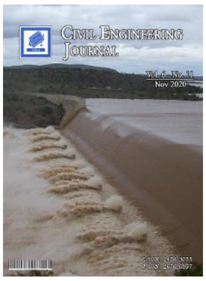
Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 6, No. 11, November, 2020



An Innovative Holistic Approach to an E-flow Assessment Model

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Received 04 August 2020; Accepted 19 October 2020

Abstract

River water resources provide a wide range of necessary ecosystem services, including regulating, provisioning, supporting and cultural services. Ecosystem services are linked to an appropriate level of functionality of river water resource processes, which can be connected with river basin environmental objectives. Environmental objectives can be achieved only if appropriate flow and sediment regimes and related river morphology quality are guaranteed. The obligation to define environmental flow (E-flow) in the European Union Water Framework Directive European (WFD) is not explicit, and the implementation of the WFD is more focused on water quality. Considering the specific climatic, hydrographic and hydrological conditions and the definition of E-flow, each EU country has developed procedures for their investigation and determination. In the Republic of Croatia, no methodology has been elaborated, nor is there any legal regulation to define E-flow downstream of a dam or water intake site. This paper presents the significant pressures that have affected the transboundary rural Sutla River basin between Croatia and Slovenia. These pressures can cause changes in the hydrological regime and biological elements of water quality. The holistic approach defines the E-flow for a profile on the Sutla River by linking hydrological, morphological, and ecological characteristics based on the exploration of the Sutla River and its biological communities. The full implementation of a holistic approach and the transition to Level III of the E-flow definition requires the enhancement of exploratory hydrological and biological monitoring that enables the use of habitat modelling.

Keywords: Environmental Objectives WFD; Good Water Status; E-flow; Measures; Holistic Approach; Sutla River Basin.

1. Introduction

Flow alteration is among the most serious threats to freshwater ecosystems. Natural seasonal increasing and seasonal decreasing water levels shape aquatic and riparian habitats, provide migration and spawning conditions, and enable rivers to function properly [1, 2]. Altering natural flow by damming, diverting or channelling water has serious impacts on biodiversity and ecosystem services [3]. The critical question to answer is how much change in flow is too much and when "change" becomes "degradation" or "unacceptable adverse impact". River water resources provide a wide range of Ecosystem Services (ESs) that can be classified into four main categories: (i) Food services, i.e., products derived from ecosystems; (ii) Regulation services, i.e., processes and functions; (iii) Habitat services; and (iv) Cultural services [4]. ESs are linked to the appropriate level of functionality of river water resource processes, which can be explained by the environmental objectives of a river basin [5]. Environmental objectives can be achieved only if

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http://dx.doi.org/10.28991/cej-2020-03091611

adequate flow and sediment regimes and the associated river morphology quality are guaranteed. The obligation to define an environmental flow in the WFD [6] is not explicit, and the implementation of the WFD is more focused on water quality.

Member states should facilitate the distribution of water between the use of water for human and aquatic ecosystems and the achievement of good water status by ensuring a hydrologic regime using a holistic approach that defines E-flow and the E-flow guidelines for the implementation of the WFD. Based on the WFD, the amount of water and the flow regime are considered to be supporting hydro-morphological elements for the biological quality elements that are necessary to achieve good ecological status, and the preservation of the hydrological regime is consistent with the achievement of the environmental objectives of the WFD in natural surface waters. Depending on the chosen criteria, various authors have developed a range of methods for determining E-flow [7]. The most common criteria include water use/abstraction, river basin management objectives, expert involvement, available time, required financial resources and legislation; thus, there is no simple or unique method for determining E-flow [5].

The determination of E-flow is a complex and demanding task that contributes to the effective management of river basin waters to maximize social and economic benefits without endangering the environment [5]. This necessitates an integrated, comprehensive, and holistic approach to water management and defines E-flow as discharge of a particular magnitude, frequency and timing that is necessary to ensure that a river system remains environmentally, economically and socially healthy [8]. This definition notes the compromise between the use of water resources and the integrity of the river ecosystem. Additional complexity in water management results from climate change impacts (with uncertainties) on land use, land cover, water resources, water use and various environmental aspects [9, 10]. Considering the specific climatic, hydrographic and hydrological conditions and the definition of E-flow, each EU country develops procedures for its own exploration and determination of E-flow [5]. Additionally, defining E-flow is one of the most effective additional measures of the WFD to conserve the water regime and improve the conditions of aquatic habitats, enabling member states to achieve the environmental objectives of each river basin [5, 9, 10].

Since there is no official methodology used to determine the E-flow approach in the Republic of Croatia, an innovative holistic model is developed and proposed in this paper. Hydrological approaches are the most commonly applied methods, and not all Member States of the EU have national legislation on E-flows [11]. Our innovative holistic approach to E-flow assessment can contribute to the field of E-flow definition. The innovation of the holistic approach to E-flow assessment includes the analysis of all data and available research, despite the lack of appropriate monitoring, to gain new knowledge about the river basin and its water bodies and to make an assessment of E-flow.

In chapter 2, the methodology of E-flow determination in EU countries and the developed holistic approach to the E-flow assessment model for the Sutla River basin case study are presented. The Sutla River is a border river between the Republic of Croatia and the Republic of Slovenia. A dam was built on the Sutla River in 1980 as a multipurpose hydrotechnical facility. This was when the biological minimum flow was defined. To achieve good water status and the environmental objectives of the river basin, rather than using the biological minimum flow downstream of the dam, it is necessary to define the E-flow. In chapter 3, the results of the Sutla River basin case study using the developed holistic E-flow assessment model and comparison with existing well-known approaches and methodologies are presented. The presented E-flow assessment model and the results of the research suggest the necessity of a holistic approach to E-flow assessment as an additional measure of the WFD.

2. Materials and Methods

Stream flow mostly results from precipitation and river basin runoff, and it depends on climate and geology [12]. In terms of flow regimes, these patterns are important for E-flow assessment because native aquatic and riparian organisms have evolved to use the water regime. The precipitation and runoff processes that prevail in a given region produce characteristic hydrographs. Dams and water abstraction obviously affect hydrography, but climate change and changes in land cover or groundwater pumping can have similar effects.

