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Definition of Ecological Flow Using IHA and IARI as an Operative Procedure for Water Management

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Abstract: It is widely recognized that the hydrological regime of natural flow plays a primary and crucial role in influencing the physical condition of habitats, which, in turn, determines the biotic composition and sustainability of aquatic ecosystems. The current hydro-ecological understanding states that all flow components might be considered as operational targets for water management, starting from base flows (including low flows) to high and flood regimes in terms of magnitude, frequency, duration, timing, and rate of change. Several codes have been developed and applied on different case studies in order to define common tools to be implemented for Eflow assessment. This work deals with the definition of an operative procedure for the evaluation of the Eflow monthly distribution to be adopted in a generic watercourse cross-section for sustainable surface water resource management and exploitation. The methodology proposes the application of the Indicators of Hydrologic Alteration methodology (IHA by TNC) coupled to the valuation of the Index of Hydrological Regime Alteration (IARI by ISPRA) as an operative tool to define the ecological flow in each monitoring cross-section to support sustainable water resource management and planning. The case study of the Agri River in Basilicata (Southern Italy) is presented. The analyses were carried out based on monthly discharge data derived by applying the HEC-Hydrological Modeling System at the basin scale using the daily rain data measurements obtained by the regional rainfall gauge stations and calibrated through the observed inlet water discharge registered at the Lago del Pertusillo reservoir station.

Keywords: ecological flow; indicators of hydrologic alteration; index of hydrological regime alteration; HEC-HMS

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1. Introduction

The recent evolution of the European and national regulatory framework, as well as the obligation to adapt and achieve the requirement of good quality in water bodies imposed by the Water Framework Directive (WFD 2000/60/EC) [1], requires the definition of ecological flow (Eflow). Eflow represents the amount, quality, and timing of water discharge required to sustain riparian and estuarine ecosystems, as well as the human livelihoods and well-being dependent on these ecosystems [2]. Ecological flow can be defined as the minimum value of discharge that needs to be maintained in a river in order to ensure good (or optimum) conditions for the existing ecosystems, according to appropriate criteria based on the hydrological and environmental conditions respecting the biological balance.

The knowledge acquired in recent years in the field of hydro-ecology has highlighted the fundamental role of the hydrological river stages and their time variability, from drought up to flood, in relation to the life of river ecosystems in terms of the maintenance, development, and evolution of habitats, flora, and benthos [3–8]. Thus, Eflow might be assumed as being the rate of natural discharge that should be left in a water body to maintain a high quality of water resources and water-related ecosystems, according to the requirements of environmental protection [9]. Furthermore, the concept of Eflow evolved from the simple idea of determining the minimum water discharge needed for the existence of ecological species [10] to the complex view dealing with the possible implications on river ecosystem management in anthropogenic-stressed basins [11–13]. In other words, Eflow should represent the imposed conditions on river hydrology that provide appropriate ecological functions under flow regulation restrictions induced by natural and/or anthropogenic stresses [14].

The European and Italian national frameworks to date, unfortunately, still note situations in which the current unavailability of specific measures and monitoring activities requires the adoption and implementation of a transitional phase in which the "no deterioration" condition of the quality status of water bodies must be achieved and guaranteed. This condition might be determined on the basis of scientific methodologies arising from relevant international experiences, as suggested by the European Commission in the guidelines on ecological flow [15].

Several methods are reported in the literature which were developed in the field of eco-hydrology for the assessment of ecological flow [16]. In a general overview, these methods can be classified in the three following groups [17–19]:

1—Hydrological indicators and/or parameters, derived from analysis of hydrological and hydraulic data arising from monitoring activities without focusing on specific species or biotic communities.

2—Habitat assessment and change forecasting, based on the principle that good habitat conditions for several species are the consequence of the interaction between water discharge, riverbed geometry, and vegetation, allowing the proper depth/flow velocity ratio necessary for species in various age groups.

3—Functional analyses through the analysis and understanding of functional relationships between hydrology and river ecosystems.

The methods for Eflow assessment should consider the natural variability of river flow by providing different flow components in order to obtain the best condition of freshwater ecosystems, habitats, and wetland species [20]. Thus, the assessment of minimum life inflow is not only subject to economic criteria but also follows the general principles of sustainable development which allow socio-economic growth according to the simultaneous maintenance of the natural balance [21–23].

Due to their simplicity and straightforward application, hydrological and hydraulic methods are commonly used to compute Eflow, which is calculated based on the given characteristic discharge observed in a watercourse. Meanwhile, hydraulic methods are supported by quantitative relationships between natural flows and habitats. These methods consider the effects of water flow variability on the habitat of the main fish species, referring to their optimal condition for living, reproduction, migration, and feeding.

The geometrical parameters, such as the wetted perimeter, maximum depth, or aspect ratio, are generally used in combination with vertical and cross-sectional flow velocity distributions. Whenever no velocity data are available, expeditive entropy-based models might be used for the assessment of the vertical velocity profile in order to derive local velocity gradients and, thus, bed shear stress [24,25]. The hydraulic methods are suggested for use in catchment areas where hydrometric observations are not available, or for controlled cross-sections [26–30]. Furthermore, in the flow-habitat models, ecological flow is calculated from interactions between the water discharge and the riverbed morphology, rather than establishing the suitable habitat conditions corresponding to the local morphological conditions. The IFIM [9,31,32] is one of the most common methodologies used to estimate environmental flow, as well as PHABISM [33,34], HABIOSIM [16], RSS [35], and MesoHABSIM [36,37].

Within this framework, this paper proposes the application of the Indicators of Hydrological Alteration (IHA) methodology (by TNC) [6,7,38,39] coupled with the Hydrological Regime Alteration Index (IARI) [40] as a practical method for monthly Eflow assessment. Eflow, indeed, represents the suitable value of the water discharge flowing in a water body able to guarantee the ecological integrity of the watercourse.

Furthermore, the rationale of this study deals with the application of "cascade models" whenever observed water discharge data are not available for each water body constituting the river network. A classical rainfall–runoff model, e.g., HEC-Hydrological Modeling System (HEC-HMS) [41], can be used for the assessment of the water discharge time distribution flowing in a generic cross-section along the water body, in order to feed the IHA-TNC. The novelty is represented by the use of the IARI as the control factor for the validation of the assessed value of Eflow. Ecological flow, indeed, is selected through the evaluation of the percentile of the water discharge distribution corresponding to the minimum discharge satisfying the boundary condition imposed by the reference value of the IARI for a "good status" at least.

2. Materials and Methods

2.1. Study Area—The Agri River Basin

The proposed analysis was applied to all of the Lucanian river networks (Basilicata region, Southern Italy), but the present study refers to the case study of the Agri River as a suitable example representing all the problems observed in the Lucanian river systems (Figure 1).

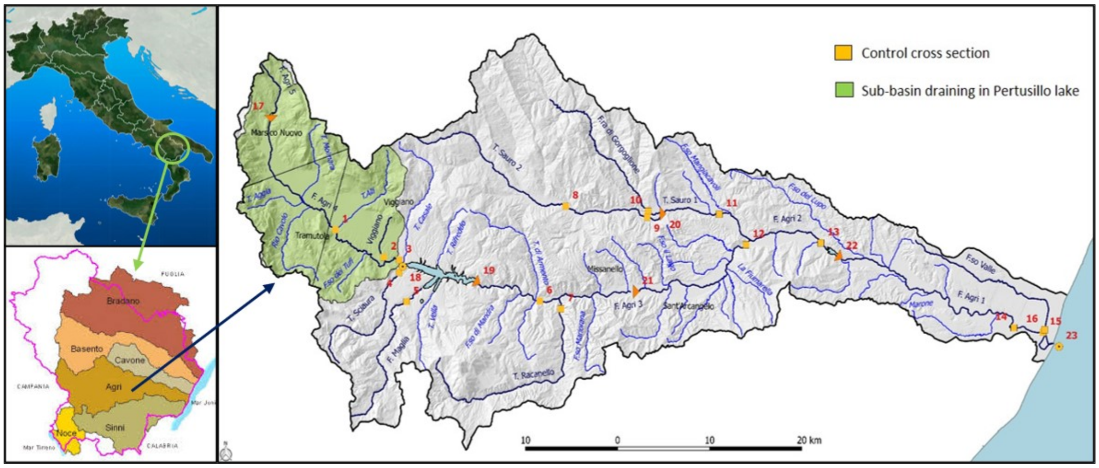


Figure 1. The study area of the Agri River, the map of the control cross-section, and an example of a sub-basin.

