or a decrease in fish productivity and diversity when important feeding and spawning habitats on the floodplain disappear [28]. The lateral effects also include effects on birds and other animals relying on the river for drinking water supply or other reasons [28]. Beside the longitudinal and lateral connectivity, flow alteration can also reduce the vertical connectivity, referring to the interaction between the surface and groundwater systems [43]. In general, changed flow conditions can decrease biological diversity and increase the success of non-native or invasive species in both fauna and flora [7] [27]. For additional literature on ecological effects, we refer to the reviews of Poff & Zimmermann [27] and Malm-Renöfält *et al.* [7] for the effects of flow alteration as well as Hayes *et al.* [26] and Greimel *et al.* [10] on the effects of hydropeaking.

Social effects of the flow alteration often arise indirectly from ecological effects or from the operation of the hydropower station. In regions where people's livelihood relies on the use of the river or floodplain areas, flow alterations often impact whole communities. The elimination of floodplain flooding for example leads to a degradation of land reducing the success of flood-based agriculture, floodplain herding, or floodplain forest yields [9] [28] [45]. In addition, the reduction of fish populations due to degraded habitats and aggravated migration leads to losses in fishery production. This can threaten people's livelihood, but also their self-supply and nutrition [9] [28]. The case study of Autti and Karjalainen [46] shows how the disappearance of salmon in a Finnish river destroyed or changed people's livelihood and thereby affected culture and social relations in the community. A study by Golden *et al.* [47] describes the impact of fish reduction due to hydropower on people's nutrition in the Mekong. Hydropower can furthermore influence the recreational use of the area by loss or degradation of land or access to land [26] [48] [49]. In any case, hydropower projects change the familiar biophysical home environment and landscape of the community and can destroy cultural heritage [45] [46] [48]. Mayeda and Boyd [48] and Andersen and Heidenreich [50] describe safety concerns of local communities connected to floodings, mudslides, or erosion which are related to new discharge patterns. In some regions, reduced water availability and quality can lead to problems in the water supply for irrigation or drinking water [48]. On the other hand, hydropower reservoirs and flow alterations can also beneficially be used for flood prevention and water supply [45] [48]. Flow alteration can further have both, beneficial and adverse effects, on different forms of recreational and touristic use of the river, like boating or fishing [49] [50]. Rygg *et al.* [51] observed that the ownership of hydropower plants can influence the social effects and social acceptance among the local population. Local ownership is associated with increased local socio-economic benefits [51]. Besides all other social effects, flow alteration, and flexible power production are used to match peaks in the electricity demand and thereby support the energy security [6].

The economic impact of hydropower is either linked to energy production, or social or environmental aspects. On the site of energy production, the revenue depends on the regulated flow [52] due to the varying energy prices in the deregulated energy markets [4]. Besides the relatively high investment costs for hydropower, the standardized costs on the total lifetime of 0.048 USD/kWh are low compared to fossil fuels [53]. A change of prevailing flow conditions through direct mitigation would either cause new investments for constructive measures or a revenue change in the case of operational mitigation. In developing countries, the implementation of hydropower can lead to local electrification and have indirect economic effects through e.g. increased work efficiency or increased touristic attractivity [48]. On the other hand, low flows can lead to a decrease in tourism and recreational activity and connected revenue [49]. However, Ferrario and Castiglioni [54] show that hydropower facilities and river regulation can also be used as tourist attractions if managed accordingly. Beside these changed use-values of the river ecosystem, flow alteration can also lead to, often adverse, changes in non-use or intrinsic values related to the intention of nature conservation [55]. An economic effect of flow regulation on individuals can be changes in the value of private properties due to environmental and biophysical changes [48] [56]. Furthermore, individuals are affected by the possible loss or change of livelihood e.g. connected to agriculture or fishing as explained. According to Adams [57], the economic production losses in fishing and flood-based agriculture could be significant in some projects if properly considered in the economic planning of hydropower projects.