Riverine systems provide a wide range of ESs, including supporting services, provisioning services, regulating services, and cultural services, for human society and human well-being. Such services are linked to the functionality of ecosystem processes in terms of achieving the environmental objectives of river basins. The WFD states that environmental objectives in watercourses can be achieved only if the appropriate flow and sediment regimes and related channel morphology quality are guaranteed. The establishment and maintenance of such flow regimes, namely, E-flows, are an essential element in preserving riverine ecosystems, and ESs and should be included as a measure of integrated water management according to the WFD and defined in national legislation [11]. E-flow refers to the typical seasonal and interannual variability of the natural flow regime rather than only the minimum amount of water that should be maintained in a river. In addition to the hydrological assessment of natural flow variability, it is necessary to link the definition of E-flow to the related hydro-morphological processes and local ecological objectives of a river [13]. Most E-flows are defined for rivers below dams that trap sediment and change the downstream flow regime. Dams disrupt the flow of sediment and the capacity of the stream to convey sediment, with broadly predictable consequences for the morphology and composition of the river below the dam and on the biota that uses the river and adjacent areas. E-flow management must consider problems caused by dams and include ways to manage them, including restoring the flow and sediment regimes downstream of dams. Strategic dam planning at the river basin level is an often overlooked opportunity that can minimize the impact of a dam on the sediment supply. Predicting climate change at any particular location is even more difficult than predicting global change. Thus, climate uncertainty adds substantially to the uncertainties already faced in the determination of E-flows [11].

2.1. Methodology of E-flow Assessment in EU Countries

The term “environmental flows” was originally referenced in the Brisbane Declaration of 2007 as follows: “E-flows describe the quantity, quality and timing of water flows required to sustain freshwater ecosystems and the human livelihoods and well-being that depend on these ecosystems”. The term “E-flow” has other names worldwide because river environmental management brings scientists from different disciplines together. The terms used across different regions of the world include “instream flow needs”, “ecological reserve and demand for water”, “environmental water allocation”, and “minimum flow”. The E-flow concept has evolved over time, and its meaning has shifted from the traditional view of the biological minimum water amount to a more holistic understanding of a river system and its dynamics [11]. In the implementation of the WFD, the term used is “ecological flow”, meaning the hydrological regime that allows the achievement of good ecological status in a water body and the environmental objectives of the WFD. The establishment and maintenance of such flow regimes, namely, E-flows, is an essential element in preserving riverine ecosystems, and the ES and should be included as a constraint in water resource assessment and in national legislative frameworks [11].

Based on an assessment of progress in the WFD implementation in its first cycle, the blueprint to safeguard Europe’s water resources stressed the urgent need to better address the over-abstraction of water, which is the second most common pressure on EU water resource ecological status, and to recognize that water quality and quantity are strongly related within the concept of obtaining a “good status”. This approach requires an ecological flow, i.e., the "amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon". To achieve this, the blueprint proposed the development of a guidance document in the framework of the WFD common implementation strategy [5] that would provide an EU definition of ecological flows and a common understanding of how these flows should be calculated so that the approach could be applied in the next cycle of river basin management plans (RBMPs) to be adopted by the end of 2015. As reported in the E-flow WFD common implementation strategy [5], the E-flow concept should not be confused with similar terminologies, such as “minimum flow”, which limits the E-flow concept to the minimum amount of water required during low-flow periods or dry seasons. The control of surface and groundwater abstractions is part of the basic measures of the WFD. In the case of dams and impacting hydro-morphological forms, it is necessary to protect and restore ecological flows through the authorization process and regular review of permits. Supplementary measures to support the achievement of the WFD environmental objectives, such as the combination of hydrological measures (e.g., ensuring the maintenance of ecological flows by all abstractions and regulations) and morphological measures (e.g., improving aquatic habitats to make them less vulnerable to flow impairments), may be the most cost-effective approach.

Related to the E-flow definition in the new guidance [11], the new approach is presented and expands the environmental objectives and definitions to include geomorphological river changes. Therefore, this guidance presents a methodology (based on knowledge and literature on river system processes) that considers hydrological and morphological aspects in defining E-flows for integrated river basin management. E-flow is important in the implementation of activities related to managing river flows and maintaining ecosystem services and human well-being. Public participation in E-flows, as related to the WFD requirements, should be developed in all phases of the water management planning process according to the WFD, and it should be ensured that participation continues in subsequent planning cycles.

E-flow assessment downstream of dams, in the context of the predicted increase in water demand and hydropower development, is essential for guaranteeing freshwater ESs and well-being. Decision-makers must assess the needs of water provisions for the environment and take necessary actions to preserve, sustainably manage, and, where necessary, restore freshwater ecosystems based on available knowledge and datasets [14].

Key decisions involve the allocation of sufficient amounts of water to ensure the sustainable functioning of human activities through E-flows [1]. It is important to note that E-flows seek to maximize the socioeconomic opportunities provided by healthy and sustainable ecosystems. The adequate management of ESs also supports ecosystem resilience and the resilience of those who depend upon these services to cope with stresses such as drought, extreme weather events, and climate change.

A variety of approaches and tools are now available for E-flow assessment, and their implementation is included in integrated water resource management for the valuation of ESs. It is essential to assess the quality, quantity, frequency, duration, timing, and rate of change of river flow to maintain the freshwater ecosystem functions, processes, and services upon which livelihoods and economic opportunities depend [2]. Together with the flow regime, the sediment regime and river morphology are important determinants that ensure the desired services of freshwater ecosystems and their economic valuation [13, 15, 16]. The concept of E-flows is now a key element in many international policies, such as the Convention on Biological Diversity signed by 194 parties, the Ramsar Convention on Wetlands signed by 168 parties, and the European Water Framework Directive [17]. Tharme [18] identified 207 methods for determining E-flows and classified them into four main groups: hydrologic, hydraulic rating, habitat modelling, and holistic/ecosystem methods. Acreman et al. [17] identified two basic E-flow approaches based on either (1) constraining alteration from a natural flow baseline to maintain biodiversity and ecological integrity or (2) designing flow regimes to achieve specific ecological and ES outcomes. It is crucial to account for a certain flow and sediment regime for the maintenance of freshwater ecosystem functions and the ES they provide to people within integrated river basin management. On a global scale, there is significant momentum to incorporate E-flows into policymaking and RBMPs. E-flows are already addressed in international agreements such as the United Nations Watercourses Convention, which was first implemented in 2014 [19], The Economics of Ecosystems and Biodiversity (TEEB) from 2010 [20] and regional frameworks such as the WFD [5, 6]. These methods have been categorized in different ways (Table 1).

