


# Monthly Hydrological Indicators to Assess Possible Alterations on Rivers' Flow Regime

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**Abstract** Assessing potential deviations of the fundamental river basins' hydrological processes and streamflow characteristics from the “natural trajectory” represents a high-priority objective to understand the biological impact of altered flow regime on river ecosystems. Existing approaches are mainly based on the analysis of daily-based indicators of hydrologic alteration, which requires wide database, including “pre-impact” and “post-impact” daily flow data frequently unavailable. The hydrological modeling is commonly used to face data missing problems or reconstruct natural conditions, even if models, especially at the daily scales, are often complex and computationally intensive. The use of simpler and more parsimonious models results, sometimes, essential for practical applications, also in consideration of the typical scarce availability of some data. This paper proposes an alternative approach for the evaluation of rivers flow regime alterations, based on different monthly hydrological indicators that are first computed and then combined to provide a global index of alteration. The procedure, conceptually derived from the Range of Variability Approach (RVA), is applied

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and tested on two Sicilian river basins (Italy) subject to anthropogenic influence. Streamflow regime for both the basins results differently disturbed by upstream human pressures. An alteration index is computed using available observations as “post-impact” monthly flow time-series, while time-series relative to “pre-impact” conditions have been reconstructed by the Tri.Mo.Ti.S. model, an innovative monthly and high-performing regional regressive hydrological model. The methodology, easily transferable to other regions, has revealed particularly efficacious in identifying and quantifying the existing human pressures and can be considered as a suitable tool for water resource management and policy planning activities.

**Keywords** Hydrological change · Dam impacts · Flow regime alteration · Hydrological indicators · IARI · IHA

## 1 Introduction

Ecosystem services, i.e. benefits and services that human population receive from ecosystems (e.g., climate regulation, flood protection, air and water purification, erosion and nutrient regulation, etc.) are widely recognized to be essential elements of community well-being (e.g. Almagir et al. 2016). The health status of a river and its ability to provide ecosystems services depend on several physical and ecological factors, among which streamflow probably has the main influence (e.g., Bunn and Arthington 2002). The hydrological regime is, in fact, the main driving force of river ecosystems, shaping many of their fundamental ecological characteristics and controlling all the physical habitat and biotic interactions. It is widely recognized that all the characteristics of the flow regime, including magnitude of discharge, frequency, duration, timing and rate of change, are crucial in determining the ecological integrity and stability of riverine ecosystems (e.g. Yang et al. 2012).

The growing anthropization of natural environments and the widespread development of hydraulic infrastructures for water resource exploitation and streamflow regulation at different scopes, as well as the human induced modifications on land use and climate, are deeply modifying rivers' streamflow regime in many regions of the Earth with heavy fallouts on the underlying ecosystems (Viola et al. 2016). There is, then, an increasing and urgent need of developing new tools for identify and quantify human induced alterations on flow regimes and understand the biological impact of such modifications on river ecosystems in order to restore the natural status, define new efficacious eco-hydrological targets and enhance the management of the existing hydraulic infrastructures and the planning of new ones.

This pressing need is also confirmed by the growing interest of the socio-political sector on this thematic, with the issuing of public policies accounting for the hydrological regime as health descriptor of water bodies. For instance, the Water Framework Directive (WFD) 2000/60/CE (EC 2000) defines quality elements that must be used for the assessment of ecological status/potential of water bodies, including some hydro-morphological aspects. The hydrological regime is explicitly recognized (Annex V, WFD) as part of the hydro-morphological quality elements.

Recent years have been witnessing an increasing development of different methodologies for the evaluation of changes in the hydrological regime of river basins due to human pressures and/or climate changes (e.g. Gao et al. 2009; Pekárová et al. 2016). A general approach consists in: (i) a preliminary selection of some hydrological descriptors, which may directly or indirectly describe the status of river ecosystems and their biological communities; (ii) the

evaluation/estimation of the current values for the selected metrics; (iii) the evaluation/estimation of the hydrological descriptors under a baseline condition that can be considered as “un-impacted” or “natural”; (iv) the comparison between the current and the natural values of the selected indicators. The quantitative analysis of the degree of alteration is usually based on opportunely defined “global” indices, which should be capable of measuring the overall divergence of the current flow regime from the baseline through the comparison of the selected hydrological descriptors.

Several hydrological indices have been developed in literature and applied to synthesize the different characteristics of the rivers’ flow regime (Poff et al. 1997). The most commonly used alteration metrics probably are the Nature Conservancy’s Indicators of Hydrological Alteration (IHA) used for the Range of Variability Approach (RVA), a methodology proposed by Richter et al. (1996, 1997) that considers a full range of flow regime properties, with 33 different indicators categorized into five groups of hydrological features. Zuo and Liang (2016), for instance, studied the effects of several dams on the flow regime of the Shaying River (China), starting from daily flow records, dividing the time-series in two subsets (pre-impact and post-impact period) and evaluating the IHA/RVA indicators.

This method has gained considerable prominence not only in the theoretical research field but also in practical applications and European policy. For instance, the Italian Decree 260/2010 (D.M. Ambiente n.260, 2010; Annex 1; Tab. 4.1.2/a) adopts technical criteria, based on IHA indicators, to classify the hydrological and morphological conditions of rivers and evaluate potential alterations in the flow regime of rivers, in order to fulfill the requirements of the WFD 2000/60/CE. The hydrological status is defined through an index of hydrological alteration, IARI (*Indice di Alterazione del Regime Idrologico*; i.e. *Index of Hydrological Regime Alteration*), computed by the ISPRA (*Istituto Superiore per la Protezione e la Ricerca Ambientale*; i.e. the Italian governmental authority *Higher Institute for Environmental Protection and Research*) multi-step procedure (ISPRA 2011), and classified according three possible classes: high ( $0 \leq \text{IARI} \leq 0.05$ ) or unaltered status; good status ( $0.05 < \text{IARI} \leq 0.15$ ); critical status ( $\text{IARI} > 0.15$ ).

Other similar approaches, alternative to the IHA/RVA, have been developed in recent years, such as: (i) the IAHRS (*Indices de Alteracion Hidrologica en RioS*; i.e. *Indicators of Hydrologic Alteration in Rivers*) method by Martínez Santa-María and Fernández Yuste (2008), with 21 indices of alterations that are categorized into three groups (ordinary, flood and drought flow indicators) and combined to provide three Global Alteration Indices (IAG), and (ii) the HIT (*Hydrological Index Tool*) method by Henriksen et al. (2006), based on a very large number of statistical hydrological indices.

All the aforementioned approaches require the consideration of sufficiently long and high temporal resolution (e.g. daily) flow datasets, representative of the historical “natural” (pre-impact or undisturbed) and the current (potentially impacted) regime.

The ISPRA procedure, for instance, distinguishes between cases with sufficient flow data availability (not less than 5 years for recent observations and 20 years for historical observations), and cases with insufficient historical and/or recent daily data; only for the first case the IARI global index can be computed directly from the observed data without resorting to a hydrological modelling.

Despite a considerable development of new and promising monitoring techniques (Lo Conti et al. 2015; Pumo et al. 2016a), most of the rivers are not gauged and/or do not have sufficient long periods of record, especially with regard to the availability of data under pristine conditions. In many practical cases, the only possible way to assess potential alterations

in the flow regime of river ecosystems is to use appropriate hydrological models to generate “un-impacted” and/or “impacted” scenarios. Only in some rare cases, natural flow data could be directly reconstructed starting from “disturbed” observations, if other information are available; for example, for a river section with an upstream presence of an artificial reservoir, where only “post-impact” data are available, natural flow values could be derived by a simple water balance equation, if the water volumes interested by the reservoir operations are known.