In detail, the study area consists of the Agri River basin. The Agri River is one of the six major rivers of the Basilicata region, with a drainage basin area of over 1715 km^2 and varying morphology from mountainous and hilly, in the medium-high upstream part, to low hilly and flat, in the downstream portion.

The hydrographic network is substantially ramified, presenting a main stream of about 113 km in length, whose mountainous reach has an NNW–SSE trend, crossing the intermontane depression of the Alta Val d'Agri and then assuming a fairly regular W–E trend, reaching the Ionian coast of Basilicata.

The average annual rainfall is quite homogeneous along the basin, following the distributions aligned to the NW–SE ridge, with a reference value of about 900 mm/y (Figure 2).

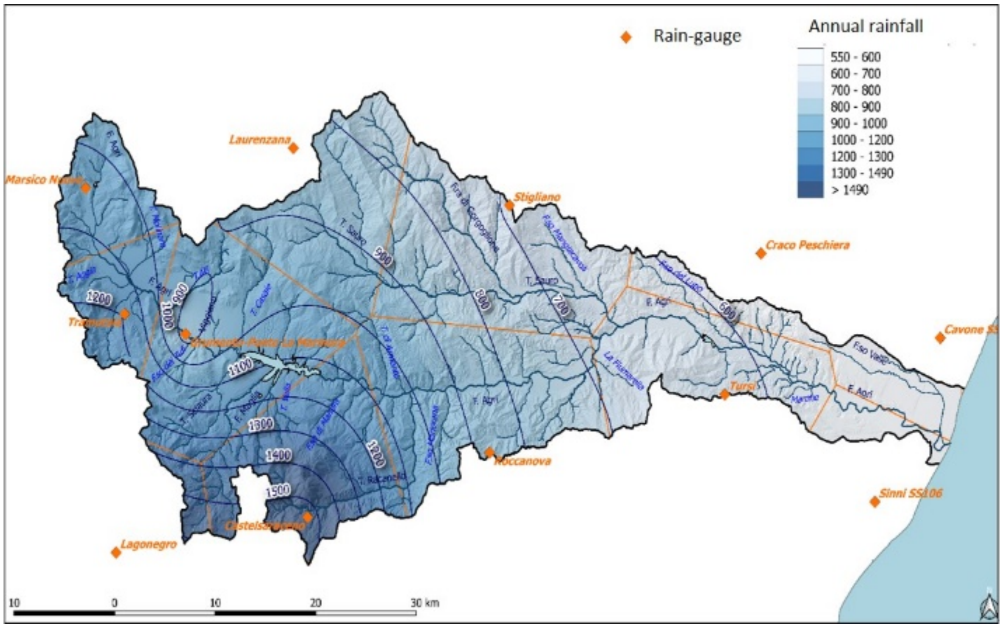


Figure 2. Rain gauge network, the average annual regional rainfall, and Agri River basin maps.

The Agri basin is representative of a generic river system, where several pressure elements are present in terms of both anthropogenic activities and infrastructural intervention (Pertusillo dam, hydropower station, oil district, extensive farming, urban areas, etc.)

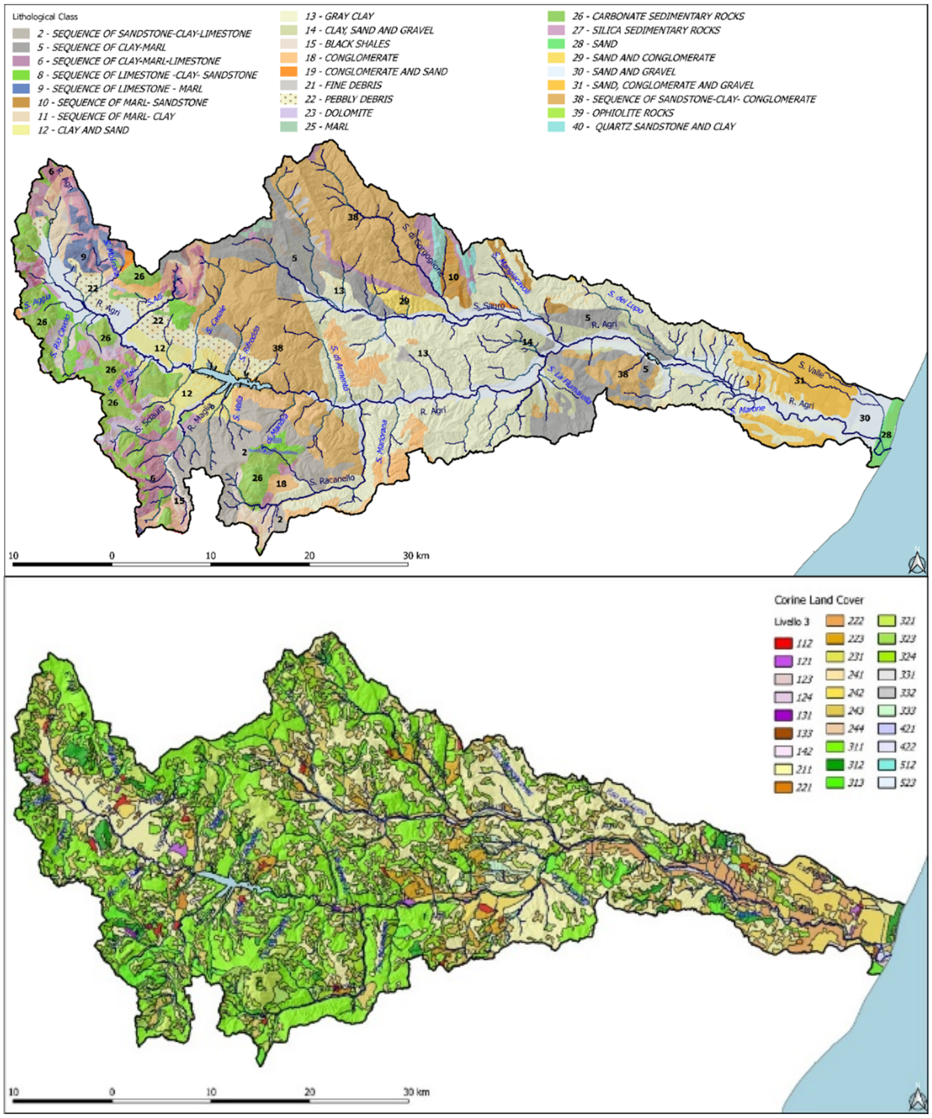
2.2. Advanced Integrated Hydrological Modeling (AIHM) for Water Resource Management

The catchment data were obtained by carrying out Advanced Integrated Hydrological Modeling (AIHM) for water resource management at the basin scale, developed based on multisource data paired with a distributed hydrological numerical model [42]. The AIHM proposes the implementation of an advanced computing hydrological routing on a regional spatial decision support system (SDSS) integrating land and resource management as well as human and natural risks. In detail, the project envisages the application of a hydrological computational module of an expandable SDSS based on open-data catalogues, able to manage and display both the basic information, including the relative metadata, and post-processing data with open-source change-detecting codes and hydrological modeling.