The appearance of effects is strongly influenced by the morphology of the river reach, which can dampen or amplify flow effects [58]. The direction and amplitude of the effects often depend on the impact management of the hydropower project [8]. To increase the sustainability of hydropower projects enhanced participation can help to consider all affected groups and all effects [59], social and environmental impact assessment and action plans can be used as management tools [8], and mitigation measures can be implemented to reduce the adverse effects [50] [52]. Due to the numerous and often opposing effects and stakeholder interests, trade-offs are usually necessary.

3.2. Effects of Hydropower Connected to Hydraulic Modeling

The studies in this part of the review result from the structured search and the selection process described in the methods section. They all investigate the modeling of effects of flow alteration on river reaches. The majority of 28 studies investigate effects of hydropeaking events on a narrow time scale (**Figure 3(a)**). Other investigated phenomena are environmental flows [15] [60] [61] [62] [63] [64], flow alterations due to abstraction or diversion of discharge [41] [44] [49] [65] [66], seasonal flow alteration [67] [68], or long-term effects of different flow alterations [69].

The thematic grouping of papers revealed that the focus of studies is mostly

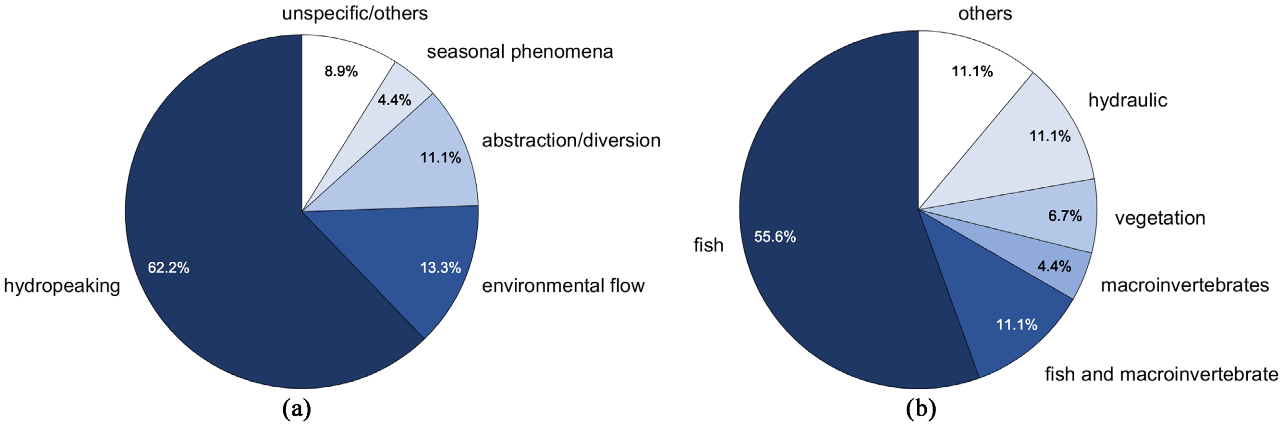


Figure 3. Investigated flow alterations (a) and main effects modeled (b).

on environmental effects of river regulation. 39 out of the 45 papers have a clear focus on environmental aspects. The five papers on hydraulic effects partially include influences on ecology. Bowen *et al.* [67], for example, draw assumptions for fish habitat from the investigated patterns of shallow-depth, slow-velocity areas. Of the environmental studies, 25 articles model the impact of flow alterations on fish species by combining hydraulic investigations with ecohydraulic knowledge (**Figure 3(b)**). The other environmental studies focused on the influence on benthic organisms or vegetation, investigated the influence of hydropeaking on river ice [70] [71], or combined several effects (**Table 1**).

While the combination of hydraulic investigations with ecological effects formed its own discipline "ecohydraulics", the studies show that it is less common to couple economic or social effects with hydraulic modeling. Only Pisaturo *et al.* [72] focused on the social aspect of human safety. Six of the studies approach to include economic factors. Juarez *et al.* [30], Pragana *et al.* [73], and Casas-Mulet *et al.* [33] evaluate the costs of operational mitigation measures for the hydropower operator. Person *et al.* [52] also include the costs for structural mitigation measures. Possible economic benefits of mitigation are not included in these studies. Adeva-Bustos *et al.* [15] compare the costs of mitigation measures and revenue losses with the economic benefits of recreational fishing. Carolli *et al.* [49] trade off possible incomes from touristic activities, namely white-water rafting, against revenue from hydroelectricity production. At the same time, they state the problems to include the third investigated ecosystem service, fish habitat, in an economic evaluation. Carolli *et al.* [49] emphasize a need for further research in the field of economic evaluation of ecosystem goods. Fong *et al.*, Watts *et al.*, and Carolli *et al.* [49] [60] [74] demand further investigations of the relationships between flow and ecologic effects. Choi *et al.*, Le Coarer *et al.*, and Bowen *et al.* [29] [67] [75] see a need for more complex studies including multiple factors and increasing the application of multidisciplinary approaches [75].