A variety of hydrological models could be used to generate long flow data time-series from which the desired flow regime indicators can be inferred; some examples are the ModAba (Pumo et al. 2014), the HBV (Bergström 1995), the SAC-SMA (Burnash 1995) and the TOPDM (Noto 2014). In De Girolamo et al. (2015), for instance, following the ISPRA procedure, the IARI was computed on the basis of daily time-series of natural streamflow simulated by the SWAT model (Arnold et al. 1998; Srinivasan et al. 1998).

The use of complex models in the majority of real cases is hampered by serious difficulties in retrieving all the ancillary information and model input necessary for model calibration, setting and running (Viola et al. 2017). The reduction of modelling complexity and the use of more parsimonious models are often essential to make theoretical approaches suitable for practical applications.

The adoption of coarser time-scales (e.g., monthly) for the hydrological indicators allows for using simpler models, which usually warrant a good ease of use, suitability and transferability associated to a relevant accuracy. The same ISPRA procedure, for the most common case of insufficient data availability, requires to reconstruct/estimate natural flow series at the monthly time-scale and derives the IARI only on the basis of a limited set of monthly hydrological indicators. Laizé et al. (2014) used the WaterGAP model (Alcamo et al. 2003) and evaluated alterations through monthly flow regime indicators derived from the IHA/RVA approach.

This paper tracks a possible way to ameliorate the ISPRA procedure for assessing the global index of hydrological regime alteration under the widespread situation of insufficient data availability. The main aim of this paper is to explore a possible alternative to the use of a limited set of IHA for all those cases in which current and/or un-impacted flow data availability is null or insufficient in size, or where data are available only at the monthly time-scale. A further aim of the paper is to highlight some advantages related to the use of monthly hydrological statistics to assess flow regime alteration indicators, that represents the main novelty of the proposed approach and that, on the one hand, allows for an enlargement of the range of possible applications on real cases and, on the other hand, warrants the possibility to use simpler and more parsimonious models for the generation of synthetic un-impacted and/or impacted flow scenarios. This last aspect could be extremely useful in preparing the way for massive extensive evaluations of the ecological status of rivers at regional, national or continental level.

These aims are here achieved through the following specific objectives: (1) identification of the monthly flow statistics and descriptors that better synthesize all the flow regime characteristics; (2) definition of a global index of flow regime alteration; (3) selection of a hydrological model able to emphasize the advantages related to the proposed approach; (4) application and test on real cases.

For the first objective, an approach similar to that used in Laizé et al. (2014) has been followed in the attempt to reshape the set of IHA from the daily to the monthly scale, taking into account the redundancy of some variables, the impossibility of a temporal up-scaling of some daily variables and the scarce meaningful of some variables when up-scaled at the

monthly scale. For the second objective, the same approach of the ISPRA procedure has been adopted, extending the IARI definition in order to include all the monthly hydrological indicators previously identified. The third objective has been achieved by selecting the Tri.Mo.Ti.S. model (Pumo et al. 2016b, 2017), a recent and very simple regional regressive model for the reconstruction of monthly time series of several hydro-climatic variables, among which also the natural streamflow. Finally, the entire modelling chain has been tested on two case studies in Sicily (Italy), where possible sources of disturbance for river flow are present, evaluating potential flow regime alterations at different sections of the river network also through the comparison with unaltered natural conditions in terms of flow duration curves (FDCs).

## 2 Materials and Methods

### 2.1 Monthly Indicators of Hydrological Alteration

Similarly to the IHA-RVA method (Richter et al. 1996, 1997), the general approach for the evaluation of potential changes in the hydrological regime is here based on a multi-step procedure: (i) defining the data series for pre-impact and post-impact periods; (ii) calculating intra-annual values of all the previously identified hydrological attributes for each year of the natural and the post-impact period; (iii) computing interannual statistics (measures of central tendency and dispersion) for the hydrological attributes of the natural and the post-impact periods; (iv) measuring the distance of the interannual statistics of the post-impact periods from a previously defined target range based on the interannual statistics of the natural period (i.e. indices of hydrological alteration); (v) computing a global index of hydrological alteration that synthesizes the information arising from the different indices computed at the previous step.

Except for the last step, the entire chain essentially coincides with those relative to the IHA-RVA, while the adopted hydrological attributes are different in number and they are provided only at monthly scale (Table 1). The considered interannual statistics are alternatively median or mode for the post-impact period while the IQR (interquartile range) of the hydrological attributes for the pre-impact period defines the target ranges for natural conditions. An approach basically analogue to the IARI computation procedure (ISPRA 2011) is used for the last two steps. In particular, the generic  $k$ -th indicator of hydrological alteration,  $p_{i,k}$  (with  $k$  from 1 to  $N$ ,  $N = 22$ ) belonging to the generic  $i$ -th statistics group (with  $i$  from 1 to 5) and related to the generic monthly hydrological attribute  $X_{i,k}$  is obtained as:

$$p_{i,k} = \begin{cases} 0 & , \quad XN_{25,i,k} \leq XP_{i,k} \leq XN_{75,i,k} \\ \min \left( \left| \frac{XP_{i,k} - XN_{25,i,k}}{XN_{75,i,k} - XN_{25,i,k}} \right|, \left| \frac{XP_{i,k} - XN_{75,i,k}}{XN_{75,i,k} - XN_{25,i,k}} \right| \right) & , \quad otherwise \end{cases} \quad (1)$$

where  $XN_{25,i,k}$  and  $XN_{75,i,k}$  are the percentiles (25th and 75th, respectively) of  $X_{i,k}$  computed over the natural (pre-impact) time-series, while  $XP_{i,k}$  is the mean, median or mode (depending on the hydrological attributes) of  $X_{i,k}$  computed over the post-impact time-series.

Once an indicator of hydrological alteration is computed for each hydrological attribute, a partial index for each group, named MI-HRA<sub>i</sub> (*Monthly Index of Hydrological Regime*

**Table 1** Statistical groups and associated regime characteristics, indicators, hydrological attributes, analogue IHA, pre-impact (Pre) and post-impact (post) variables statistics. The values of  $w_i$ ,  $F_i$  and  $L_i$  of eqs. (2) and (3) for each statistical group are also indicated

Group	Monthly Index [ $w_i$ , $F_i$ , $L_i$ ]	Regime characteristics	Indicator	Intra-annual Hydrological Attributes	Analogue IHA var.				
					Pre	Post			
Group 1: Magnitude of monthly water conditions <b>MI-HRA1</b> [ $w_1=12; F_1=1; L_1=12$ ]		Magnitude; Timing	$p1,1$	January - MMS	January - MMS	IQR median			
			$p1,2$	February - MMS	February - MMS	IQR median			
			$p1,3$	March - MMS	March - MMS	IQR median			
			$p1,4$	April - MMS	April - MMS	IQR median			
			$p1,5$	May - MMS	May - MMS	IQR median			
			$p1,6$	June - MMS	June - MMS	IQR median			
			$p1,7$	July - MMS	July - MMS	IQR median			
			$p1,8$	August - MMS	August - MMS	IQR median			
			$p1,9$	September - MMS	September - MMS	IQR median			
			$p1,10$	October - MMS	October - MMS	IQR median			
			$p1,11$	November - MMS	November - MMS	IQR median			
			$p1,12$	December - MMS	December - MMS	IQR median			
			$p2,13$	Ann. min 3-month flow	Ann. min 90-day means	IQR median			
			$p2,14$	Ann. min 6-month flow	n/a	IQR median			
			$p2,15$	Ann. max 3-month flow	Ann. max 90-day means	IQR median			
			$p2,16$	Ann. max 6-month flow	n/a	IQR median			
			Group 2: Magnitude and Duration of annual extremes of seasonal conditions <b>MI-HRA2</b> [ $w_2=4; F_2=13; L_2=16$ ]		Magnitude; Duration	$p3,17$	Month of maximum flow from 1 (May) to 12 (Apr)	J.date of 1-day ann. max	IQR mode
$p3,18$	Month of minimum flow from 1 (May) to 12 (Apr)	date of 1-day ann. min				IQR mode			
$p4,19$	Yearly number of monthly low pulses < 90th perc. nat. series	Daily low pulse count				IQR median			
$p4,20$	Yearly number of monthly high pulses > 10th perc. nat. series	Daily high pulse count				IQR median			
$p5,21$	Median of positive differences between consecutive MMS	Median of positive differences between consec. daily means				IQR median			
$p5,22$	Median of all negative differences between consecutive MMS	Median of all negative differences between consec. daily means				IQR median			
Group 3: Timing of annual extreme water conditions <b>MI-HRA3</b> [ $w_3=2; F_3=17; L_3=18$ ]		Timing							
Group 4: Frequency of high and low pulses <b>MI-HRA4</b> [ $w_4=2; F_4=19; L_4=20$ ]		Magnitude; Frequency							
Group 5: Rate and Frequency of change in water conditions <b>MI-HRA5</b> [ $w_5=2; F_5=21; L_5=22$ ]		Frequency; Rate of change							