Table 1. Three schemes for classifying E-flow assessment methods (adapted from [12])

Organization	Categorization of methods	Sub-category	Examples
IUCN (Dyson et al., 2003)	Methods	Look-up tables	Hydrological (e.g. Q95 Index)
			Ecological (e.g. Tennant Method)
		Desk-top Analyses	Hydrological (e.g. Richter Method)
			Hydraulic (e.g. Wetted Perimeter Method)
			Ecological
		Functional Analyses	BBM, Expert Panel Assessment
			Method, Benchmarking Methodology
		Habitat Modelling	PHABSIM
	Approaches		Expert Team Approach
			Stakeholder Approach (expert and non-expert)
	Frameworks		IFIM, DRIFT
World Bank (King and Brown, 2003)	Prescriptive approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert panels	
		Holistic Approaches	BBM
	Interactive approaches		IFIM, DRIFT
IWMI (Tharme, 2003)	Hydrological index Methods		Tennant method
	Hydraulic rating Methods		Wetted Perimeter Method
	Habitat Simulation Methodologies		IFIM
	Holistic Methodologies		BBM, DRIFT, Expert Panels, Benchmarking Methodology

BBM= building block methodology; PHABSIM= Physical Habitat Simulation model; IFIM= Instream Flow Incremental Methodology; DRIFT= Downstream Response to Imposed Flow Transformation

The most commonly used holistic methodologies are the "building block methodology" (BBM) [19] and the "downstream response to imposed flow transformation" [21]. Arthington [22] and Tharme [18] provided thorough reviews of various holistic methodologies. In addition, the ecological limits of the hydrological alteration (ELOHA) framework has been developed to meet the needs of managing E-flows at regional, provincial, or basin scales [23].

ELOHA is a "top-down" method that defines E-flow in terms of acceptable levels of change from the natural flow regime. The method involves the quantification of stress-response ecological relationships. Depending on the depth of evaluation, data collection, and extent of expert consultation, applications of the holistic framework can be time-consuming and expensive. Moreover, holistic methodologies still lack consideration of river morphological processes as well as the integration of E-flow assessment with sediment management and dynamics [11].

Recently, Acreman & Arthington [24] identified four basic challenges to defining E-flows: (1) the political decision to recognize the need to maintain sufficient water in rivers and wetland systems; (2) defining the flow requirements of an ecosystem; (3) the practical issues and costs of implementation to achieve the required environmental flow regime; and (4) the design and maintenance of robust monitoring systems to assess the ecological and other outcomes of E-flows in an adaptive management framework. The recent definition of E-flow described above suggests the need to explicitly link river flows with ES outcomes and human well-being such that the flow requirement of each biophysical component of the wetland ecosystem (e.g., fish, invertebrates, plants) is analysed individually and then combined to produce an E-flow regime [17], and water stress areas under climate change are linked to E-flow provision for the WFD [4].

2.2. Holistic Approach to an E-flow Assessment Model

The holistic approach presented here for E-flow assessment consists of the described methods. Procedural steps have been conceived for use in water resource management and can be applied to any typology of rivers. In accordance with the objective of this approach, the procedure used to define E-flows encompasses four main parts: (1) morphological characterization of the river system, (2) hydrological and sediment regime analysis, (3) ecological response to altered flow regime and selection of target communities, and (4) comparison and selection of possible E-flow release scenarios.

Figure 1 and the following sections describe each methodological step of the holistic E-flow assessment model. The methodological approach integrates tools developed from different disciplines, such as hydrology, fluvial geomorphology, and biology, and analyses existing holistic E-flow assessment methodologies in Europe and around the world. However, based on available data from existing monitoring programmes and targeted research, it has been found that these approaches cannot be applied in this case. Therefore, the methodologies used in the surrounding countries were analysed, namely, hydrological-hydraulic methods and the Slovenian method, which has hydrological-hydraulic and biological elements. Based on the research conducted, the analysis and the available data and information, a holistic methodology (Figure 1) is proposed for the determination of the E-flow with the following elements:

1. Analysis of available data – monitoring programme, considering climatological, hydrological, hydraulic, water status, protected areas of the implemented measure in the river basin.

2. Analysis of pressures and impacts on river basins, including actions and regulations within Drivers – Pressures - Impacts – States –Responses (DPSIR)

3. Whether the environmental goals of the river basin have been achieved represents a key element in providing ESs and enhancing human well-being. ESs (supply, regulation support, and cultural services) cannot be realized without solving the E-flow problem. Additionally, the objectives for the protection of river basin waters under NATURA 2000 are analysed.

4. If YES – Goals are achieved, advance to the first step of analysis of available data based on the monitoring programme.

   If NO - Goals are not achieved, check whether the water bodies have obtained a good water status.

5. Good water status of water bodies. For all river basin bodies, the following elements are analysed:
   - Analysis of water and sediment quality,
   - Analysis of ecological data,
   - Analysis of hydro-morphological characteristics of characteristic parts of water courses,
   - Analysis of historical maps of river flow and dam construction to form reservoirs,
   - Analysis of the NATURA 2000 sites and definition of an indicator fish species.
   - Analysis of longitudinal river flow and characteristic cross-sections,
   - Hydrological analysis of historical data on flows and water levels with characteristic profiles and the defined biological minimum downstream of the dam.

6. The gap analysis identifies good water status for each water body, which consists of identifying water bodies that are at risk of not achieving good water status and environmental goals.

   If YES – there is a need to know the E-flow,

   If NO, return to the first step, Analysis of available data, based on the monitoring programme.

7. Assessment of the E-flow. This step begins with an analysis of the whole set of elements, the first of which is an analysis of the approach for defining E-flow.
8. Methodological analysis in surrounding countries and a comparison of values.
9. LEVEL I – Preliminary assessment by hydrological methods.
10. LEVEL II – Collecting field data and applying holistic methods.
11. Is there a possibility of habitat modelling?

    If YES – go to LEVEL III – holistic methods with habitat modelling.

    If NO – use the holistic approach for defining the E-flow for two characteristic profiles/locations for different hydrological periods (dry and rainy periods).
12. Defining the E-flow as the measure.
13. Monitoring of the E-flow and return to the first point, Analysis of the available data.