Regarding the methodology, 13 of the studies applied one-dimensional hydraulic models, and 23 studies used two-dimensional depth-averaged models (see **Figure 4(a)**). Some authors used several models with different dimensions, while two articles do not specify the model dimensions (see **Table 1**). Pisaturo *et al.* [76] compared 2D- and 3D-models, while Shen and Diplas [77] applied a 3D-model. When considering the publication dates of the studies, the number of studies with 1D- and 2D-models published until 2015 is almost equal (**Figure 4(b)**). From 2016 onwards the 2D-studies outnumber the others. Contrasting to this observation, Pisaturo *et al.* [76] present weaknesses of depth-averaged models compared to 3D-simulations and recommend applying 3D-models in habitat simulation to increase the accuracy of the results. They modeled the habitat for brown trout based on bottom velocities from 3D-modeling, depth-averaged velocities from a 2D-model, and bottom velocities calculated from the 2D-model with the logarithmic law of the wall and obtained the best representation of

Table 1. Modeling methods and investigated and included effects of the different studies.

Article	Main Effects Modeled	Other Effects Investigated	Hydraulic Models		Integrated Modeling
Hydraulic Effects					
Bowen *et al.* 2003 [67]	depth, velocity	-	River2D	2D	-
Richmond & Perkins 2009 [90]	dewatered area, pool formation	-	Modular Aquatic Simulation System (MASS1)	1D	-
Watts *et al.* 2016 [60]	velocities, inundation area	-	2D Eonfusion Flood	2D	-
Fong *et al.* 2016 [74]	ramping rates, duration, Qpeak	-	HEC-RAS	1D	-
Burman *et al* 2020 [91]	water surface elevation, wetted area	-	Delft3D	2D	-
Effects on Fish					
Casas-Mulet *et al.* 2014 [33]	egg mortality	costs of mitigation	HEC-RAS	1D	thresholds
Casas-Mulet *et al.* 2015 [78]	stranding	-	HEC-RAS	1D	comparison of wetted areas
Tuhtan *et al.* 2012 [92]	stranding	-	SRH-2D	2D	CASiMiR (fuzzy rules)
Juarez *et al.* 2019 [30]	stranding	operational cost for mitigation	HEC-RAS	2D	variation of wetted areas and ramping rates
Alfredsen *et al.* 2022 [93]	stranding		HEC-RAS	2D	thresholds
Le Coarer *et al.* 2023 [94]	stranding and trapping		TELEMAC	2D	thresholds
Alfredsen 1997 [84]	habitat		Hec-2, AquaDyn, SSIIM	1D, 2D, 3D	preference curves
Alfredsen *et al.* 1997 [64]	habitat		Hec-2, AquaDyn, SSIIM	1D, 2D	preference curves
Borsányi *et al.* 2001 [95]	habitat	stranding risk	BOSS DAMBRK	1D	HABITAT, preference curves
García *et al.* 2011 [96]	habitat	-	HECRAS	1D	CASiMiR (fuzzy rules)
Boavida *et al.* 2013 [97]	habitat	-	River2D	2D	HSC[a]
Person *et al.* 2014 [52]	habitat	hydropower operation/revenue, measure costs	HYDRO_AS-2D	2D	CASiMiR (preference curves)
Wilding *et al.* 2014 [65]	habitat	-	PHABSIM, GHM	NN	PHABSIM and generalized habitat model
Buddendorf *et al.* 2017 [34]	habitat quality	-	River2d	2D	generalized additive models