IQR interquartile range; MMS Mean Monthly Streamflow; Ann. min and Ann. max are the annual minima and maxima, respectively; J.date Julian date

Alteration for the  $i$ -th group) is computed averaging all the indicators of hydrological alteration belonging to the same group ( $i$  from 1 to 5):

$$MI-HRA_i = \sum_{k=F}^{L_i} \frac{P_{i,k}}{w_i} \tag{2}$$

where  $F_i$ ,  $L_i$  and  $w_i$  are, respectively, the first, the last and the total number of indicators ( $p_{i,k}$ ) belonging to the  $i$ -th statistics group (with  $i$  from 1 to 5, see Table 1). Each index, then, is descriptive of potential alterations in different characteristics of the hydrological regime (Table 1); for example  $MI-HRA_1$  describes changes in the magnitude of monthly water conditions while  $MI-HRA_2$  describes changes in the magnitude and duration of extreme seasonal water conditions.

Finally, a global index, GMI-HRA (*Global Monthly Index of Hydrological Regime Alteration*), is computed following an approach analogue to that used for the assessment of the IARI under sufficient data availability (ISPRA 2011):

$$GMI-HRA = \sum_{\substack{1 \leq i \leq 5 \\ 1 \leq k \leq N}} \frac{P_{i,k}}{N} = \sum_{i=1}^5 \frac{w_i \cdot MI-HRA_i}{N} \tag{3}$$

where symbols are the same used for Eqs. (1) and (2).

In Table 1, all the 22 selected monthly hydrological attributes and the corresponding indicators of hydrological alterations used in the proposed methodology are summarized together with indications about the group and the analogue IHA variables. As it can be noticed, some of the IHA variables cannot be computed at the monthly scale (e.g. annual minima/maxima 1-,3-,7-day means, etc.) and have been excluded, while, except for the the group 1 variables (that are the same considered in the IHA group), all the other hydrological attributes have been adapted to be suitable through a monthly-based method.

The proposed methodology includes eight of the nine MFRI indicators considered in Laizé et al. (2014), neglecting only the variable related to low flows and based on the number of sequences at least 2-month long below threshold (95th-percentile of the natural series).

Basically, the procedure here presented represents an extension of the methodology by ISPRA (2011) for the computation of the IARI under the widespread condition of insufficient data availability (De Girolamo et al. 2015). The IARI under such conditions is, in fact, equivalent to the  $MI-HRA_1$ , while the other partial indices, which are computed with the here proposed method (i.e.,  $MI-HRA_i$ , for  $i$  from 2 to 5), provide further useful information about possible alterations in other characteristics of the hydrological regime (see Table 1).

The global index GMI-HRA embeds several additional information (e.g., on the magnitude, duration, timing and frequency of extreme water conditions and low/high pulses) that can be inferred from monthly flow time-series and that are neglected in the IARI formulation under “insufficient data availability” condition.

## 2.2 Natural Streamflow Reconstruction by Tri.Mo.Ti.S.

A hydrological model is used in the real cases application of the proposed methodology, for estimating flow time-series representative of pristine conditions. The selected model is the Tri.Mo.Ti.S. (*Trinacria model for Monthly Time-Series*), an information model implemented as a plug-in within the open source GIS software Quantum GIS 2.14 (Pumo et al. 2017) and aimed to the assessment of monthly time-series for several hydro-climatic variables (i.e., precipitation, temperature, natural runoff, potential and actual evapotranspiration and soil

moisture storage). Only a brief description of the model, with emphasis on the specific module for runoff time-series reconstruction, is reported below, while interested readers are referred to the original papers (Pumo et al. 2016b, 2017) for a more detailed discussion.

The plug-in can be used within an entire region and it is supported by a preliminarily developed spatial data warehouse which is derived from a wide database of hydro-climatic data series and some regional information layers. The Tri.Mo.Ti.S., originally designed for the Sicily region (Italy) but easily transferable to other regions, includes automatic procedures for basin delimitation and data retrieving and processing; more specifically, once the desired basin outlet section and time-window are selected, the model uses appropriate spatial techniques and algorithms to identify the basin drainage area and estimate the corresponding mean areal rainfall and temperature series. A recent regional regressive rainfall-runoff model, briefly described below, is successively applied for the assessment of the runoff series. Finally, monthly potential and actual evapotranspiration series, as well as the soil moisture storage series are estimated through other specific model' sub-modules, based on water balance models and opportunely implemented within the same plug-in.

The rainfall-runoff model in Tri.Mo.Ti.S. is based on the following regression-based equation:

$$\begin{cases} Q_y(t) = a_{1,y} \cdot P_y(t)^{a_{2,y}} \cdot T_y(t)^{a_{3,y}} Q_y(t-1)^{a_{4,y}} & \text{if } Q_y(t-1) > 0 \\ Q_y(t) = a_{1,y} \cdot P_y(t)^{a_{2,y}} \cdot T_y(t)^{a_{3,y}} & \text{if } Q_y(t-1) = 0 \end{cases} \quad (4)$$

where  $y$  refers to the analyzed basin,  $Q_y(t)$  and  $Q_y(t-1)$  are the monthly runoff values (mm) at the month  $t$  and  $t-1$ , respectively,  $P_y(t)$  and  $T_y(t)$  are the mean monthly precipitation (mm) and temperature (°C), respectively, for the  $t$ -th month.

The four site-specific model parameters  $a_{i,y}$  ( $i = 1, 2, 3, 4$ ) of Eq. (3) can be computed as function of four basin attributes ( $MAP_y =$  mean annual precipitation,  $p_y =$  seasonal precipitation index,  $H_y =$  mean basin altitude;  $CN_y =$  mean areal Curve Number) through the following regional relationships, derived for three homogeneous sub-zones within the Sicilian region (i.e. sub-zone A, B and C):

$$\begin{cases} a_{1,y} = b_{1,1,Z} \\ a_{2,y} = b_{2,1,Z} + b_{2,2,Z} \cdot MAP_y + b_{2,3,Z} \cdot p_y + b_{2,4,Z} \cdot H_y + b_{2,5,Z} \cdot CN_y \\ a_{3,y} = b_{3,1,Z} + b_{3,3,Z} \cdot MAP_y + b_{3,3,Z} \cdot p_y + b_{3,5,Z} \cdot H_y + b_{3,5,Z} \cdot CN_y \\ a_{4,y} = b_{4,1,Z} + b_{4,2,Z} \cdot A_y + b_{4,3,Z} \cdot z_y + b_{4,4,Z} \cdot H_y + b_{4,5,Z} \cdot CN_y \end{cases} \quad (5)$$

with the symbol  $Z$  referring to the sub-zone ( $Z = A, B$  or  $C$ ) of the  $y$ -th basin, while  $b_{i,j,Z}$  (with  $i = 1,2,3,4$ ;  $j = 1,2,3,4,5$ ) are 16 regional regression parameters estimated for each Sub-Zone with the least squares method.