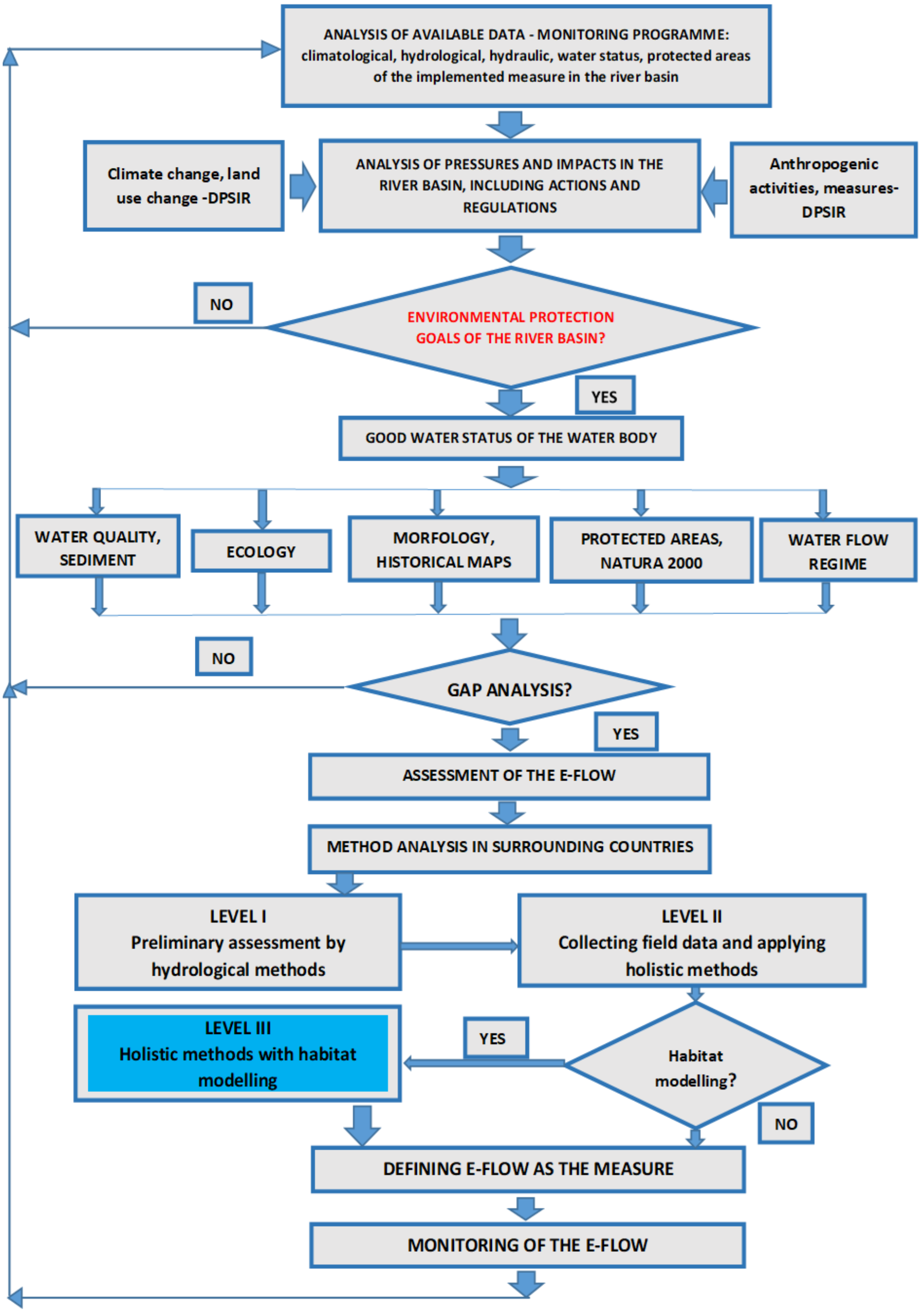

Figure 1. Flow chart of the holistic approach to the E-flow assessment model

Prescribing E-flow needs is inherently an interdisciplinary process. For any water body, nature protection, or other protection measures, it is recommended to use a hierarchical framework to identify the holistic E-flow assessment methodology that will most rapidly lead to the implementation and adaptive management of flow provisions. This three-level framework method, shown in Table 2, is designed so that E-flow practitioners can identify the “best” method — or more likely, methods — based on the number of resources and available data, the most important issues and uncertainties. The hydrological regime necessary for aquatic ecosystems to achieve environmental goals should determine the E-flow assessment. Together, the flow regime, sediment regime, and river morphology are important determinants that ensure ESs [11].

Table 2. Required data and publicly available data [7]

Assessment Level	Characteristics	Methods	Requirements & Results
LEVEL I PRELIMINARY Hydrological methods - Look-up tables - Reconnaissance surveys	Regional planning Setting preliminary reference flows using historical records Initial screening and analysing information for next level	Tennant method RVA method IHARIS method	Require large sets of long-term (20 year) historical hydrological data Enable comparison between historically derived and biologically derived reference flows
LEVEL II INTERMEDIATE Holistic methods (expert judgment based) requiring multidisciplinary input	Ecological, considering the flow requirements of multiple ecosystem components Setting biologically-derived reference flows, targeting to flow regime	ELOHA BBM DRIFT	Require monthly sampling from an inter-disciplinary team of experts, A stand-alone approach to set biologically-derived reference flows from scratch
LEVEL III COMPREHENSIVE Species-oriented, data-driven, habitat simulation	Reach-scale planning Species-specific reference flows Can be included in a holistic framework if applied for multiple ecosystem components	BBM/DRIFT in combination with habitat modelling using PHABSIM	Very cost- and time-consuming, requiring high level of expertise The most comprehensive approach

As illustrated in Table 3, E-flows sustain provisioning, regulating, supporting and cultural ESs. While some of these services are difficult, if not impossible to quantify economically, their economic, environmental and societal benefits are often self-evident [25].

Table 3. Examples of the provisioning, regulation, supporting, and cultural ecosystem services of E-flow dependent ecosystems [25]

	Provisioning	
Ecosystems, which depend on E-flows, provide basic materials of direct value and use to people.	• • • • Water • • • Food • • Fiber and fuel • Biochemical Genetic	• • • • Supply of clean water • • • • Recharge of aquifers • • • Fish, game, fruits, fodder etc. • • Firewood, peat, construction • Pharmaceutical materials Resistance to pathogens
	Regulating	
E-flows regulate adverse conditions and environmental risks.	• • Water • Climate Biodiversity	• • Flood control • • Flushing of waste water and pollutants • Sink for greenhouse gasses • Regulation of local climate Prevention of invasive species
	Cultural	
E-flows sustain diverse and unique environments of cultural importance.	• • Recreation, esthetics and inspiration • Ceremonies and rituals Education	• • Outdoor activities, tourism • Natural beauty • Spiritual values Opportunities for learning
	Supporting	
E-flows support bio- and geochemical cycles and processes.	• • • Nutrient cycling • • Sediment cycling • Soil formation Biodiversity	• • • Transportation, storage, recycling of nutrients • • Transportation, storage, weathering of sediment • Retention and accumulation of organic matter Habitat for species

The framework presented in Tables 2 and 3 emphasizes the strategic deployment of resources to an integrated programme of E-flow assessment, development, and implementation in integrated water management [7].