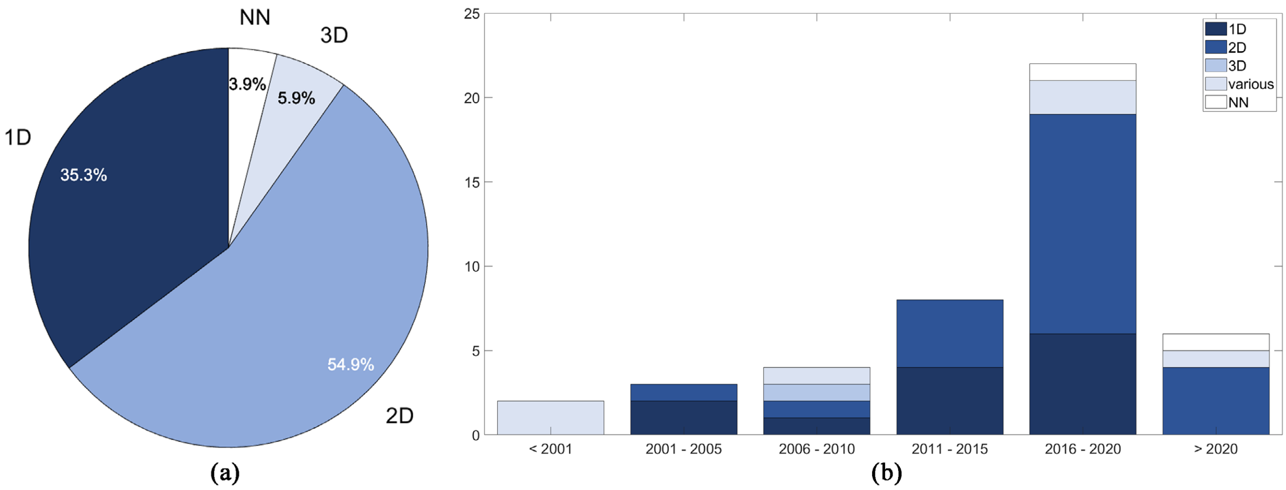
Continued

Hauer *et al.* 2017 [98]	habitat	hydraulic retention	HYDRO_AS-2D	2D	HSC[a]
Le Coarer *et al.* 2017 [75]	habitat	-	TELEMAC-2D	2D	preference data
Pisaturo *et al.* 2017 [76]	habitat	-	NN	2D, 3D	CASiMiR (preference curves)
Pragana *et al.* 2017 [73]	habitat	revenue losses	River2D	2D	CASiMiR (fuzzy rules)
Stamou *et al.* 2018 [61]	habitat	-	TELEMAC-2D	2D	HSC[a]
Gibbins & Acornley 2000 [99]	habitat, drift, stranding	-	PHABSIM	NN	PHABSIM, HSC[a], thresholds
Shen & Diplas 2010 [77]	drift, erosion/redd scouring	-	CFX	3D	thresholds
Sauterleute *et al.* 2016 [86]	stranding, population development	-	HECRAS	1D	IB-Salmon (Individual-based model)
Adeva-Bustos *et al.* 2017 [15]	wetted area, smolt production	energy cost, habitat modification cost, benefit,	HECRAS	1D	IB-Salmon (Individual-based model)
Holzapfel *et al.* 2017 [100]	weighted epibenthic feeding area	-	HYDRO_AS-2D	2D	HSC[a]
Yao *et al.* 2021 [69]	habitat, population development	-	NN	2D	preference curves and population modeling
Bakken *et al.* 2023 [87]	ecological impact	population vulnerability, hydropeaking effect	HEC-RAS	2D	impact classes
Other Effects					
Bratrich *et al.* 2004 [101]	fish and macroinvertebrate habitat qualities	-	AQUASIM	1D	CASiMiR
Vanzo *et al.* 2016 [58]	Hydromorphological index of diversity (HMID), macroinvertebrate drift, stranding risk	-	GIAMT2D	2D	thresholds
Choi *et al.* 2017 [29]	habitat, fish stranding, macroinvertebrate drift	-	River2d	2D	HSC[a] and thresholds
Bürgler *et al.* 2023 [102]	habitat suitability, macroinvertebrate drift, stranding risk	-	BASEMENT	1D, 2D	Preference curves
Waddle & Holmquist 2013 [66]	macroinvertebrate habitat	-	River2D	2D	empirical indices
Wiseman *et al.* 2016 [41]	benthic biomass production	-	HEC-RAS, River2d	1D, 2D	RivBio
Yarnell *et al.* 2010 [68]	amphibian egg and tadpole habitat, scouring	-	River2D	2D	HSC[a], ecological functions