An appreciable accuracy can be ascribed to theoretical reconstruction of runoff time-series, as demonstrated by the performances, in terms of Nash-Sutcliffe Efficiency –  $NSE$  (Nash and Sutcliffe 1970), measured over the entire Sicily region from the comparison with observations (the  $NSE$  computed over 53 calibration basins and 6 validation basins was, on average, about 0.70, with a maximum of 0.90 and only two cases with  $NSE$  below 0.5; Pumo et al. 2016b).

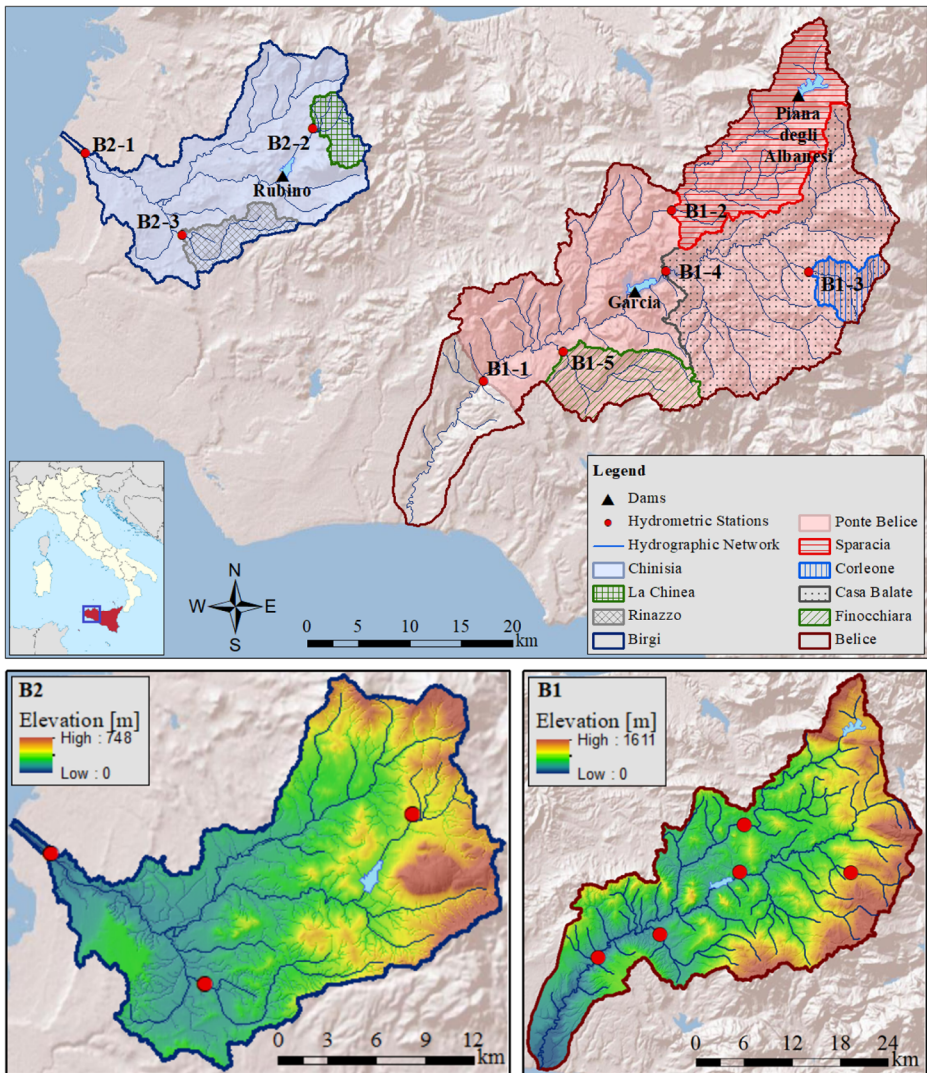
### 2.3 Case Studies

The case studies have been selected within the Sicily (Italy), since the Tri.Mo.Ti.S. has been already calibrated and validated for this region (Pumo et al. 2017). It is worth emphasizing that



the spatial data warehouse of Tri.Mo.Ti.S. is based on a regional database, constituted by long historical runoff, rainfall and temperature time-series collected by the OA-ARRA (*Osservatorio delle Acque - Agenzia Regionale per i Rifiuti e le Acque*; i.e. *Water Observatory - Regional Agency for Waste and Water*) from 1916 to 2013, a 100 m DEM (*Digital Elevation Model*) of the region and the spatial layer of CN, i.e. the Curve Number parameter for the Soil Conservation Service Runoff *Curve Number method* (USDA-SCS 1993).

The selected case studies, depicted in Fig. 1, are the *Belice river basin* and the *Birgi river basin*. Hereafter we will refer to the *Belice river basin* as B1 (Basin 1) and to the *Birgi river basin* as B2 (Basin 2).



**Fig. 1.** *Belice river basin* (B1) and *Birgi river basin* (B2) with indication of the main river network, the dams and the OA-ARRA hydrometric stations with corresponding nested sub-basin analyzed in this study. In the bottom graphs, the DEM for the two basins

The first basin has an extension of about 955 km<sup>2</sup> and the main stream has a length of 107 km. The river network is constituted by two main streams (i.e., the *Fiume Belice Destro* and the *Fiume Belice Sinistro*) and different minor tributaries (i.e., *Torrente Senore*, *Torrente Batticano*, *Torrente Realbate*) which are classified as “not a risk” for potential hydrological alteration, according to the classification of the second Commission’s Assessment of the Italian River Basin Management Plans (2nd Italian RBMPs for the period 2016–2021 following the WFD 2000/60/EC). Other main streams of the basin river network are influenced by the presence of two artificial reservoirs: *Piana degli Albanesi* (functions: power generation, irrigation and water supply; construction duration: from 1921 to 1923) and *Garcia* (functions: irrigation and water supply; construction duration: from 1977 to 1985). An important diversion dam (i.e., weir *Perciata*) is also present at a section of the *Fiume Belice Destro*, and it transfers part of streamflow (arising from a drainage area of about 72.3 km<sup>2</sup>) toward a reservoir (i.e., *Poma* dam) of a neighboring basin (i.e., *Jato river basin*); this diversion dam and its effects are however neglected here, since it was built only after the period considered for the analyses carried out in the present study. A further water input (on average 1 million of m<sup>3</sup> per year) to the natural streamflow is also provided by 13 civil wastewater treatment effluents, 5 of which along the stream *Fiume Belice Sinistro* carrying about the half of the total contribution. Five different OA-ARRA hydrometric stations are present within the basin, as depicted in Fig. 1, and they have collected data during the time periods reported in Table 2.