2.3. Sutla River Basin: Case Study

The Sutla River is a border river between the Republics of Croatia and Slovenia (Figure 2). It originates on the southern slopes of Macelj and flows as a left tributary into the Sava River near the town of Ključ, downstream of Brežice. The Sutla River basin is irregular in size, with an area of 584 km^2, of which 451 km^2 (77%) is located in the Republic of Slovenia and 133 km^2 (23%) is located in the Republic of Croatia. The basin is a narrow belt with an average width of 1-2 km (maximum 5 km). The length of the Sutla River is approximately 90 km. On the Slovenian side, larger tributaries include the Mestinjščica and Bistra tributaries, while on the Croatian side, the tributaries are smaller and mostly torrent. The average annual rainfall in the Sutla River basin is 1200 mm, and evapotranspiration is approximately 650 mm. The Sutla River has a major initial decline over 7 km, with a change from 620 m a.s.l. to 250 m a.s.l. Thereafter, the drop decreases to 112 m a.s.l. at the mouth of the Sava River. At the Zelenjak water metre (downstream of the dam), the average flow is 7.3 m³/s (minimum 0.9 m³/s and maximum 129 m³/s). The Sutla River flow regime is of the Pannonian type with two identical peaks, one in early spring and the other in late fall. Low flows occur in summer and winter, and the lowest flows occur in August [26]. The E-flow determination downstream of the Vonarje dam on the boundary of the Sutla River in 1980 (Figures 2 and 3) is presented as an example of E-flow determination. Vonarje Reservoir/Sutla Lake was constructed as a multi-purpose hydro-technical facility to provide public water supply, irrigation, flood defence, and tourism, and the site was eutrophicated and discharged in 1989. Sutlansko Lake/Vonarje Reservoir was built using natural retention, with a volume of 12.4 million m³, a length of approximately 6 km, and a surface of 195 ha (Figure 3, Figure 4). It now functions as a retention system for flood defence. At the bottom of the retention area, a wetland ecosystem has developed, the dam has been restored, and there are plans to re-establish a reservoir (Figure 5).

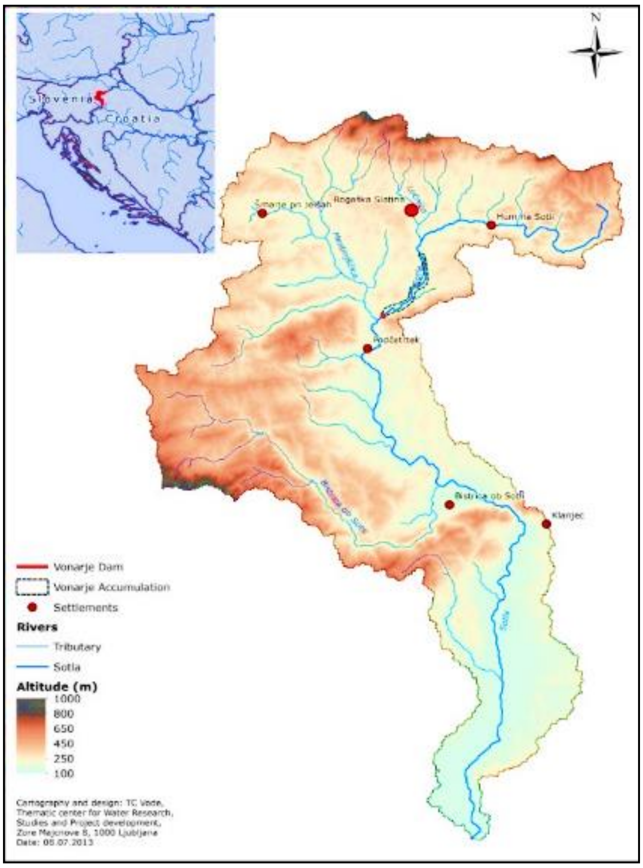

Figure 2. Location of Sutla River and Vonarje Reservoir/Sutla Lake [27]

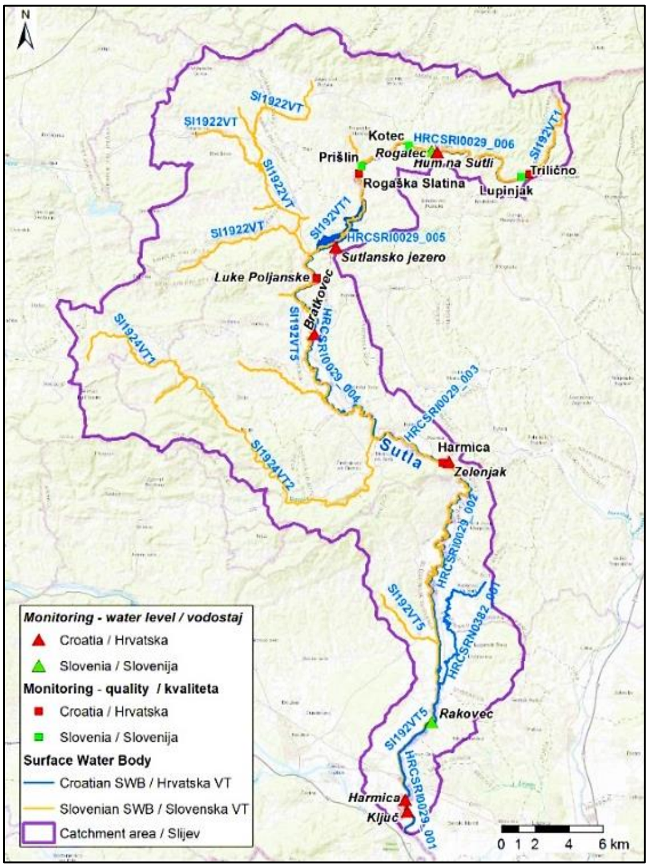

Figure 3. Transboundary Sutla River basin, surface water bodies and monitoring stations

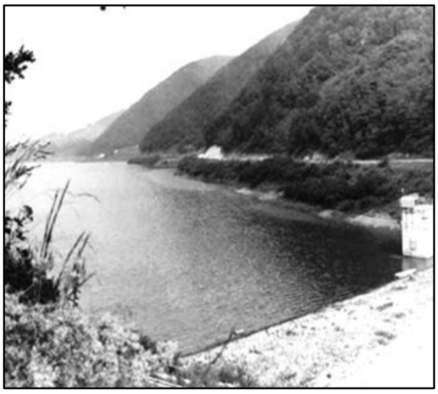

Figure 4. Sutla Lake in the past [26]

Figure 5. Sutla Lake today [26]

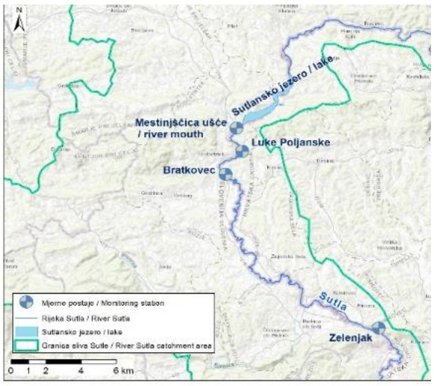

Figure 6. Vonarje dam and the locations of the measuring stations

Sutlansko Lake is located upstream of the mouth of Mestinjščica in Sutla at a distance of 150 m (Figure 6). The biological minimum below the dam is defined as a flow of 120 l/s. The monitoring stations are *Luke Poljanske* (2.5 km downstream) and *Bratkovec* (9.1 km downstream)

The Sutla River in Croatia, downstream of Sutla Lake, belongs to the lowland, medium and large rivers, with catchment areas of 100-1000 and 1000–10000 km^2. However, these sites are where the boundary of the catchment area is, where it flows from the middle part in large rivers or where the changing size of the basin is not defined. Immediately below Sutla Lake, the river declines within the medium river catchment area of 100-1000 km^2 before the tributaries flow into it. The source of the Sutla River belongs to type 1 - mountain and lowland small rivers, while the lower part of the Sutla River belongs to type 4 - lowland medium-large rivers. Following the restoration of the dam, when the reservoir is restored, it will be necessary to define an E-flow because of the importance of preserving the biodiversity of the Sutla River, which flows throughout the NATURA 2000 area. The Sutla River, as part of the NATURA 2000 ecological network, is important for the conservation of seven fish species and one shellfish species under the Habitats Directive [26, 28].