Continued

Shafroth *et al.* 2010 [62]	establishment and mortality of tree seedlings	-	HECRAS, MDSWMS	1D, 2D	HEC-EFM
Diehl *et al.* 2018 [63]	vegetation guild presence, topographic change	-	FaSTMECH	2D	flow response curves
Scott & Merritt 2020 [44]	distribution of riparian vegetation guilds	-	HEC-RAS	1D	guild distribution models
Carolli *et al.* 2017 [49]	suitability of ecosystem services	-	HEC-RAS	1D	1D CASiMiR, preference curves
She *et al.* 2012 [71]	ice consolidation	-	River1D	1D	River1D (ice jam process model)
Sukhbaatar *et al.* 2020 [70]	ice formation	-	HEC-RAS	1D	HEC-RAS (ice-occurrence)
Pisaturo *et al.* 2019 [72]	human safety	-	HECRAS	2D	empirical functions and algorithm

a. HSC = Habitat Suitability Curves.



(a) (b)

Figure 4. Studies applying 1D-, 2D- and 3D-hydraulic models in total (a) and over time (b).

niche habitats in the 3D-approach (see **Figure 5**). Already in 1997, Alfredsen *et al.* [64] named the higher spatial resolution as a strong advantage of the application of multidimensional hydraulic models in habitat modeling. On the other hand, Casas-Mulet *et al.* [78] emphasize the low data amount and low computational effort as advantages of 1D-simulations. The large scale of river simulations in combination with the high computational effort and necessary expertise for 3D-simulations make them often unsuitable. The reviewed studies reveal that 3D-simulations are currently not state-of-the-art in ecohydraulic studies investigating whole river stretches and that depth-averaged simulations are commonly accepted as suitable and sufficient. 3D-simulations are more commonly used for ecohydraulic investigations of smaller sections or technical structures like

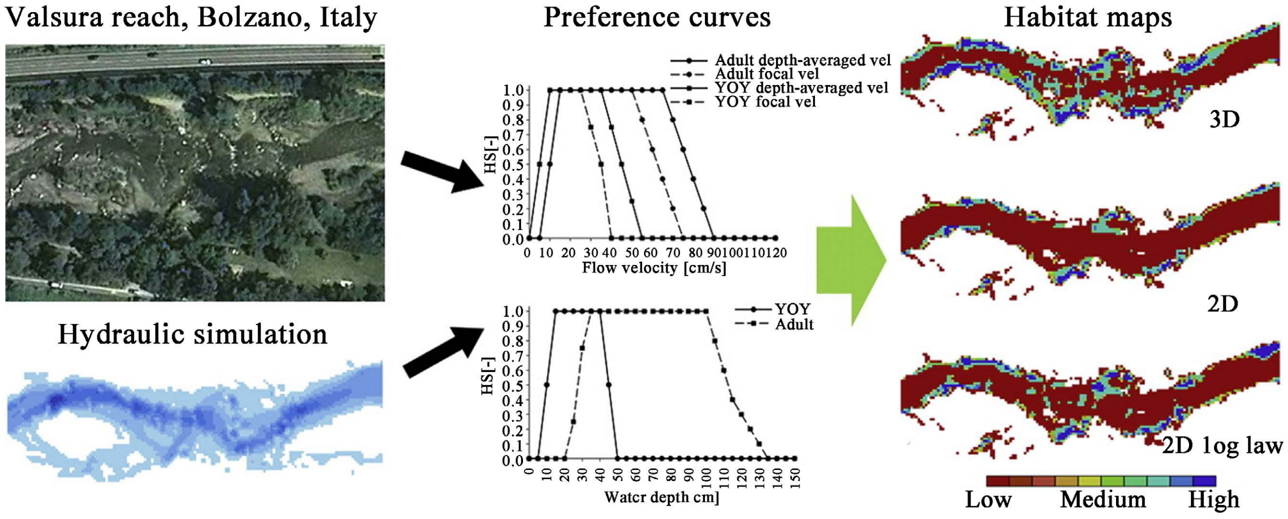


Figure 5. Approach for ecohydraulic simulation of fish habitat [76].

fishways [79] [80] [81].