The *Birgi river basin* has an extension of about 330 km<sup>2</sup> and its main stream length is about 38 km. It is fed by the following tributaries: *Torrente Chitarra* and *Torrente Cuddia* which includes three minor streams: *Fiume Bordino*, *Fiume Cuddia* and *Torrente Fastaia*. The last two are disconnected by the artificial reservoir *Rubino* (function: irrigation; construction duration: from 1967 to 1970). Although only one civil wastewater treatment effluent is present

**Table 2** River sections (with information about the corresponding hydrometric station and indication of the here associated ID code) and data availability periods (size refers to the actual number of complete years of observation)

Basin	Hydrometric station		Observation period			Sect. ID	Class	Upstream dam Other sources of disturbance
	Station name	Watershed	from	to	size (yr)			
B1 Belice	Ponte Belice	Belice	1955	1976	20	B1–1a	CD	Piana degli Albanesi - WTE
	Ponte Belice	Belice	1986	1994	3	B1–1b	CD	Piana degli Albanesi - Garcia - WTE
	Sparacia	Belice Destro	1955	1987	33	B1–2	CD	Piana degli Albanesi - WTE
	Piano Scala	Corleone	1958	1963	6	B1–3	PD	WTE
	Case Balate	Belice	1955	1980	26	B1–4	PD	WTE
	Finocchiarà	Senore	1961	1986	26	B1–5	PU	–
B2 Birgi	Chinisia	Birgi	1971	2001	23	B2–1	CD	Rubino - D.Dam - WW- WTE
	La Chinaea	Fastaia	1962	1998	35	B2–2	PD	D.Dam - WW
	Rinazzo	Chitarra	1972	1988	17	B2–3	PD	D.Dam - WW

2 missing years: 1966 and 1967

6 missing years: from 1988 to 1993

8 missing years: 1976, 1977, from 1989 to 1992, 1998 and 1999

2 missing years: 1985 and 1993

The expected class (potentially undisturbed – *PU*, certainly disturbed – *CD*, and potentially disturbed – *PD*) refers to the selected time-period and is based on the available information about the upstream presence of possible disturbance sources (such as dams, diversion dams - D. Dam, wastewater treatment effluents - WTE, or water withdrawals - WW)

within the basin, carrying on average about 0.06 million of m<sup>3</sup> per year, all the streams of the basin river network are considered “at risk” for potential hydrological alteration, according to the aforementioned 2nd Italian RBMPs, also due to the presence of some little diversion dams in the upstream part of the basin and diffuse water withdrawal for agricultural and zootechnical use. Three different OA-ARRA hydrometric stations are present within the *Birgi river basin* (Fig. 1), with dataset specified in Table 2.

The proposed procedure for assessing potential flow regime alteration is here applied to all the gauged river sections monitored by the OA-ARRA, which are identified by the different codes reported in Table 2. Considering all the available information (i.e. the classification of risk for potential hydrological alteration of the water bodies provided the 2nd Italian RBMPs, the location of each river section with respect to the location of the dams and the knowledge of the position of some other possible sources of flow disturbance, such as some diversion dams or wastewater treatment effluents) and taking into account also the period of observation of each station with respect to the period of construction of each dam, we classified the flow regime for the available time-series runoff data of each river section as “potentially undisturbed” (*PU*), “certainly disturbed” (*CD*) or “potentially disturbed” (*PD*) by anthropogenic pressures; obviously, such rough classification, reported in Table 2, is relative to the only period of analysis specified in the same table.

From Table 2, one can observe that the section (B1–1), which is associated to the *Ponte Belice* hydrometric stations, is analyzed two times (B1–1a and B1–1b), relatively to two different time-windows, before and after the construction of the *Garcia* dam; since the main target is to test the capability of the proposed procedure in assessing potential changes of the hydrological regime, an higher global index of alteration is, in fact, expected for the second case (i.e., B1–1b).

### 3 Results

The potentially “disturbed” period (post-impact period) at each analyzed river section, for which the evaluation of possible flow regime alterations is performed, has been assumed as coincident with the entire “observation period” available at the corresponding gauging station (Table 2). In order to make possible a comparison between the results arising from the application of the proposed methodology and those that would arise from the use of the ISPRA (2011) methodology according to the Italian Decree 260/2010 (D.M. Ambiente n.260, 2010), we have assumed the “natural” (“undisturbed” or “pre-impact”) period for each station as equal to the entire period before the post-impact period (i.e., from the first month that can be reconstructed through the Tri.Mo.Ti.S. model, i.e. January 1918, to December of the last year before the observation period, for a total duration ranging from 37 to 54 years).

A different assumption for the choice of the natural period could be to reconstruct the series for the same period for which the flow regime alteration assessment is required; nevertheless, we did not consider this alternative option since it is not contemplated by the ISPRA methodology and, in addition, it would not have ensured for all the cases a sufficient long (20 year at least) time-window of natural data. It is worth emphasizing that section B1–1 is characterized by the upstream presence of the only *Piana degli Albanesi* dam for the post impact period B1–1a (1955–1976) and the presence of a further dam (the *Garcia*) for the successive period B1–1b (i.e., 1986–1994); nevertheless, a unique natural period (from 1918 to 1954) is considered.

In Table 3, the outlet coordinates of each analyzed section are reported; once they are set in Tri.Mo.Ti.S., it automatically identifies the corresponding drainage basins, whose main characteristics (drainage area and mean elevation) are also reported in the same table, and computes the monthly time-series of different variables for the selected period. Table 3 shows the mean annual values (mm/year) of precipitation (MAP), runoff (MAR) and actual evapotranspiration (MAET) computed by Tri.Mo.Ti.S. for both the natural and the post-impact periods. It is also reported, for each section, the resulting percent variation of the aridity index  $\Delta AI$  of the post-impact period with respect to the natural period; the considered index is the well-known UNESCO (1979) aridity index AI, given by the ratio between MAP and the potential evapotranspiration, PET.

It is worth emphasizing that the post-impact values in Table 3 refer to “natural” series, reconstructed during the “post-impact” period (Table 2) by Tri.Mo.Ti.S.; thus, the percent variation of AI denotes the divergence of the climatic conditions of the post-impact period with respect to a previous period (chosen as reference period and identified as “natural” period) due to only climatic variability. For example, we can observe how, for the sections B1–1a and B1–3, the climatic conditions (MAP and temperature) during the post-impact period (i.e. 1958–1963) are quite close to those characterizing the selected reference period for natural condition (i.e., 1918–1957); this implies very similar values of MAET and MAR for the two periods and an almost null  $\Delta AI$ . On the contrary, in the section B1–1b, precipitation during the post-impact period was significantly lower (ca -20%) than during the natural period, leading to both a reduced mean annual runoff (about -36%) and a marked reduction of  $\Delta AI$  (-24% ca.), denoting a shifting toward drier conditions. Such types of considerations might be extremely useful to distinguish the relative weight of anthropic pressures and “natural” climatic variability in determining hydrological changes.

The flow duration curves (FDCs) display streamflow values against their relative exceedance time (expressed in days per year); thus, they efficiently synthesize the river ability in providing flows of various magnitudes. Usually they are computed at daily or finer time scale, since some important details of the variations in flows can be obscured when the FDCs are reconstructed from data with coarser time-scales. Nevertheless, the use of FDCs at the monthly

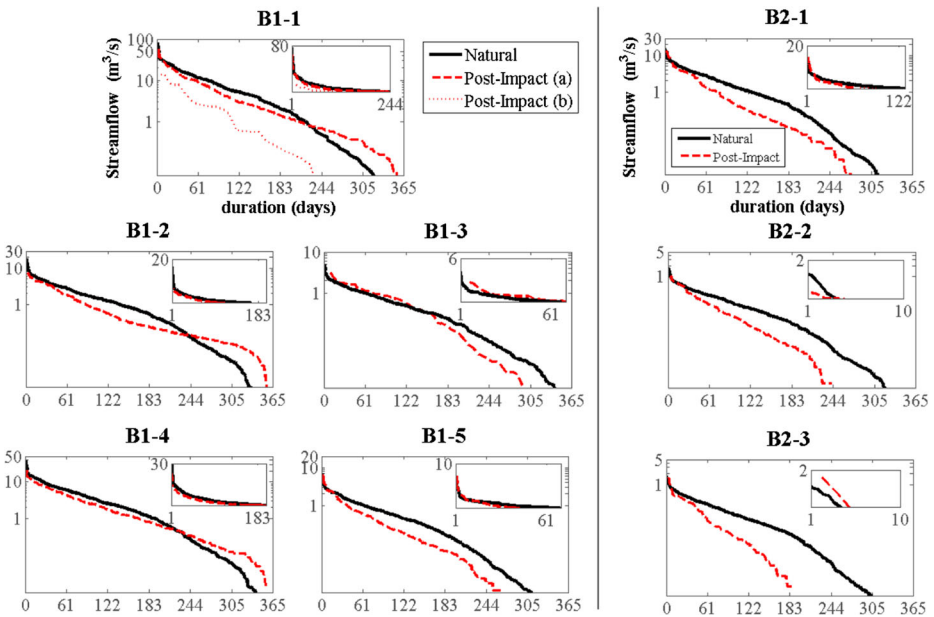
**Table 3** Outcomes from Tri.Mo.Ti.S. application: analyzed sections’ coordinates (*longitude-est* and *latitude-north*) and main characteristics (Dr. Area = drainage area in  $km^2$ ; Mean Elev. = mean elevation in *m a.s.l.*) of the corresponding drainage basins. Mean annual value in *mm/year* of runoff (MAR), precipitation (MAP) and actual evapotranspiration (MAET) for both the natural (*Nat.*) and the post-impact (Post-Imp) periods. Percent variation of the Aridity Index ( $\Delta AI$ )