2.4. Database

According to the WFD, significant pressures that can affect change in the hydrological regime and that affect the biological elements of water quality have been assessed in the water bodies in the Sutla River basin (Figure 2 and Table 4). Specifically, good surface water status and E-flow are defined as "a hydrological regime that is consistent with the achievement of the WFD environmental goals in natural surface waters".

E-flow assessment in integrated water management, although focused on a short segment of the river, needs to be placed within a watershed context to better understand the hydro-morphological processes that characterize the watercourse and the human activities that affect its state. Furthermore, a proper watershed-scale assessment is needed to identify hydro-geomorphological patterns together with the reference aquatic community structure [11]. Based on the available data sources obtained from monitoring in the Sutla River basin and available knowledge of the river basin (Table 4 and Figure 3), analyses were made according to the proposed concept of the holistic E-flow approach (Figure 1).

Table 4. Available data sources for defining E-flow based on monitoring in the Sutla River basin

Monitoring station	Location	Types of monitoring	Water body	Assessment of the state
Lupinjak	upstream of the dam	water quality	CSRI0029_006	is no longer operational
Hum na Sutli	upstream of the dam	hydrology	CSRI0029_006	no dam impact natural hydrological regime
Prišlin	upstream of the dam	sediment	CSRI0029_006	anthropogenic impact
Prišlin	upstream of the dam	water quality	CSRI0029_006	bad, poor to good water status
dam Vonarje and Sutlansko Lake			CSRI0029_005	no assessment
Luke Poljanske	downstream of the dam	hydro-morphology	CSRI0029_004	slightly changed status
Luke Poljanske	downstream of the dam	water quality	CSRI0029_004	bad, poor to good water status
Bratkovec	downstream of the dam	hydrology	CSRI0029_004	impact of the dam, slightly changed hydrological regime
Zelenjak	downstream of the dam	hydro-morphology	CSRI0029_003	change due to anthropogenic impact
Zelenjak	downstream of the dam	hydrology	CSRI0029_003	low dam impact, natural hydrological regime

Zelenjak	downstream of the dam	water quality	CSRI0029_003	good water status
Harmica	downstream of the dam	hydro-morphology	CSRI0029_001	change due to anthropogenic impact
Harmica	downstream of the dam	water quality	CSRI0029_001	good to poor water status
Ključ	downstream of the dam	hydrology	CSRI0029_001	low dam impact, natural hydrological regime

Since no data were available for the section of watercourse 150 m downstream before the mouth of the Mestinjščica watercourse, the available data for Bratkovec (9.1 km downstream), water body CSRI0029_004, and Zelenjak (28.5 km downstream), water body CSRI0029_003, were analysed. Luke Poljanske (2.5 km downstream), water body CSRI0029_004, became the new monitoring station for water quality and hydro-morphology. For the Bratkovec and Zelenjak hydrological measuring stations, hydrological data were analysed, including the impact from the dam, the altered natural hydrological regime, and the flow, velocity, and height of the water column for the indicator species Barbus balcanicus.

Barbus balcanicus (Figure 7) is one of the eight important fish species necessary for the preservation of the Sutla River as part of the NATURA 2000 ecological network [28].

Figure 7. Barbus balcanicus

The basic ecological conditions for fish are water depth, water velocity, and submerged habitat [29]. The conservation of aquatic ecosystems and ESs for human well-being is significantly influenced by river morphology, which includes the processes of sediment transport and deposition. Due to the strong connection between fish and hydrological conditions, the variations are affected by the speed of the water (i.e., the slope and roughness of the riverbed), and fish are suitable indicators downstream of the dam that can be used to maintain the biological balance of watercourses.

3. Results and Discussion

3.1. Results

Related to the flow chart of the holistic approach to the E-flow assessment model shown in Figure 1, Tables 5 and 6 show the relevant steps of the methodology/holistic approach to the E-flow assessment model and the results for the case study of the Sutla River.

There are many gaps in the monitoring results, especially hydrological ones, due to incomplete data sets. Therefore, it was not possible to conduct systematic analyses and define trends related to individual environmental objectives, and we had to rely more on expert knowledge. In this article, the risk of not achieving environmental goals was prepared for the whole river basin based on the DPSIR approach. The risk of not achieving good water status – GAP – for the hydro-morphological pressures and status was prepared based on existing studies [28, 30], assessments prepared for specific goals and periods without a regular hydro-morphological monitoring programme. The risk of not achieving good water status – forecast – was prepared on the basis of the River Basin Management Plan 2016-2021, Excerpt from the Register of Water Bodies, rather than on the measured data because Luke Poljanske, a representative water quality monitoring station for the water body downstream of the Vonarje dam, has existed for only the last few years.

Tables 5 and 6 explain all of the steps of the “tailor made” E-flow proposal based on a holistic approach for the CSRI0029_004 water body of the Sutla River. Changes in longitudinal continuity on the Sutla River are caused by the construction of hydraulic structures in the watercourse bed (e.g., dams, overflow thresholds). The impact of the river basin structure is mostly related to the upstream retention of sediments, which directly affects the morphology of the cross-sections of the watercourses of the downstream regions.

The overall hydro-morphological assessment for the section at the measuring station of Luke Poljanske located downstream of the Vonarje dam, as well as that for the entire water body, reflects a slightly changed state. The hydrological state is slightly altered, and the longitudinal connection is unbroken. The morphological condition is good, i.e., slightly changed. The banks of the stream are natural, with slightly altered coastal vegetation. Erosion sedimentation processes reflect a moderate deviation from the natural state. The lateral connection of the river with the floodplain and the possibility of lateral movement of the riverbed are natural [29].