For the 1D-simulations HEC-RAS was the most recurring Software. HEC-RAS, formerly known as Hec-2, is a hydraulic modeling program developed by the United States Army Corps of Engineers [82]. Since 2016 the program does also include a hydraulic 2D-model [82], which was used in several studies. Among the 2D-depth-averaged models, River2D was applied the most. The model was developed by the University of Alberta and also includes a fish habitat module [83]. Other models applied can be seen in **Table 1**.

The coupling of the ecologic evaluation to the hydraulic model was done in different ways depending on the modeled effect. When it comes to habitat modeling Alfredsen [84] and Melcher *et al.* [85] distinguish between empirically based habitat suitability models and process-based population models or bioenergetic models. In habitat suitability models usually preference or suitability curves are applied [84] [85]. They represent the relation between abiotic (hydraulic) parameters and the biotic system stating either a relative suitability or an absolute suitability or avoidance. In the second case, a threshold value for the hydraulic component can be derived marking the border between suitable and unsuitable conditions. The models and functions can be univariate or multivariate. Yao *et al.* [69] for example assess the habitat quality for fish in a multivariate approach based on preference curves relating habitat suitability to depth, velocity, and substrate. This coupling of hydraulic data and ecological preference data can also be done by habitat models like CASiMiR, which is used in seven of the reviewed studies (**Table 1**). Pisaturo *et al.* [76] for example used CASiMiR with habitat suitability curves (HSC) for depths and velocities to calculate the habitat suitability for brown trout (**Figure 5**). An alternative habitat model is PHABSIM, which also includes a hydraulic model. The results of such habitat simulations are often habitat suitability indices (HSI) or weighted usable areas (WUA). For certain discharges, the suitability can be spatially represented on habitat suitability maps. These can be used to compare the habitat suitability during different discharges. In **Figure 5** these maps are even used to compare different modeling approaches. The habitat availability can also be represented as relations between the suitable area and the discharge or the duration (**Figure 6**).

The suitability or preference methods can also be used for other investigations than the shear habitat suitability. Casas-Mulet *et al.* [78] for example evaluate the potential stranding area of fish based only on the drying area between peak and baseflow. Juarez *et al.* [30] define the drying area as the maximum potential stranding area and include a threshold for the water level ramping rate. Transgression of the threshold in a drying area indicates a high risk of fish stranding. Pisaturo *et al.* [72] even use hydraulic preference curves for social impact assessment. For the evaluation of human safety in flows, they use curves for the stability of children and adults in flowing water and an algorithm to determine escape routes.

Only a few studies apply other ecological models. Sauterleute *et al.* [86], Wiseman *et al.* [41], and Adeva Bustos *et al.* [15] used process-based population models based on knowledge about the biological processes of population dynamics for the investigated species. Bakken *et al.* [87] suggest a new method where they classify the effect of different hydraulic factors in hydropeaking events from "small" to "very large". In another classification, the vulnerability of the fish population is characterized and the combination of both classifications for a specific river leads to the total impact of the hydropeaking event.

3.3. Ways to Integrate Social and Economic Effects

While the first part of the review revealed significant social and economic effects of flow alteration, the second part shows a lack of studies integrating social and economic aspects to hydraulic models. Nevertheless, to assess the impact of hydropower and to manage future hydropower projects as well as the decision on mitigation measures holistic assessment tools are needed. To assess and compare