Sect. ID	Coordinates		Dr. Area km <sup>2</sup>	Mean Elev. m a.s.l.	MAR (mm/year)		MAP (mm/year)		MAET (mm/year)		$\Delta AI$ %
	Long. E	Lat. N			Nat.	Post-Imp.	Nat.	Post-Imp.	Nat.	Post-Imp.	
B1–1a	12°56'32"	37°42'31"	852	454	225	200	782	764	461	461	0.4%
B1–1b						143		623		417	-24.2%
B1–2	13°08'48"	37°51'43"	168	510	319	248	854	775	456	447	-8.8%
B1–3	13°17'59"	37°48'38"	29	800	371	328	881	841	464	443	-0.5%
B1–4	13°08'29"	37°48'32"	339	569	269	229	814	764	463	450	-2.0%
B1–5	13°01'46"	37°44'09"	74	406	210	170	740	662	453	442	-9.2%
B2–1	12°29'43"	37°54'00"	335	189	116	81	627	561	464	463	-14.1%
B2–2	12°44'48"	37°55'39"	23	326	183	134	706	651	467	492	-12.2%
B2–3	12°36'18"	37°49'52"	35	156	112	81	609	533	458	436	-11.9%

scale is rather common (e.g., Vogel and Fennessey 1995) to characterize the flow regime and summarize the hydrological signature of a river. In Fig. 2, the comparison between the flow regime of the natural and post-impact periods in term of FDCs is reported. The data of the post-impact period are those observed at the corresponding OA-ARRA stations. In order to improve graphic rendering and facilitate understanding of the figure, each FDC is shown both in a semi-log plot (in the main graphs) and in a linear plot (inset graphs) for the part of the FDCs with discharge greater than 1 m<sup>3</sup>/s.

Almost all the post-impact FDCs (red dashed curves) are downshifted with respect to the natural curves (black curves) for great part of the duration domain, denoting a lowering of the observed flow during the analyzed period with respect to the “undisturbed” conditions, which could be partially attributable to a relevant degree of exploitation of water resources in the upstream part of the basin. Comparing the two post-impact FDCs relative to the section B1–1, it is possible to noticed how the presence of the *Garcia* dam (curve relative to the section B1–1b, see Table 2) seems to be the principal responsible for a significative divergence of the flow regime with respect to natural conditions, while the alteration of the hydrological regime of the only *Piana degli Albanesi* dam (FDC relative to B1–1a) up to the year 1976 results much less marked.

For the only section classified as “potentially undisturbed” in Table 2 (i.e., B1–5), the post-impact and natural FDCs are actually extremely close, with some slight variations of the frequency associated to the extremely low streamflow values (lower tail of the FDC). Differently from what expected from the analysis of the ancillary information and potential sources of disturbance (see classification of the B2 sections in Table 2), the comparison of the FDCs for the basin B2 shows a less “disturbed” regime at the section B2–1 (that was classified



**Fig. 2.** Comparison between flow duration curves (FDCs) derived from the flow series relative to the natural and the analyzed observation (post-impact) periods for all the analyzed river sections and periods (Table 2). Main graphs show the entire FDC in a semilog plot, while inset graphs show, in a linear plot, only the part of the FDC with streamflow over 1 m<sup>3</sup>/s. Left graphs refer to the basin B1 while right graphs to the basin B2. In the graph for the section B1–1, Post-Impact (a) curve refers to B1–1a (1955–1976) while Post-Impact (b) curve refers to B1–1b (1986–1994, see Table 2)

as “certainly disturbed”) and a more marked distance between the natural and the post-impact curves for the other two sections (B2–2 and B2–3).

Table 4 synthesizes the results of the application of the proposed procedure to the different cases study; more specifically, for each section, the entire set of computed hydrological indices is reported, including the 22 single indicators  $p_{i,k}$  obtained by Eq. (1), the 5 monthly partial indices for each statistical group, MI-HRA<sub>*i*</sub> (with  $i = 1, 2, \dots, 5$ ), obtained by Eq. (2), and the global index GMI-HRA, obtained by Eq. (3).

In order to better clarify how the global index GMI-HRA is computed, Fig. 3 shows two examples of calculation of the different indices MI-HRA<sub>*i*</sub> (with  $i$  ranging from 1 to 5) for the most downstream sections of each basin. More specifically, left plots refer to B1–1a, while right plots to B2–1. The upper plots show the mean monthly streamflow (MMS in m<sup>3</sup>/s) for the post impact period (red markers) and the target range (colored area) based on the reconstruction of natural conditions; the MI-HRA<sub>1</sub> then measures how distant are the post-impact values from the target area. Analogously, the middle plots compare the post-impact annual extremes (i.e. annual minimum and maximum mean flow for 3 and 6 consecutive months in m<sup>3</sup>/s) and the corresponding “natural” (target) range, measured by the MI-HRA<sub>2</sub>. The other three indices plots (i.e., those relative to the MI-HRA<sub>3</sub>, MI-HRA<sub>4</sub> and MI-HRA<sub>5</sub>) are jointed in a unique plot, and reported in the bottom panels of the figure.

The two global indices computed at the sections B1–1 (Table 4), highlight the role that the two dams have had in modifying the original flow regime. The construction of the *Piana degli Albanesi* dam (B1–1a) has significantly modified the magnitude of monthly flow conditions (indicators of Group 1), the magnitude and duration of seasonal conditions (Group 2 indicators) and the rate and frequency of changes in flow conditions (Group 5 indicators) with respect to the natural conditions, leading to an index GMI-HRA of 0.17. The successive construction of the *Garcia* dam in the upstream part of the basin has further exacerbated the flow regime condition at the section (i.e., B1–1b) with a GMI-HRA considerably incremented (equal to 0.24).

Our knowledge on the possible sources of disturbance to the flow regime identifies the section B1–5 as the unique potentially not disturbed (Table 2); surely, one could expect for this section, located on a tributary not affected by the presence of the two dams, an alteration index relevantly lower than, at least, that computed, for almost the same period (post-impact period) in the most downstream section of basin B1 (B1–1a). Actually, as it can be noticed from Table 4, the GMI-HRA obtained by the proposed procedure at section B1–5 (=0.13) was the only index below the critical threshold 0.15 that we have obtained in the two basins, denoting, according to the aforementioned Decree 260/2010, a “good status”.