Table 5. Results of the conducted analyses of available data

Level	Location	Type of processing/analysis	Description	Values
Risk of not achieving environmental goals	Whole river basin	DPSIR analysis of pressures, state and implemented measures	Assessment of the impact of N, P and sediment quantifications using a mathematical model SWAT	The highest intake of nutrients and deposits at the Prišlin station
Risk of not achieving good water status- GAP	Prišlin and Luke Poljanske	Water status Hydro-morphology	Depending on the measurements One measurement	Bad, poor, good Moderately well
	Whole river basin	Analysis of the historical maps, longitudinal flow cross-sections	Analysis of military maps I and II LIDAR project recording FRISCO Analysis of the cross-sections	The river Sutla was always a border river, and the flow did not change significantly Characteristics of individual stocks rivers
Risk of not achieving good water status-forecast	General data about the water body CSRI0029_006	River Basin Management Plan 2016-2021 Excerpt from the Register of Water Bodies	**(Lupinjak) and Prišlin** Ecological status - poor Biological status – poor Chemical status – good	The estimate is not reliable
	General data about the water body CSRI0029_005		Present nature retention, future Sutlansko Lake No monitoring station -Moderate	
	General data about the water body CSRI0029_004*		**Luke Poljanske** Good water status*	
	General data about the water body CSRI0029_003		**Zelenjak** Good water status	
	General data about the water body CSRI0029_002		No monitoring station Good water status	
	General data about the water body CSRI0029_001		**Harmica** Ecological status - poor Biological status – poor Chemical status – good	

*For the water body downstream of the dam

Selection of the biological indicator species of the fish Barbus balcanicus downstream of the dam is important because the entire Sutla River is protected as a NATURA 2000 site. The analysis of the methods and experiences of the surrounding countries shows that all methods are hydrological; only Slovenia includes studies [28, 30] without additional field research. The E-flow has been defined for the hydrological monitoring station Bratkovec, 9.1 km downstream of the dam. The water quality monitoring station Luke Poljanske, which is important for the assessment of water status, is 2.5 km downstream of the dam.

Table 6. E-flow proposal with a holistic approach

Level	Location	Type of processing	Description	Values
Protected areas	All water bodies	River Basin Management Plan 2016-2021 Excerpt from the Register of Water Bodies	All water bodies are located in protected areas, NATURA 2000	Indicator species of fish Barbus balcanicus, downstream of the dam
Method analysis in surrounding countries	Monte Negro, Bosnia and Herzegovina and Slovenia	Methods for determining environmental flow	All methods are hydrological	Slovenian method includes the ecological aspect
I Level methods	Whole river basin Bratkovec and Zelenjak	Hydrological analyses	Slovenian method Dry and rainy season	Values

II Level methods	downstream of the dam Bratkovec and Zelenjak Luke Poljanske, Prišlin	Hydrological analyses Ecological analyses Hydromorfological analyses Sediment analyses	Expert knowledge- Analysis of hydrological series Field research results	* Barbus balcanicus Water depth and speed increased flow
III Level methods	Downstream of the dam	Lack of all data	Habitat modelling	Not implemented
Defining of the E-flow	Bratkovec	Hydrological versus ecological requirements	Comparison of minimum flow series at Bratkovec station	Final environmental flow
Monitoring of the E-flow	Bratkovec and whole river basin	Hydrological analyses Ecological analyses Hydromorfological analyses	Proposal for E-flow monitoring	Monitoring stations

* The Bratkovec monitoring station started operating in 1993 - the dam was built in the 80's

The blockage of watercourses represents a significant pressure, and the change in water status is reflected by the changed hydrological characteristics of watercourses downstream of the dam as well as by the quantity and quality of sediments necessary for the preservation of ichthyofauna. Biological response methods are based on the relationship between habitat and flow and certain bioindicators, such as characteristic fish species. Watercourses or parts of watercourses with a bottom drop between 1.5 and 3.2% are characteristically inhabited by barbel with accompanying fish species [31] or brook barbel for the middle-course rivers.

The greatest impact on the ichthyofauna of the Sutla River, in addition to foreign and invasive species, is probably due to water pollution, i.e., constant anthropogenic pressure, and attention must be paid to reducing the intake of organic matter and nutrients. The trophy level increases due to untreated wastewater and the leaching of large amounts of nutrients from agricultural and forestlands [31].

The results of the E-flow methodology applications in the legislation of the surrounding countries were compared for the CSRI0029_004 water body of the Sutla River, and the results are presented in Table 7.

Table 7. The results of the E-flow methodologies in the surrounding countries and comparison of the values obtained

Method	Parameter	Values of Bratkovec
CROATIA	Minimum mean monthly flow 95% probability of occurrence	Q min.mean.95%= 0.15 m^3/s
MONTENEGRO, [32]	$\frac{\mathrm{Qmean.min}}{\mathrm{minQmean}} = \frac{3.687\ \mathrm{m}^3/s}{1.045\ \mathrm{m}^3/s} = 3.53 \leq 10$ $\mathrm{Q_{E-flow}} = \begin{cases} \mathrm{meanQ_{min}} & \text{for } \frac{\mathrm{mQ_{min}}}{\mathrm{mQ_{M(j)}}} < 10 \\ 0.2 \times \mathrm{meanQ_{min}} & \text{for } \frac{\mathrm{mQ_{min}}}{\mathrm{mQ_{M(j)}}} \geq 10 \end{cases}$	July - August: Q = 0.185 and 0.157 m³/s January: $Q_{E-flow} = Q_{mean}$ = 1.045 m³/s
BOSNIA AND HERZEGOVINA [33]	$\mathrm{Q_{E-flow}} = \begin{cases} 0.1 \times \mathrm{Q_{mean}}; \text{for the period May} - \text{October} \\ 0.15 \times \mathrm{Q_{mean}}; \text{for the period November} - \text{April} \end{cases}$	May - October: 0.504 – 0.680 m³/s (water depth 40 cm and water velocity 50 cm/s) November - April: 0.380 - 0.680 m³/s (water depth 30 cm and water velocity 40 cm/s)
SLOVENIA [34, 35]	Hydrological (average per annual flow, average minimum flow, average decade flow) Characteristics of abstraction technical solutions (returned, non-returned) Disposition (distance between points of abstraction and returning water) $\mathrm{Q_{E\text{-}flow= f\ x}}\ \mathrm{Q_{aver,min}}$ The amount of abstracted water	$Q_{mean,\ mm}$ = 0.95 m³/s Q_{E-flow}= 0.95 m³/s (whole year and dry period) - returned abstracted water Q_{E-flow}= 1.52 m³/s (rainy period) - returned abstracted water

From a hydraulic perspective, at Bratkovec station, the wet table range and width of the water face grow exponentially with the rise in water levels, unlike the results at Zelenjak station, where the growth is linear due to the different transversal profiles of the observed stations. Based on a 2015 survey, it was concluded that the Sutla River is an extremely rich river for fish species. A total of 42 species have been recorded in the Sutla basin in only 92 km of river; this number is high, which further indicates the need to conserve the Sutla River. The holistic approach defines the E-flow for the Bratkovec profile by linking the hydrological, morphological, and ecological characteristics. Ichthyological studies have established that this part of the Sutla River is dominated by *Barbus balcanicus* (Figure 7), which belongs to the Cyprinidae family (carp); thus, this species was selected as the bioindicator organism.