The SDSS includes the development of integrative methodologies for systematic and continuous catchment monitoring, interfaced in an open-source WebGIS environment dialoguing with the Regional Spatial Data Infrastructure (RSDI). The general SDSS as well as the single hydrological routine provides the integration of ground and remotely sensed data with open-source information technologies for basic and advanced analyses as well as web publishing of geographic data for a simple and intuitive end-user consultation.

Geographic data are processed through the interoperability WMS standards defined by the OGC by implementing data processing techniques to obtain territorial information, based on PSInSAR and change detection methodologies widely and robustly implemented in the analysis of extended targets such as basin and sub-basin areas and/or coastal zones [43–45]. In such a context, the proposed AIHM firstly provides a detailed historical analysis of the entirety of the data and measures available from different sources and refers to distributed rainfall, temperature, water discharge, and evapotranspiration gauges coupled with a multitemporal change detection analysis of the DEM, technical map, land use, soil properties, and urban areas as well. All the analyses refer to a 20 × 20 grid as the optimal spatial resolution derived from multisource data, including satellite, topographic, and Lidar data.

The second step leads to the assessment of the effective runoff, based on detailed geological and pedological studies and implementing the Soil Conservation Service method to provide suitable values of CN all over the catchment. The final values of CN adopted in the simulation correspond to medium-high saturation ground (CNIII) (Figure 3). Furthermore, the processing routine of the catchment hydrological model was developed using the open-source HEC-HMS implemented in the Q-GIS environment (Figure 4).



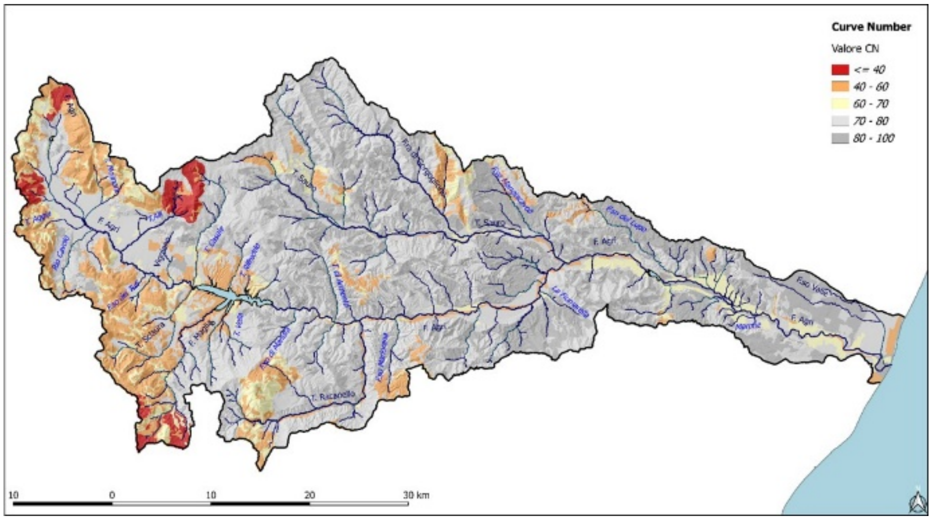
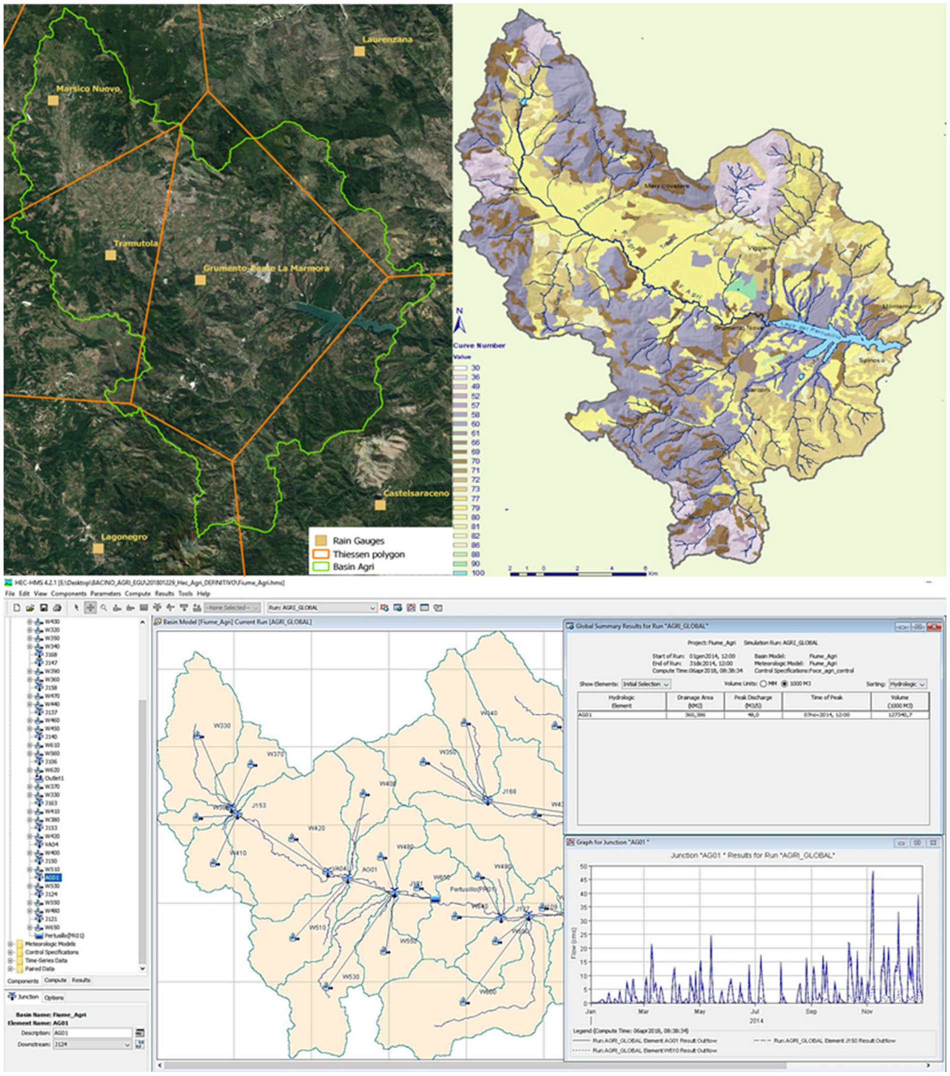


Figure 3. Lithological soils, Corine Land Cover, and curve number maps of the Agri River basin.



Global Summary Results for Run "AGRI_GLOBAL"

Project: Fiume_Agri Simulation Run: AGRI_GLOBAL

Start of Run: 01gen2014, 12:00
End of Run: 31dic2014, 12:00
Compute Time: 06apr2018, 08:38:34

Basin Model: Fiume_Agri
Meteorologic Model: Fiume_Agri
Control Specifications: Foce_agri_control

Show Elements: Initial Selection
Volume Units: ○ MM ● 1000 M3
Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (1000 M3)
AG01	360,386	48,0	07nov2014, 12:00	127340,7

Basin Name: Fiume_Agri
Element Name: AG01
Description: AG01
Downstream: J124

Figure 4. The processing routine of the catchment hydrological modeling by HEC-HMS implemented in the Q-GIS environment.

The numerical results were validated based on observed time series of water discharge data measured on the inlet cross-section of the Pertusillo reservoir along the Agri River. The routines implemented refer to the monthly and yearly water balance as well as event-scale analysis robustly supporting the short and medium planning and decision making phases as pre-operational and operational tools for both fields of water resource management at the catchment scale.

2.3. Methodology

The evaluation of the hydrological regime alteration of a watercourse, both in terms of characterization and quantification, is a problem still not fully solved, leaving significant degrees of arbitrariness for decision makers, and depending on direct and indirect assessments of hydrological functional scenarios.

In the literature, several methodologies have been proposed for evaluating the alteration of the hydrological regime [46], as summarily reported in Table 1.