The results relative to the basin B2 in Table 4 indicate that all the sections are in a “critical status” according to the Decree 260/2010 (i.e., GMI-HRA over 0.15) and show an apparent incongruence; the index computed at the section B2–1 (=0.15), certainly disturbed by the presence of the *Rubino* dam, would denote conditions less disturbed (lower indices) than that resulting at the other two considered sections of the basin B2. It is worth noticing that basin B2 was subject to a considerably climatic shift toward more arid conditions (see Table 3), whose effects could overlap to the effects of the exploitation of the water resources by diffuse water withdrawals. The combination of natural and human factors may have caused the significative alteration of all the regime characteristics observed at basin B2, with, in particular, a consistent modification of the frequency and magnitude of low and high pulses (indicators of the statistical Groups 4) and of the rate and frequency of changes in flow conditions (indicators of the statistical Group 5). Moreover, B2–2 and B2–3 resulted also the unique two sections with alteration in the timing of annual extreme water conditions, with a significative shift in the

**Table 4** Comparison between natural (pre-impact) and potentially impacted (post-impact) periods for all the analyzed river sections of both the basins B1 and B2

Natural		B1-1a		B1-1b		B1-2		B1-3		B1-4		B1-5		B2-1		B2-2		B2-3	
1918-1954		1918-1954		1918-1954		1918-1954		1918-1957		1918-1954		1918-1960		1918-1970		1918-1961		1918-1971	
1955-1976 <sup>a</sup>		1986-1994 <sup>b</sup>		1955-1987		1958-1963		1955-1980		1961-1986		1971-2001 <sup>c</sup>		1962-1998 <sup>d</sup>		1972-1988			
MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind	MI	Ind
<i>p</i> <sub>1,1</sub>	0.05	0.24	0.40	0.22	0.14	0.29	0	0.23	0	0.24	0.27	0.20	0.35	0.11	0.28	0.15	0.51	0.17	0
<i>p</i> <sub>1,2</sub>	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0
<i>p</i> <sub>1,3</sub>	0	0	0	0	0	0	1.13	0	0	0	0	0	0	0	0	0	0	0	0
<i>p</i> <sub>1,4</sub>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>p</i> <sub>1,5</sub>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>p</i> <sub>1,6</sub>	0.76	0	0.02	0	0.13	0	0.76	0	0.93	0.46	0	0.04	0.04	0	0.13	0.04	0.06	0	0
<i>p</i> <sub>1,7</sub>	1.02	0	0.03	0	1.46	0	0.15	0	0.75	0.04	0	0.04	0	0	0.04	0	0	0	0
<i>p</i> <sub>1,8</sub>	0	0	0.21	0	0.45	0	0.36	0	0	0.04	0	0.04	0	0	0.04	0	0	0	0
<i>p</i> <sub>1,9</sub>	0	0	0	0	0	0	0.37	0	0	0.11	0	0.11	0.03	0.18	0.11	0.11	0.11	0.11	0.11
<i>p</i> <sub>1,10</sub>	0.13	0	0.49	0	0.23	0	0.32	0	0.12	0.20	0.11	0.20	0.13	0.33	0.33	0.33	0.37	0.37	0.37
<i>p</i> <sub>1,11</sub>	0.70	0	0.92	0	0.74	0	0.32	0	0.86	0.82	0.37	0.37	0.37	0.43	0.43	0.43	0.49	0.49	0.49
<i>p</i> <sub>1,12</sub>	0.23	0	0.57	0	0.31	0	0.29	0	0.27	0.48	0.48	0.48	0.45	0.34	0.34	0.34	0.51	0.51	0.51
<i>p</i> <sub>2,13</sub>	0.58	0.14	0.25	0.45	0.25	0.06	0.35	0.12	0.48	0.12	0.15	0.10	0.35	0.13	0.26	0.20	0.40	0.40	0.33
<i>p</i> <sub>2,14</sub>	0	0	0.41	0	0	0	0.13	0	0	0.07	0.19	0.15	0.07	0.33	0.33	0.38	0.38	0.38	0.38
<i>p</i> <sub>2,15</sub>	0	0	0.53	0	0	0	0	0	0	0	0.03	0	0	0.05	0.05	0.20	0.20	0.20	0.20
<i>p</i> <sub>2,16</sub>	0	0	0.61	0	0	0	0	0	0	0	0.02	0	0.10	0.16	0.16	0.35	0.35	0.35	0.35
<i>p</i> <sub>3,17</sub>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.50	0.50	0.50	0.25
<i>p</i> <sub>3,18</sub>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	1.00	1.00	1.00	0
<i>p</i> <sub>4,19</sub>	0	0	0	0	0	0	0	0	0	0	0	0	1.00	1.00	1.00	1.50	1.50	1.50	0.75
<i>p</i> <sub>4,20</sub>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>p</i> <sub>5,21</sub>	0.22	0.16	0.84	0.42	0.83	0.49	0.12	0.06	0.04	0.04	0.05	0.08	0.41	0.25	0.52	0.26	0.79	0.79	0.40
<i>p</i> <sub>5,22</sub>	0.11	0	0	0	0.15	0	0	0	0.07	0.09	0.09	0.08	0.08	0.08	0	0	0	0	0
<b>GMI-HRA</b>	<b>0.17</b>	<b>0.24</b>	<b>0.21</b>	<b>0.15</b>	<b>0.16</b>	<b>0.13</b>	<b>0.15</b>	<b>0.15</b>	<b>0.16</b>	<b>0.13</b>	<b>0.15</b>	<b>0.15</b>	<b>0.23</b>	<b>0.28</b>	<b>0.23</b>	<b>0.28</b>	<b>0.28</b>	<b>0.28</b>	<b>0.28</b>

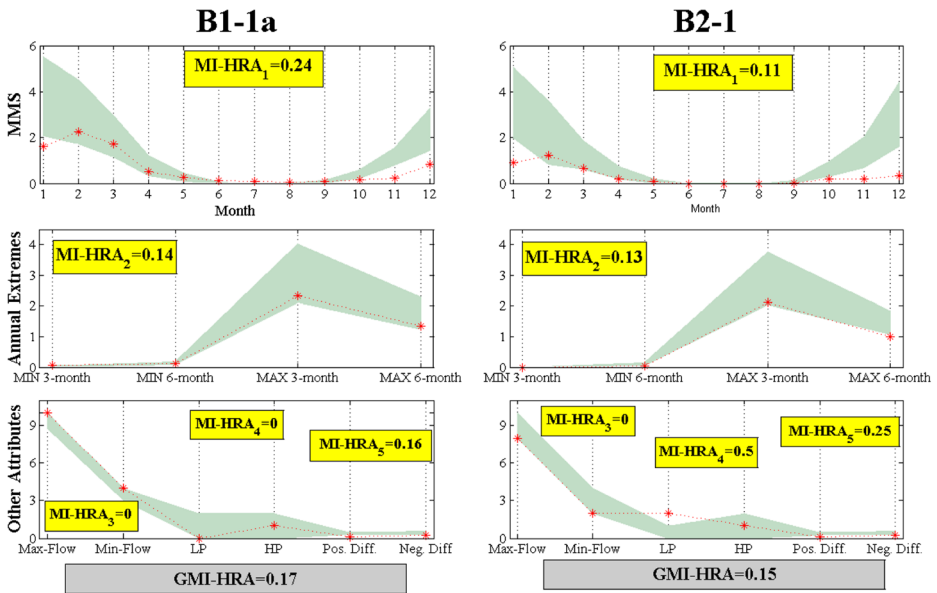
<sup>a</sup> 2 missing years: 1966 and 1967

<sup>b</sup> 6 missing years: from 1988 to 1993

<sup>c</sup> 8 missing years: 1976, 1977, from 1989 to 1992, 1998 and 1999

<sup>d</sup> 2 missing years: 1985 and 1993

Single Indicators (*Ind*) of hydrological alteration (*p<sub>1,k</sub>*), Monthly Indices (MI) of Hydrological Regime Alteration for each statistical group (MI-HR<sub>*i*</sub>) and Global Monthly Index of Hydrological Regime Alteration (GMI-HRA) for each river section and analyzed period



**Fig. 3.** Interannual statistics comparison: red lines and markers refer to the post-impact period, while the coloured areas define the target range derived from natural flow series. Left plots are relative to the section B1–1a, while right plots to the section B2–1, that are the most downstream river sections of the two basins (B1 and B2, respectively; see Fig. 1). In the yellow boxes are also reported the monthly indices of hydrological regime alteration for each statistical group while the resulting global indices are reported in the bottom gray boxes. Statistics (MMS - mean monthly streamflow in m<sup>3</sup>/s) for the Group 1 are reported in the upper panels. Group 2 statistics are reported (again in m<sup>3</sup>/s) in the middle panels. Bottom panels report all the other attributes necessary to compute the other groups’ monthly indices (see Table 1): month of maximum and minimum flow; yearly number of low and high pulses; median of positive and negative difference between consecutive months. Last values (negative dif) are reported with opposite sign

months of maximum and minimum flow and high values for the index MI-HRA<sub>3</sub>; this could be explained by the upstream presence of diversion dams.