The E-flow obtained by the hydrological method in vegetation, which amounts to 0.504 m³/s, should be increased to 0.68 m³/s to meet the requirements of *Barbus balcanicus* and allow the ecosystem to function normally. *Barbus balcanicus* spawn between April and June, and the spawning period requires a water depth greater than 40 cm and a water velocity greater than 49 cm/s. These criteria are not met in the Bratkovec profile and should be provided. Thus, the E-flow must be increased by 0.3 m^3/s to meet the value defined by the E-flow hydrological method. The final E-flow of 0.68 m^3/s is the result of the E-flow assessment based on the developed innovative holistic approach presented in this paper.

3.2. Discussion

Water use, withdrawals, and consumption by different sectors are generally based on estimates rather than measurements [14]. In the context of the predicted increase in water demand and hydropower development, E-flow assessments are essential for guaranteeing freshwater ESs, continued access to water for people, and human well-being. It is imperative for decision-makers to assess the needs of water provisioning for the environment and take the necessary actions to preserve, sustainably manage and, where necessary, restore freshwater ecosystems based on available knowledge and datasets [14]. Based on this, it is necessary to assess the E-flow for certain sections of watercourses. E-flow represents one of the most important complementary water management measures.

Based on the available data, the concept of a holistic approach to the E-flow assessment model was prepared using three profiles/locations, Bratkovec, Luke Poljanske, and Zelenjak, in different periods of the hydrological year (dry and rainy) and in accordance with the requirements of the WFD to achieve good water status [7]. The implementation of a comprehensive and holistic approach to an E-flow assessment framework proposal, following the global trends in the EU, requires a three-level approach to integrate hydrological, hydraulic-habitat, and holistic methods.

Based on the Sutla River basin case study and scientific research results, it was noted that the available hydrological data are insufficient, as are the data on long-term anthropogenic and natural changes in the water regime, including climate change. This indicates the need to improve the supervision of monitoring and the operational monitoring network to provide hydrological information directed to the specific objectives of the E-flow. It is a prerequisite to conduct research with the three-level method and obtain the results, as shown in the article by Theodoropoulos and Skoulikidis [7].

The implementation of the holistic approach to the E-flow assessment model, shown in Figure 1, requires the implementation of several levels of defining the E-flow according to the WFD:

- Level I - preliminary analysis by hydrological methods, involving water bodies unable to achieve WFD objectives due to hydrological changes – conducted;
- Level II - detailed analyses requiring field data collection according to holistic approaches – partially conducted;
- Level III - a combination of holistic methods using terrain and habitat models to implement measures to establish an E-flow – future research.

On the basis of the holistic method of E-flow assessment (Level I, Level II, and Level III), the Programme Of Measures (PoM) will be prepared and checked with data from hydrological, morphological, and biological monitoring.

These changes are necessary to identify water level and flow trends and to predict impacts. Additionally, the greatest impact on the ichthyofauna of the Sutla River must be determined to define the E-flow with the holistic approach. In addition to the damming and channelling of watercourses and the appearance of alien and invasive species, water pollution and constant anthropogenic pressure from point and diffuse sources of pollution were found to have the greatest influence using the mathematical Soil Water and Assessment Tool (SWAT) model [27]. According to the number of dissolved nitrates and orthophosphates at the Prišlin measuring station, the water status corresponds to good and moderately good. Related to Pistocchi et al. [36], the European E-flow concept proposed the identification of water bodies that failed to meet good ecological status due to hydrological alternation, and there was a gap between the current and reference state. Additionally, different application programme measures were assessed, and the need to establish hydrological, morphological and ecological monitoring programmes was identified.

Finally, we assessed the required E-flows using the proposed model with the holistic approach. The alteration of flow regimes, such as those caused by storage and diversion of a dam, causes changes in various ESs both upstream and downstream of such interventions and from the use of diverted flows. Therefore, the definition of E-flow, as an additional measure according to the WFD, should be prepared by Croatia and Slovenia and represents a key measure for the conservation of biodiversity, ESs, and human well-being in the Sutla River basin.

4. Conclusions

Several E-flow assessment methods have been developed worldwide, ranging from simple hydrological methods over habitat flow models to more comprehensive methodologies that include socioeconomic aspects. While much effort has been dedicated to the development of these methods, the biological effects of environmental flow regulations have been evaluated in only a small number of cases.

In this paper, the implementation of a holistic approach to the E-flow assessment model with three levels of E-flow definition according to the WFD was presented, and the Sutla River basin was used as a case study to apply the model. Based on the available data, a holistic E-flow assessment was prepared using three profiles/locations, Bratkovec, Luke Poljanske, and Zelenjak, in different periods of the hydrological year (dry and rainy) and in accordance with the requirements of the WFD to achieve good water status. The E-flow was defined for the Bratkovec profile by linking hydrological, morphological, and ecological characteristics based on the bioindicator organism *Barbus balcanicus*.

The full implementation of a holistic approach and the transition to Level III of the E-flow assessment requires improvements in hydrological and biological monitoring to enhance the use of habitat modelling. Further research is necessary to better understand the response of biota and riverine ecosystems to flow restoration by holistic assessments, including interactions with river morphology, sediment transport, groundwater, and floodplain dynamics. The available hydrological and long-term anthropogenic data and climate change data are insufficient. It is necessary to define a three-level holistic approach to E-flow assessment. Additionally, hydrological and biological monitoring should be improved, an integrated approach involving a range of disciplines should be developed, and the usage of habitat models is encouraged.

Considering that Sutla River basin is a transboundary basin, it is necessary to harmonize hydrological and water quality monitoring in Croatia and Slovenia and to harmonize the locations of measuring stations in relation to the new requirements. Appropriate monitoring is needed to confirm the E-flow. Effective water management is needed, with sufficient data and information as well as expert knowledge. It should also include public participation

5. Funding

The research for this article and the publication of this article were funded by the University of Rijeka within the projects "Implementation of Innovative Methodologies, Approaches and Tools for Sustainable River Basin management" (UNIRI-TEHNIC-18-129) and "Hydrology of Water Resources and Identification of Flood and Mudflow Risks in Karst" (UNIRI-TEHNIC-18-54).

6. Conflicts of Interest

The authors declare no conflict of interest.

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