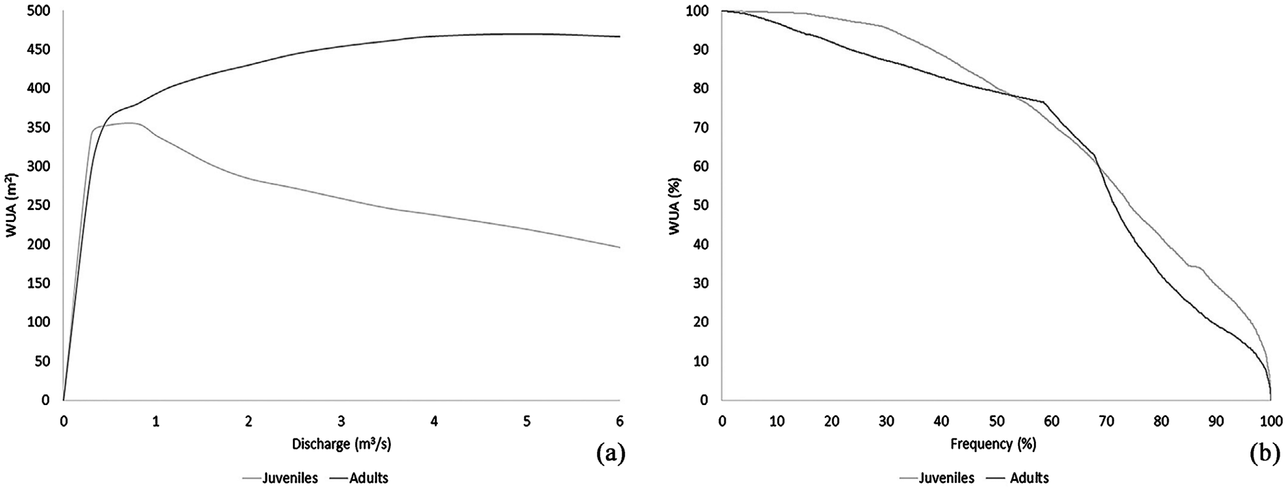


Figure 6. Weighted usable area for brown trout related to (a) discharge and (b) as habitat duration curve [73].

measures and their sustainability before implementation hydraulic modeling could be a suitable and cost-efficient tool. Sustainability is usually associated with the three dimensions of ecology, economy, and society. To create powerful decision tools, ways to combine the social and economic effects with hydraulic and ecological effects are therefore needed.

For this purpose, qualitative or quantitative assessment methods could be used. Bakken *et al.* [87] developed a qualitative impact classification method in which the hydropeaking effect and the fish population vulnerability are classified. This approach might be extended by more general ecosystem vulnerability or even parameters to classify the social vulnerability for a river reach. This would enable the comparison of different scenarios or mitigation measures in terms of their impact on the environment and society. Nevertheless, a quantitative assessment method would additionally enable the direct comparison of benefits and adverse impacts of a project and should therefore be preferred.

The connections and interactions between ecological, social, and economic effects were already touched on in the first part of the review. In our understanding, social effects can either be directly linked to hydraulic changes or environmental effects. Economic effects are assumed to result either from social and ecological effects or from energy production or mitigation measures. Furthermore, economic quantification can be used as a method to make the different aspects comparable. Trade-offs between energy production and environmental- and social aspects are expected to be easier when both are quantified in the same unit. Our conceptual approach for such an integrated model to holistically investigate the flow effects is presented in **Figure 7**.

For the social effects that directly result from hydraulic changes, the ecohydraulic preference methods could be transferred to some socio-hydraulic models. Pisaturo *et al.* [72] made a first attempt when using multivariate (depth and velocity) functions for human stability in the flow and combined it with a classification of