Table 1. List of international methodologies for hydrological regime alteration.

Acronym	Method	Country	Reference
IHA	Indicators of Hydrologic Alteration	USA	Richter et al., (1996; 1997) [8,38]
IARI	Indice di Alterazione del Regime Idrologico	Italy	Ispra (2011) [40]
DHRAM	Dundee Hydrological Regime Alteration Method	Scotland	Black et al., (2005) [17]
HIT	Hydrologic Index Tool	USA	Henriksen et al., (2006) [18]
HAI	Hydrology Driver Assessment Index	South Africa	Kleynhans et al., (2005) 194]
QM-HIDRI	HIDRI-Protocolo 3	Spain	Munné et al., (2006) [47]
HAI	Histogram Matching Approach	Taiwan	Shiau and Wu (2008) [48]
IAHRIS	Indices de Alteracion Hidrologica en Rios	Spain	Martínez Santa-María et al., (2008) [49]

All of the procedures mentioned in Table 1 are generally based on the comparison between an undisturbed condition and an “altered” condition, both characterized by the value assumed by several descriptive parameters for different aspects of the hydrological regime.

In particular, ISPRA (2011) [40] proposes the implementation of the combined use of the “Indicators of Hydrologic Alteration” (IHA) and the “Hydrological Regime Alteration Index” (IARI) as a useful tool for assessing changes in the hydrological regime of a watercourse induced by anthropogenic pressures such as dams, diversions, hydroelectric plants, or any other type of action affecting the naturalness of the river system [39,50]. Obviously, the present study focuses on the ISPRA approach, which is the methodology suggested for Italian basins, and the produced results might be immediately adopted by the regional authorities.

The analysis of the hydrological regime alteration of a watercourse can be carried out at a cross-section of the watercourse on the basis of the IARI methodology, which provides a measure of the deviation of the hydrological regime, assessed on a daily or monthly scale, compared to the natural datum corresponding to the absence of any anthropogenic pressure.

Furthermore, the IHA can be calculated using parametric (mean/standard deviation) or non-parametric (percentile) analysis, starting from the time series of water discharge. The IHA parameters and their influence on the ecosystem are attributable to five main hydrological groups, HG, [6,7] and five different environmental flow components, EFC (Table 2).

Table 2. Short description of IHA’s hydrological groups and environmental flow components.

Hydrological Group	**Description**
Group 1	Monthly condition of the watercourse
Group 2	Minimum and maximum flow conditions at 3-7-30-90 days, zero flow days, and base flow rates
Group 3	Extreme conditions of the watercourse and the number of days with the same flow rate
Group 4	Frequency and duration of high and low impulse flows
Group 5	Frequency of variability of the flow rate
Environmental Flow Component	**Description**
Type 1	Minimum flow rate: represents the dominant condition in most watercourses and represents the base flow
Type 2	Extreme drought: present during drought periods, with very low levels of flow if not completely zero, to which correspond conditions of particular criticality for some types of organisms and could be a source of life for other species
Type 3	High flow rate pulses: include any flow rate increase, such as significant rain periods, which are necessary and important for the relief of ecosystems at minimum flow rates
Type 4	Small floods: these promote the mobility of aquatic fauna usually confined to swamps, ponds, and shallow wetlands that usually correspond to poorly accessible habitats
Type 5	Major floods: correspond to a reorganization of the biological and physical structure of a stream

The entire range of flow conditions represented by the EFC components (globally 33 parameters) must be maintained in order to ensure the river ecological integrity.

The IARI is determined from the flow data, by comparing the “altered” flow rates with the corresponding natural flow rates, as indicated by the ISPRA [40] according to the following criteria:

(1) Provide a quantitative measure of the deviation of the observed hydrological regime from the natural one that would occur in the absence of anthropogenic pressures;
(2) Take into account the general and widespread scarcity and/or absence of data;
(3) Be able to use all available hydrological information;
(4) Use tools, methods, and results already available from the competent entities that carried out the hydrological and water balance in the water protection plans;
(5) Be easy to implement and calculate with the usual calculation tools.

The procedure has the following characteristics:

(a) It is defined at successive levels of in-depth analysis;
(b) It is defined primarily on the basis of the monthly average flow rates to take into account the effect of seasonality and to use the results of the water balance of the protection plans;
(c) It is defined differently for river sections with or without flow measurement instrumentation;
(d) It is derived from the IHA method, and the statistics used in the procedure can be easily calculated with the corresponding open-source software IHA.

With regard to the reference values for the IARI, it is useful to point out that, conventionally, the following ranges are adopted:

- $0 \leq \text{IARI} \leq 0.05$ excellent
- $0.05 < \text{IARI} \leq 0.15$ good
- $\text{IARI} > 0.15$ poor

Thus, the procedure for the assessment of the status of the hydrological regime through the determination of the IARI is divided into three phases (Figure 5):

1. <u>*Phase 0—preliminary analysis*</u>: An analysis of the basin-scale pressures shall be carried out in order to identify the detectable conditions in the considered section by selecting one of the following conditions:
    - No or negligible pressure on the hydrological regime—it can be assumed that it is unchanged;
    - Significant or non-negligible pressures leading to impacts that cannot be assessed a priori—a necessary assessment must be made on an objective basis.
2. <u>*Phase 1—calculation of the index*</u>: If in Phase 0, the identified conditions show an impact on the hydrological regime due to pressure, the quantitative assessment of the alteration is carried out through the calculation of the IARI index.
3. <u>*Phase 2—direct evaluation or consultation*</u>: This step is activated whenever the results obtained in Phase 1 reveal critical elements. In such a case, a detailed analysis essentially based on the qualified information given by experts is provided in order to explain the causes and to confirm the exposed criticalities.

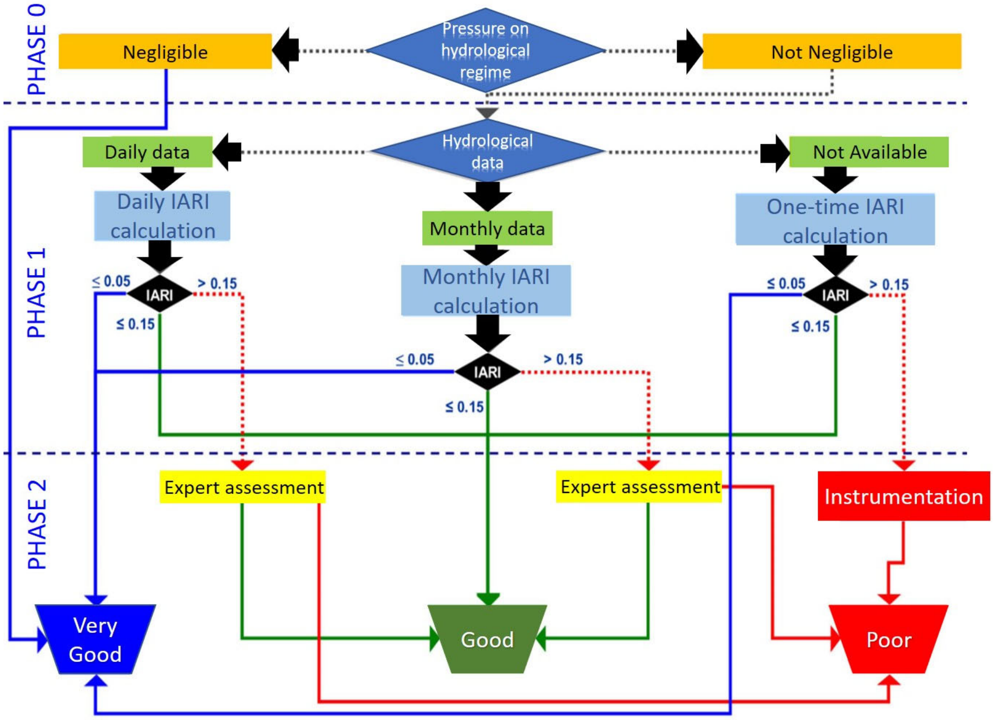


Figure 5. IARI evaluation procedure.