From Fig. 3, and in particular from the upper panels of the figure, it is possible to notice the effects of dams and typical streamflow regulation in Sicily on river flow regime, where a significant amount of the autumnal-winter water recharge is usually retained for interannual regulation purposes. This typically implies a reduction of peaks (i.e., reduction in the number of high pulses), and, in general, of the monthly water volume (i.e., reduction in MMS) released. On the contrary, a certain water volume is always released, even during the July–August months (higher MMS) when natural condition could lead also to no-flow (ephemeral regimes), in order to ensure a minimum vital flow for the survival of local wildlife species. As a consequence, the maximum deviations of the post-impact indicators with respect to the target range derived from “natural” values, occurs during the wetter period (about from November to January) and the driest month (about July).

### 4 Discussion

In this work, we have simulated real applications for the assessment of flow regime alteration, at different river sections and for two different basins. Possible flow regime alterations are



assumed to be due to potential disturbance sources occurring during post-impact periods coincident with data availability at any section and considering monthly natural flow estimates availability from 1918 up to the beginning of each post-impact period. The underlying idea is that the proposed indicators should be able to detect the presence of anthropic pressures that can alter the hydrological regime in a section and, at the same time, these indicators should be proportional to the intensity of the effects due to the disturbance factors.

According to the ISPRA (2011) methodology, for the assessment of the IARI, the simulated cases fall all within the category of cases with availability of recent (post-impact) data and absence or insufficient availability (<20 years) of data under pristine conditions. Under such conditions the method for computation of the IARI is exactly coincident with that for the computation of the MI-HRA<sub>1</sub> through the here proposed procedure, and the two indices are essentially the same.

Consistently with the GMI-HRA, the IARI indices (see MI-HRA<sub>1</sub> in Table 4) computed for the section B1 over two different periods (B1–1a and B1–1b) would provide values (over 0.22) denoting a “critical status” and, then, the necessity of further analysis according to the Italian Decree 260/2010. An interesting point is that, in contrast to what one could expect due to both anthropic causes, such as the presence of the *Garcia* dam, and natural causes, such as the high percent variation of the aridity index (Table 3), the IARI computed at B1–1b resulted lower than that relative to B1–1a (Table 4). On the contrary the GMI-HRA computed at B1–1a resulted consistently lower than at B1–1b (0.17 vs. 0.24); this could be a clear evidence of the improvements in alteration degree assessment of the proposed methodology with respect to the IARI procedure.

Further evidence is provided from the comparison among the indices resulting at the sections B1–5, which, according to our knowledge, should be, among the cases considered in this study, the river section less affected by anthropic pressures. Actually this would seem to be confirmed by the proposed procedure, with the lowest global index (GMI-HRA = 0.13) at the section B1–5 (which is also the only denoting a “good status”). Although also the ISPRA procedure would confirm the section B1–5 as that less “disturbed” among the analyzed sections of basin B1, the IARI computed for the same section (=MI-HRA<sub>1</sub> = 0.20) would indicate: (i) an alteration more intense than that detected over the basin B2 (all below 0.17, see MI-HRA<sub>1</sub> values for basin B2 in Table 4); (ii) a classification of the status of the section as “critical” (over 0.15).

The results relative to the basin B2, actually, highlight some further limits related to the IARI procedure; the IARI computed at the section B2–1 (=0.11), certainly disturbed mainly due to the presence of the *Rubino* dam, would inconsistently denote a “good status” of the river and, however, a condition less disturbed than that resulting at the other two considered sections, whose values of MI-HRA<sub>1</sub>, and then of the IARI, range from 0.15 to 0.17. Actually, as already mentioned, this last incongruity persists also using the proposed procedure, even if, in this case, for all the sections of basin B2 the global indices denote a “critical status”.

The quantitative assessment through the proposed procedure of the global monthly indices of hydrological regime alteration (Table 4) seems to confirm the evidences provided by the qualitative comparison between natural and post-impact periods in terms of FDC (Fig. 2), such as an intensive exploitation of the water resources with respect to the “natural” availability.

The effects of the human pressures on the selected river sections are also perfectly consistent with other findings in literature; for example, the main conclusion in Zuo and Lian (2015), coherently with what found also in this study, was that dams profoundly affect the hydrology of rivers, with reduced annual peaks, decreased range of variability for the discharge

values, altering the timing of high and low flows and the timing of the yearly maximum and minimum flow and increasing the frequency of low pulse events.

## 5 Conclusion

Improving the existing methods to quantify hydrological changes is becoming a priority. The procedure here proposed allows some improvements with respect to the most widely used methods mainly due to the adoption of monthly indicators, which considerably extends its field of applicability thanks to the fact that, on the one hand, it requires much more accessible data, and, on the other hand, it allows for the use of simpler and equally accurate models for natural flow reconstruction, such as that considered in this work (i.e., Tri.Mo.Ti.S.). The proposed procedure essentially enlarges the methodology of ISPRA (2011) for the computation of the IARI hydrological alteration index under the situation of “insufficient data availability”, accounting for further hydrological indicators capable to detect possible alterations of some characteristics of the hydrological regime neglected in the original IARI formulation (e.g., the magnitude, duration, timing and frequency of extreme water conditions and low/high pulses).

Some of the advantages associated with the adoption of this procedure have clearly emerged in this study from the application to the selected cases study and the comparison with the methodology currently adopted by the Italian Government (IARI index, according to the Decree 260/2010); in particular, the GMI-HRA indices resulting from the proposed method seem to adequately reflect the degree of anthropization reconstructed in each analyzed river section from the analysis of the available auxiliary information. Furthermore, the proposed method allows for overcoming some of the incongruities that have emerged during IARI index computation.

The method, especially if coupled with other ecological indicators of ecosystem integrity, should prove to be extremely useful for various management activities, from the design of appropriate ecological restoration and conservation strategies to the planning and the evaluation of alternative, structural and not-structural, water development proposals.

The advantage of the proposed procedure in terms of simplicity related to the use of monthly scales may be, however, counterbalanced by the fact that the identification of certain types of hydrological impacts such as, for instance, the pulse-type-flows effects often associated to power generation at dams, could be hampered by the use of such a temporal coarse data and indicators. Actually, this represents the major limit of all the monthly-based approaches with respect to the daily-based method, such as the IHA/RVA. Another important limit of the proposed procedure is that it is not able to identify the origin (anthropic or “natural”) of the pressures which determine hydrological changes. Actually, the use of a hydrological model, such as the Tri.Mo.Ti.S., capable to perform scenario-based simulations, would allow to quantify the relative weights of climate change and anthropic pressures in determining hydrological regime modifications through their separate application in dedicated scenarios.

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### Compliance with Ethical Standards

**Conflict of Interest** None.

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