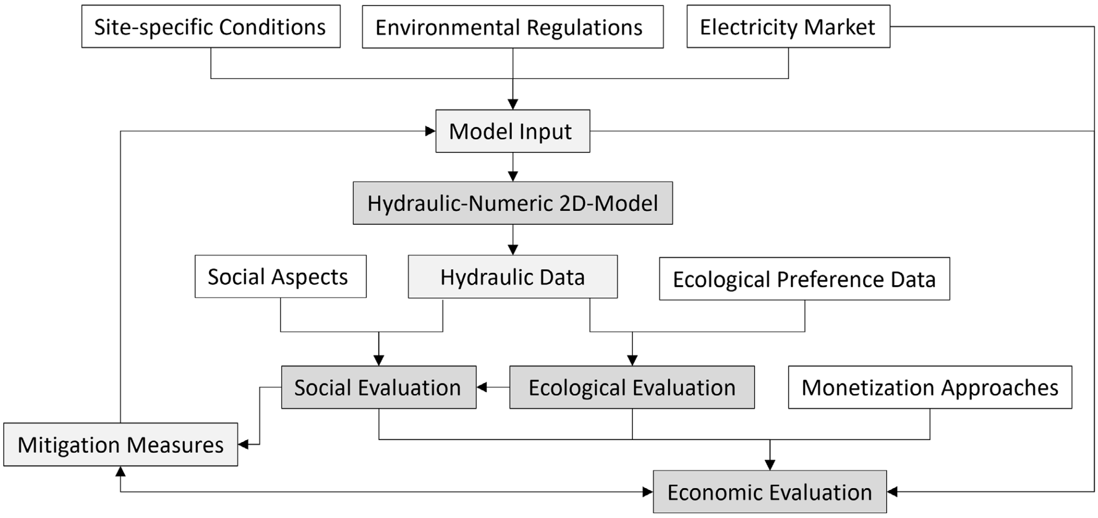


Figure 7. Approach for an integrated model of effects of flow alteration.

escape routes to assess human safety in hydropeaking events. Carolli *et al.* [49] used a suitability curve relating the rafting suitability to water depths to assess one recreational use of the river. Similar applications of suitability curves for other recreational or touristic uses seem realistic. Regarding the livelihood of people suitability functions for floodplain agriculture or floodplain herding based on inundation time or other hydraulic parameters might be possible. For the representation of such social effects suitability maps or graphs of the cumulated or weighted suitable area could be used, similar to the ecohydraulic methods (**Figure 5**, **Figure 6**).

The economic quantification appears to be a larger challenge. While Casas-Mulet *et al.* [33], Juarez *et al.* [30], and Person *et al.* [52] all economically evaluated the changes on the energy production side in the case of operational measures, Carolli *et al.* [49] state problems to monetarize the ecological effects. Ecosystem values are commonly distinguished into use and non-use values [55] [88]. Use values can often be directly connected to market values. Adeva-Bustos *et al.* [15] for example valued the positive effect of mitigation methods on salmon smolt production with a value of 20 EUR per smolt. Non-market values can either be monetarized with revealed or with stated preference methods detecting the willingness-to-pay for these values [55]. Especially the intrinsic non-use values are difficult to unveil.

The valuation of social effects follows similar patterns. Some social effects could be directly assessed in economic terms. Flood depth-damage functions for example can be used to quantify flood damages based on inundation depths [89]. More intrinsic values like cultural heritage or change of biophysical home environment demand more complex methods like stated preference methods. The lack of socio-hydraulic or socio-ecologic suitability data and the named difficulties in monetizing ecological effects create a necessity for further research.

4. Conclusions

The review reveals that the production of hydroelectricity and related flow alterations has numerous environmental, social, and economic effects. The coupling of such effects to hydraulic modeling has so far mainly concentrated on the field of ecohydraulics, with a special focus on effects on fish. The ecohydraulic simulations are usually done with ecological suitability or preference models. The applied hydraulic models are dominated by 2D-models, which seem to be accepted as sufficient. The hydraulic modeling software used in the studies is numerous.

The reviewed ecohydraulic studies concentrate on small numbers of species and aspects, although the complexity of the ecosystem and interactions of effects impede more holistic studies. Few of the reviewed studies include social and economic aspects in their hydraulic investigations. This integration and the creation of more holistic approaches remain a subject of future research.

In our opinion, a better comparability of different effects is necessary for informed decisions on sustainable hydropower production. A predictive tool integrating the ecological, social, and economic effects into hydraulic modeling could support such decision-making. We presented a concept integrating social and ecological impact assessment and using economic quantification for comparability. Some authors have already shown how suitability methods can be transferred from ecohydraulics to socio-hydraulic applications. Nevertheless, finding reliable relations between social effects and hydraulic or ecological parameters to advance social integration remains a subject of further research. An additional challenge remains in the reasonable and reproducible monetary valuation of ecosystem services.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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