In detail, in each control cross-section, based on the monthly time series relating to the “undisturbed” condition, the 25th and 75th percentiles, $X_{N0.25,i}$ and $X_{N0.75,i}$, must be computed for each ith IHA parameter (e.g., the monthly flow discharge).

Subsequently, for each ith parameter, the characteristic value, $X_{i,k}$, corresponds to the kth reference period in which the altered condition occurs, e.g., in the present case, this corresponds to the value of the monthly flow rate assumed as the monthly ecological flow.

Furthermore, through the comparison between the value $X_{i,k}$ and the $X_{N0.25,i}$ and $X_{N0.75,i}$, the term $p_{i,k}$ is calculated according to the procedural scheme reported in the following equation:

$$p_{i,k} = \begin{cases} 0 \text{ if } X_{N\,0.25,i} \le X_{i,k} \le X_{N0.75,i} \\ \min\left(\left|\frac{X_{i,k} - X_{N\,0.25,i}}{X_{N0.75,i} - X_{N\,0.25,i}}\right|, \left|\frac{X_{i,k} - X_{N\,0.75,i}}{X_{N0.75,i} - X_{N\,0.25,i}}\right|\right) \; X_{i,k} < X_{N\,0.25,i} \text{ or } X_{i,k} > X_{N0.75,i} \end{cases} \quad (1)$$

where i refers to the ith IHA parameter, k is the reference period, $X_{i,k}$ is the characteristic value of the ith parameter corresponding to the kth reference period in which the altered condition occurs, $X_{N0.25,i}$ is the 25th percentile of the ith IHA parameter in the natural condition (unaltered condition), and $X_{N\,0.75,i}$ is the 75th percentile of the ith IHA parameter in the natural condition (unaltered condition).

In other words, if the value of the parameter $X_{i,k}$ falls within the band delimited by the percentiles 25% and 75%, the term $p_{i,k}$ is assumed to be zero, corresponding to a condition of ordinary fluctuation; otherwise, it is equal to the minimum distance, normalized on the amplitude of the interval, from the limits of the band. IARI is therefore defined as the average of the values assumed by the terms $p_{i,k}$.

In order to identify the groups of elements which have the greatest influence on the alteration of the regime, and also to plan any intervention measures, the IARI was estimated for each group, and the average was then calculated as reported in the general form of Equation (2) based on the number of parameters belonging to the HG, j=1, 2, …,5:

$$\text{IARI}_k = \frac{1}{33}\sum_{j=1}^{5} n_j \left(\frac{1}{n_j}\sum_{i=1}^{n_j} p_{i,k}\right) \quad (2)$$

In this framework, Eflow is considered as the hydrological alteration induced in the water body. Thus, the hydrological Eflow arises from the assessment of the levels of acceptability of the Indicators of Hydrological Alteration (IHA) and the determination of the Hydrological Regime Alteration Index (IARI) at a generic river cross-section.

In the present study, therefore, the ecological flow was defined as the ith percentile of the distribution of the average monthly flows, which provides a value of the IARI corresponding to a "good" level at least, and Equation (2) becomes

$$\text{IARI} = \frac{1}{12}\sum_{i=1}^{12} p_{i,\text{monthly}} \quad (3)$$

Whenever no time series of water discharge are available, and a rain gauge network is present, classical catchment rainfall–runoff modeling can be used. In the present study, the HEC-Hydrological Model System (HEC-HMS) was employed using a suitable rainfall time series available from the regional civil protection gauge network. The HEC-HMS simulates the complete hydrologic processes of river catchment systems and includes several traditional hydrologic analyses such as infiltration, evapotranspiration, unit hydrographs, and hydrologic routing [51,52].

The significance and the validation of the reconstructed data were evaluated using two criteria: the root mean square, E_{RMS}, and mean absolute percentage error, E_{MA}, expressed as follows:

$$E_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{(X_c)_i - (X_o)_i}{(X_o)_i}\right)^2} \quad (4)$$

$$E_{MA} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{(X_c)_i - (X_o)_i}{(X_o)_i}\right| \quad (5)$$

where X_o is the observed value, and X_c is the value estimated by the application of HEC-HMS.

Following such an approach, the concept of ecological flow goes far beyond the commonly reductive idea in which the minimum ecological flow rate corresponds to a fixed percentage of the average annual flow rate. Eflow, indeed, represents the monthly water discharge inducing acceptable alterations in the hydrological regime, ensuring the functionality of the water body.

The methodology is spatial scaling and applicable to a generic cross-section of any watercourse.

3. Results and Discussion

Since the main objective of the above-described procedure is to detect any changes in the hydrological regime induced by the adoption of the Eflow, a crucial aspect is the definition of the reference condition for the hydrological regime corresponding to the “unaltered” condition. Therefore, ISPRA (ISPRA, 2011) suggests that this condition should be identified from a series of daily/monthly flow rates that can be taken as “natural” for at least 15 years, in order to ensure a sufficiently reliable hydrological evaluation. As mentioned above, in the present study, the monthly time scale was assumed as the reference period for the analysis. This assumption does not limit the proposed methodology, but it is coherent with the assessment of the minimum discharge needed in the watercourse and is able to guarantee the local ecological integrity, according to the definition of Eflow.

Omitting the detailed analysis and the numerical aspect mentioned above, the proposed methodology was applied to all the rivers of Basilicata, in order to assess the monthly hydrological Eflow to be guaranteed in each control section identified in the “Plan for monitoring surface water bodies” of the Basilicata region. The case study of the Agri River is discussed further below.

In detail, the following steps were carried out for the first assessment of the hydrological Eflow (Figure 6) of the Agri River.

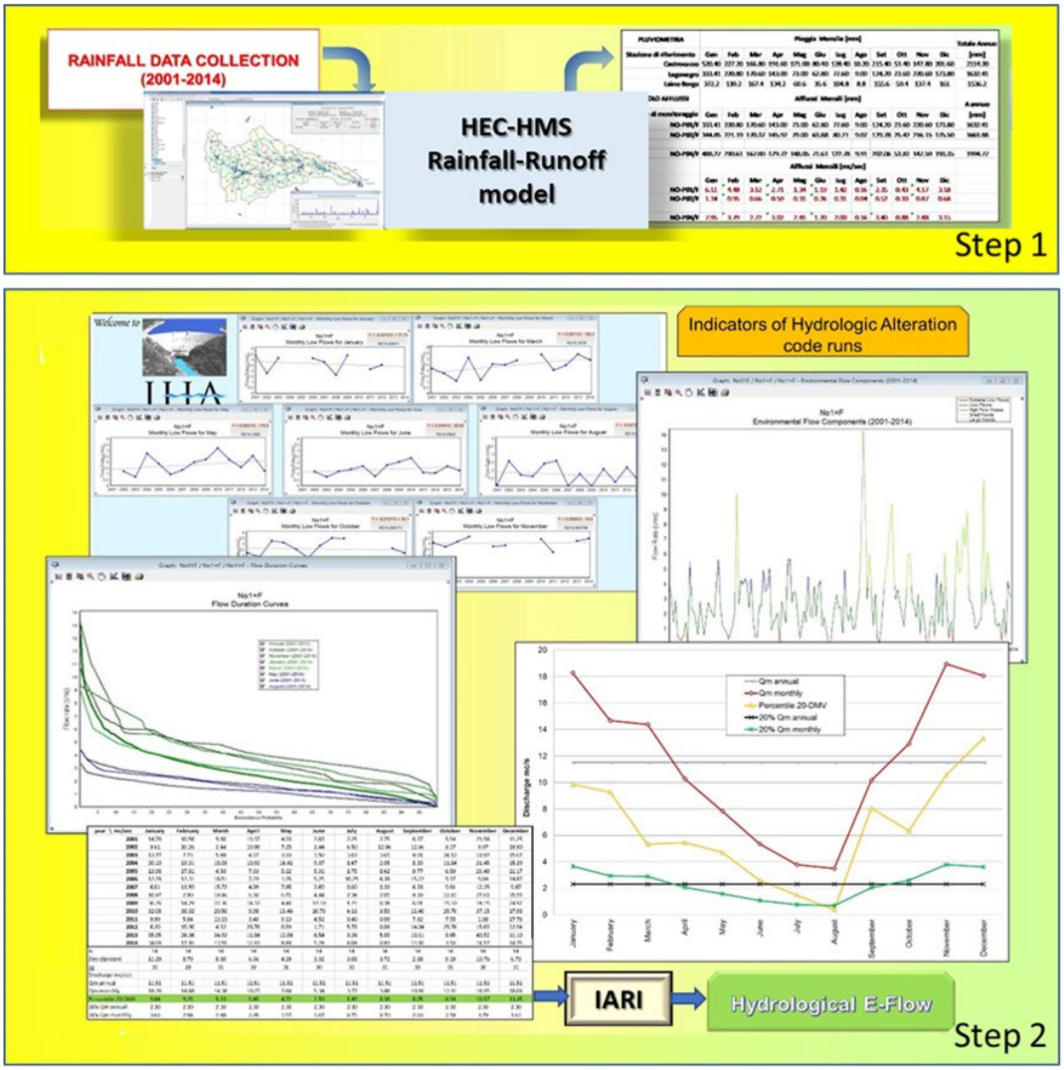


Figure 6. Logical procedure for the hydrological Eflow assessment.

3.1. Step 1: Collection of the Hydrological Data of the Agri River

The precipitation values observed at the available rain stations in the Agri basin and the flow data collected at the measuring sections along the watercourse (a minimum of 15 years) were used to populate the SDSS developed for the AIHM, and the hydrological analysis and implementation of the HEC-HMS were performed at the basin scale to compute the daily average flow rates.

3.2. Step 2: IHA Runs and IARI Computation for the Agri River

The IHA calculation code (TNC) was implemented on the reconstructed daily flow discharge time series in each control cross-section of the Agri River, obtaining the HG and EFC time distributions. Then, analysis was implemented on “a non-parametric basis” at the control cross-section scale and for the entire observation period covered by the hydrological dataset (minimum of 10 years) of the IHA code, along with evaluation of the corresponding HGs and EFCs.

Moreover, we performed the analysis of the regressive trend of the flow components and assessment of the flow rate corresponding to the 25th and 75th percentiles of the flow distributions computed and observed on the monthly time base. Finally, in each control cross-section of the Agri River, the hydrological Eflow was computed as the *i*th percentile of the monthly flow distribution, for which the corresponding value of the IARI falls in the range 0.05–0.15, consistent with the "good" level, through Equation (3); in the present case study, Eflow was assumed to be the 20th percentile of the monthly water discharge.

Tables 3 and 4 report the reconstructed and observed data, respectively, referring to the Pertusillo Lake control cross-section selected along the Agri River. The Pertusillo Lake represents the gauged section corresponding to the inlet of the reservoir in which the water discharge is measured by the management authority. The measures are generally collected daily in order to provide a daily inflow/outflow water storage balance. The data reported in the tables refer to the average monthly discharge computed by HEC-HMS and the observed data in the control cross-section.

Table 3. Reconstructed water discharge data for the control cross-section of Pertusillo Lake.

Reference Cross Section				**PR01—Pertusillo Reservoir**					**Monthly Water Discharge (mc/s)**			
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2001	8.43	7.54	6.99	7.24	4.17	2.39	2.42	1.20	2.71	4.78	2.97	7.18
2002	8.31	6.98	5.40	8.42	5.96	2.50	2.73	3.55	5.47	6.58	8.16	10.40
2003	10.05	6.19	7.51	5.15	4.11	2.60	3.38	1.06	2.48	5.16	8.69	8.55
2004	11.63	10.94	8.86	7.12	7.52	3.16	2.59	0.94	4.36	4.90	7.30	11.90
2005	6.24	4.93	11.08	3.70	4.35	1.89	2.09	2.82	3.81	5.61	11.71	16.04
2006	6.63	9.39	8.59	5.89	1.66	2.89	2.72	2.73	3.90	0.96	3.63	8.27
2007	4.12	10.19	6.54	5.32	5.22	3.30	0.23	0.40	1.73	5.28	6.75	5.85
2008	4.37	10.61	1.92	4.65	2.84	2.56	2.51	0.66	3.98	5.05	11.38	10.96
2009	20.01	18.39	7.78	15.23	6.46	1.74	2.23	2.90	3.55	6.03	8.02	11.40
2010	11.17	15.33	16.35	8.14	11.92	3.84	2.62	1.28	2.01	4.60	10.02	9.25
2011	6.03	15.41	5.18	5.58	7.10	2.70	1.21	1.48	3.09	4.16	5.38	8.47
2012	6.28	6.11	13.22	12.52	5.31	1.16	1.93	0.41	3.52	5.94	8.21	9.23
2013	17.38	17.12	14.90	4.39	5.81	4.27	2.29	2.53	2.53	5.23	6.27	13.94
2014	12.62	6.46	9.21	11.05	5.44	3.78	2.62	0.68	4.42	3.15	8.63	6.58

Table 4. Observed water discharge data for the control cross-section of Pertusillo Lake.

Reference Cross Section				**PR01—Pertusillo Reservoir**					**Monthly Water Discharge (mc/s)**			
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1987	11.35	16.57	8.00	6.60	3.74	2.73	1.77	1.23	1.50	2.45	3.33	5.32
1988	8.10	9.17	13.71	6.17	3.55	2.27	1.26	0.55	1.90	2.19	7.43	9.87
1989	3.03	8.57	9.94	5.93	3.74	2.00	1.19	0.87	1.07	3.65	4.53	8.03
1990	3.26	3.39	3.10	13.30	3.90	1.43	0.48	0.42	0.73	2.26	4.70	21.52
1991	10.81	13.50	6.77	17.33	8.10	1.87	1.26	1.52	2.07	3.13	15.07	5.39
1992	5.26	4.03	3.39	5.80	3.07	1.77	1.00	0.39	0.67	2.68	5.87	7.23
1993	6.29	3.46	11.65	6.43	4.19	1.03	0.26	0.06	1.13	2.36	4.43	12.13
1994	15.00	18.43	6.58	10.27	7.16	0.70	1.42	0.61	0.63	2.39	4.00	3.74
1995	7.81	5.89	12.06	11.70	8.42	2.20	1.87	2.00	2.57	1.94	2.53	7.26
1996	6.71	15.41	16.94	13.83	7.61	3.20	1.48	0.61	2.83	9.55	19.30	20.84
1997	15.65	8.86	6.03	6.03	5.52	1.40	1.10	1.48	1.17	4.16	12.43	12.16
1998	9.65	15.82	6.42	7.07	8.71	1.90	0.58	1.61	3.33	6.26	5.30	10.29
1999	8.16	12.14	11.61	10.87	5.36	1.63	1.07	0.45	1.97	2.58	7.63	10.48
2000	5.52	8.79	6.39	6.13	2.84	0.97	0.23	0.03	1.27	3.52	4.10	8.68
2001	11.90	6.43	6.97	7.27	3.39	2.70	2.52	2.42	4.67	2.10	2.63	4.13
2002	5.71	4.36	4.00	7.23	3.13	1.37	2.90	1.55	2.77	3.42	8.33	7.94
2003	21.94	13.04	7.55	5.13	1.87	1.33	2.71	1.13	1.47	6.13	3.70	8.74
2004	9.10	10.83	9.65	9.73	10.39	3.93	1.23	1.00	2.13	2.61	6.23	9.26
2005	9.52	13.71	10.29	11.07	6.26	3.63	1.55	1.81	3.43	2.84	6.53	15.55

2006	14.35	13.86	12.65	9.57	4.84	3.13	3.13	2.36	2.67	2.23	2.03	5.87
2007	6.10	7.75	15.06	9.87	4.16	2.83	0.55	0.55	1.13	3.00	5.00	10.00

Equations (4) and (5) were applied to both the observed and computed datasets for the same period, 2001–2007, obtaining values of 0.26 and 0.35 for ERMS and EMA, respectively, allowing us to consider the two datasets as strictly congruent. Moreover, Figure 7 shows the comparison between the computed and observed "unaltered" average monthly discharge at the upstream Pertusillo Lake cross-section, presenting a light overestimation with a very good correlation (R^2 = 0.9836). Thus, the reconstructed dataset obtained through the HEC-HMS modeling can be used as available data for the further analyses related to the IHA application and the IARI assessment. Furthermore, in order to better validate the HEC-HMS numerical results with respect to the observed data, statistical analysis of both datasets was carried out.

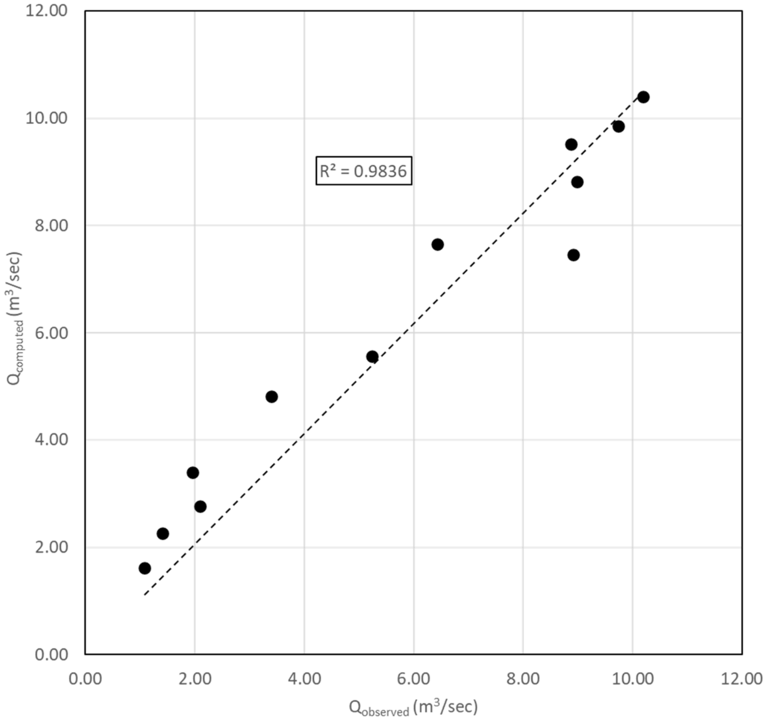


Figure 7. Computed versus observed average monthly water discharge at the Pertusillo Lake cross-section.

Moreover, Tables 5 and 6 report the computed and observed flow components in terms of annual and monthly average discharges and the related 25th and 75th percentiles, evaluated at the Pertusillo Lake cross-section, as well as the monthly distribution of the 20th percentile, here assumed to be the monthly Eflow. The corresponding values of the IARI are 0.12 and 0.05 for the computed and observed values of Eflow, respectively, both falling into the class of the "good" level.

Table 5. Computed flow components and IARI for the control cross-section of Pertusillo Lake: average annual discharge, average monthly discharge, 20th percentile of updated hydrological Eflow, 25th and 75th percentiles of monthly discharge, and IARI values for updated Eflow conditions (20th percentile).

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Average Annual Discharge (m^3/s)											
6.18	6.18	6.18	6.18	6.18	6.18	6.18	6.18	6.18	6.18	6.18	6.18
Average Monthly Discharge (m^3/s)											
9.52	10.40	8.82	7.46	5.56	2.77	2.25	1.62	3.40	4.82	7.65	9.86
25th Percentile (m3/s)											
6.25	6.59	6.65	5.19	4.22	2.42	2.12	0.74	2.57	4.65	6.39	8.32
75th Percentile (m^3/s)											
11.52	14.23	10.61	8.35	6.34	3.26	2.62	2.68	3.96	5.53	8.67	11.29
20th Percentile—Hydrological Eflow (m^3/s)											
6.16	6.36	6.08	4.95	4.15	2.19	2.03	0.67	2.51	4.42	5.91	7.83
pj,k-20th Percentile											
0.02	0.03	0.14	0.08	0.03	0.27	0.19	0.04	0.05	0.25	0.21	0.16
IARI 0.12											

Table 6. Observed flow components and IARI for the control cross-section of Pertusillo Lake: average annual discharge, average monthly discharge, 20th percentile of updated hydrological Eflow, 25th and 75th percentiles of monthly discharge, and IARI values for updated Eflow conditions (20th percentile).

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Average Observed Annual Discharge (m^3/s)											
5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69
Average Observed Monthly Discharge (m^3/s)											
8.87	10.19	8.99	8.92	5.24	2.10	1.41	1.08	1.96	3.40	6.43	9.73
Observed 25th Percentile (m^3/s)											
6.10	6.43	6.42	6.17	3.55	1.40	1.00	0.55	1.13	2.36	4.00	7.23
Observed 75th Percentile (m^3/s)											
11.35	13.71	11.65	10.87	7.16	2.73	1.77	1.55	2.67	3.52	7.43	10.48
Observed 20th Percentile—Hydrological Eflow (m^3/s)											
5.71	5.89	6.39	6.13	3.39	1.37	0.58	0.45	1.13	2.26	3.70	5.87
pj,k-20th Percentile											
0.04	0.00	0.05	0.02	0.09	0.01	0.13	0.00	0.00	0.00	0.00	0.25
IARI 0.05											

Furthermore, Figures 8 and 9 present such distribution of the main environmental flow components (average annual discharge, average monthly discharge, 20th, 25th, and 75th percentiles) for both computed and observed data, and the relative variability during the year. These plots outline how the generic assumption of Eflow as a constant value equal to a defined percentage of the average annual discharge (e.g., 20% of the average annual discharge) generates a relevant penalization on the natural river conditions, causing an overexploitation of water resources throughout the year, except for the summer season. In other words, the assumption of Eflow as a constant percentage of the average annual flow does not consider the natural variability of the river flow, which provides different flow components, in order to obtain the best condition for freshwater ecosystems, habitats, and wetland species.

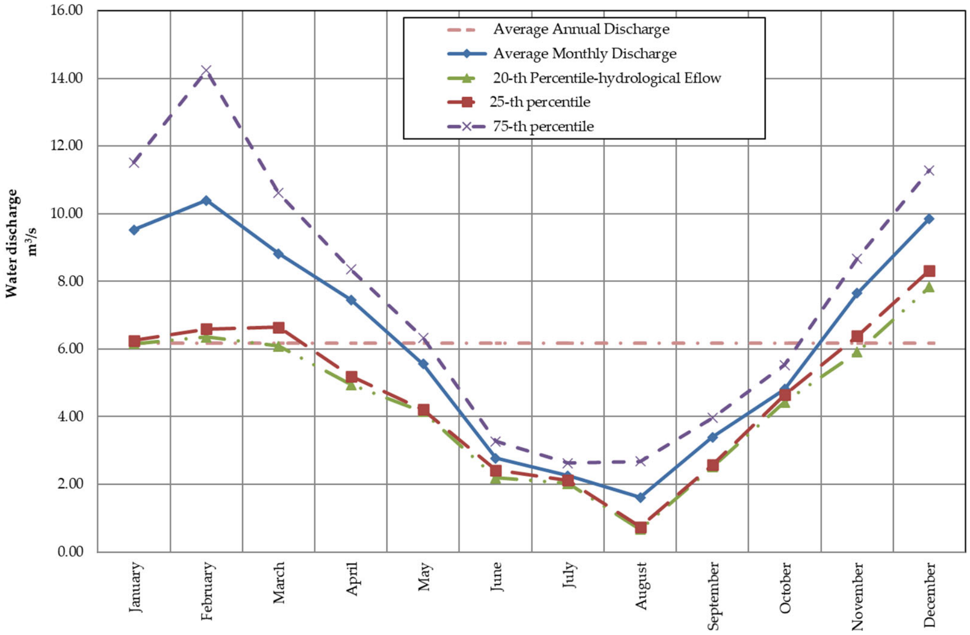


Figure 8. Computed flow rate components for the control cross-section of Pertusillo Lake.

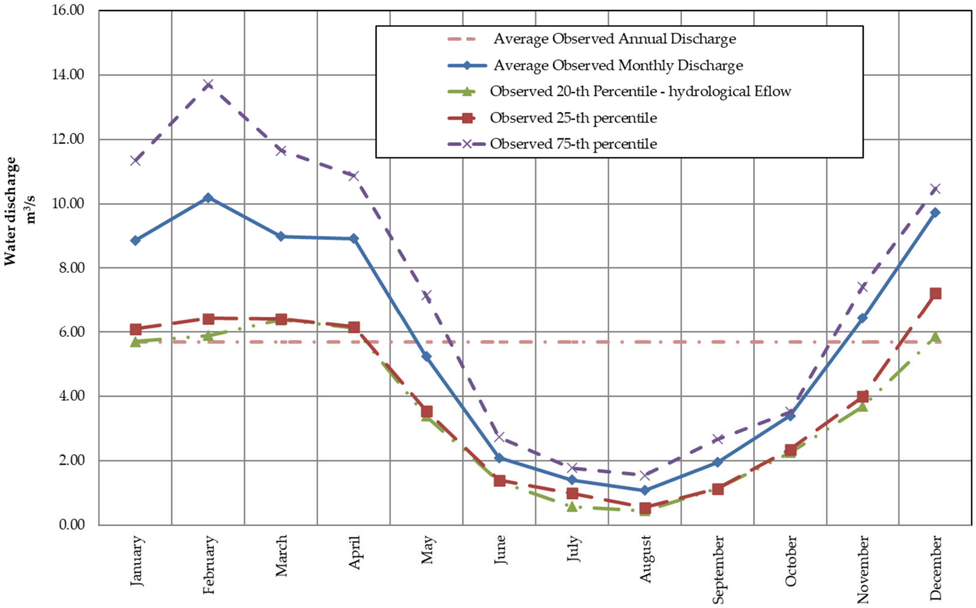


Figure 9. Observed flow rate components for the control cross-section of Pertusillo Lake.

Furthermore, Figure 10 shows the monthly distribution of the observed and computed flow rates at the upstream Pertusillo Lake control cross-section, outlining a general good response of the proposed modeling versus the real data, but, at the same time, proposes the main deviation between the two datasets. The computed monthly distributions, for both average discharge and Eflow, fit the observed values very well during the winter, spring, and, partly, in summer, while the autumnal season shows a relatively high deviation between the computed and observed values. Such a difference might be attributable to the necessity of a better calibration of the infiltration rate and aquifer recharge rate, which require further on-site data and measurement. Nevertheless, the global response of the proposed methodology still remains positive and generally conservative with respect to the water resource protection and the possible hydrological alteration induced in the river system and ecosystem.

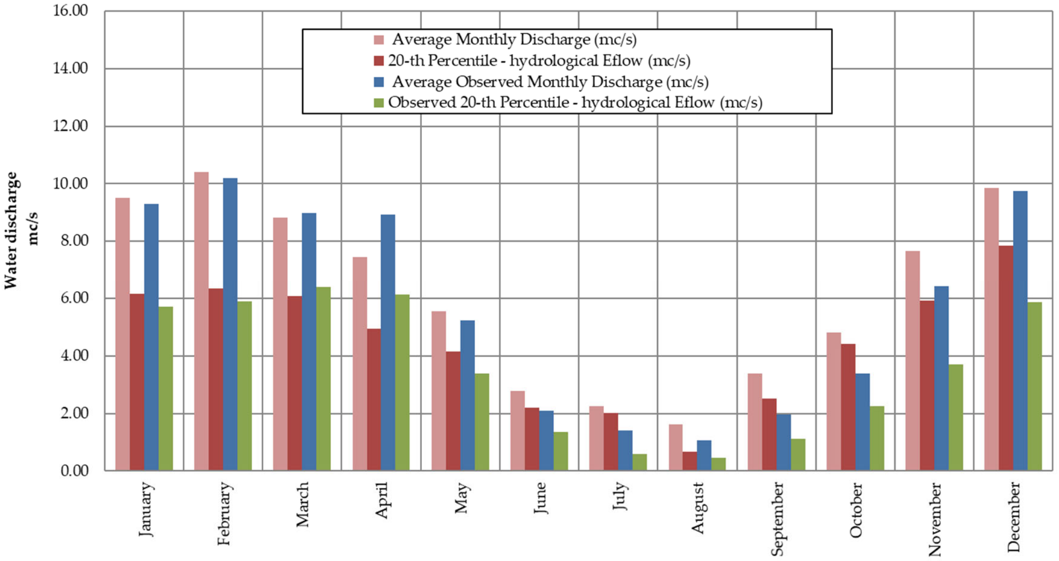


Figure 10. Monthly distribution of the observed and computed flow rates at the Pertusillo Lake control cross-section.

Finally, for the Agri River, the value of the hydrological Eflow corresponding to the 20th percentile of the time series distribution of the monthly discharge provides the real meaning of ecological flow, taking into account the seasonal variability of the water discharge and generating an environmentally sustainable response of the watercourse.

The difference between the average monthly discharge and Eflow represents the volume of the surface water resources to be managed for a sustainable exploitation of the watercourse without generating critical environmental conditions for ecosystems and human beings.

Moreover, the proposed procedure also allows us to perform a periodic upgrading of the Eflow relating to the catchment hydrological variability induced by anthropogenic activities as well as that imposed by local climate change conditions.

4. Conclusions

The aim of this study was to propose a hydrologically based methodology to define ecological flow based on the application of the Indicators of Hydrologic Alteration methodology (IHA by TNC) coupled with the valuation of the Index of Hydrological Regime Alteration (IARI by ISPRA).

The proposed methodology considers the maintenance of the environmental flow components' variability as a relevant and essential condition to cope with the impacts induced in the river system by anthropogenic water discharge alteration. It does not represent a limitation of the water resources, but rather the valorization and enhancement of the river environmental heritage.

The approach deals with the application of cascade models starting from a classical rainfall–runoff model, such as the HEC-Hydrological Modeling System (HEC-HMS), for the assessment of the daily/monthly water discharge flowing in a generic control cross-section along the water body, feeding the IHA. Then, the methodology defines ecological flow as the *i*th percentile of the distribution of the average monthly flows, which provides a value of the IARI corresponding to a "good" level at least. That is, the IARI should not be used as the measure of the anthropogenic impact on the watercourse, but to represent the triggering value enabling the assessment of the sustainable monthly flow rate below which the riverine ecosystem and human beings' livelihoods come under critical environmental threat.

Moreover, the methodology copes with the objective gap in detailed observed flow rate data using robust advanced hydrological modeling for generating water discharge time series, through which the watercourse environmental flow components are computed. The procedure was carried out based on monthly discharge data derived by applying the HEC-Hydrological Modeling System at the basin scale of the Agri River, using the daily rain data measurements obtained by the regional rainfall gauge stations and calibrated through the observed inlet water discharge registered at the Lago del Pertusillo reservoir station.

Finally, the 20th percentile of the monthly water discharge distribution fits the results well, and the corresponding values of discharge were assumed as the monthly Eflow.

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