Science of the Total Environment 969 (2025) 178961

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Development of an eco-hydrological distance index and improved environmental flow assessment by integrating ecological monitoring and hydrological modeling

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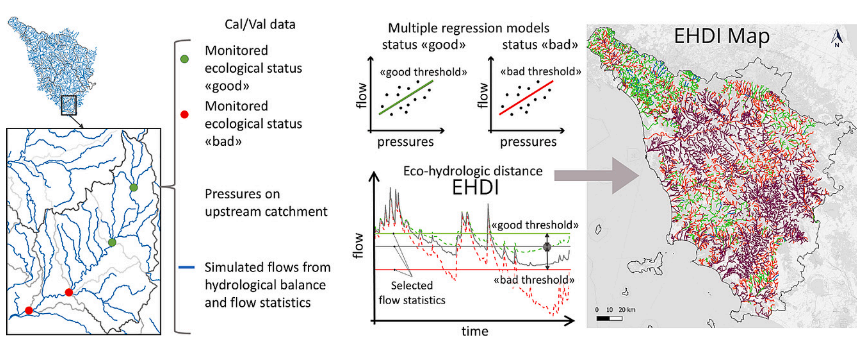
HIGHLIGHTS

- *E*-flow is based on water balance, pressures on the catchment and ecological status
- Theoretical thresholds of 'good' and 'bad' e-flows are introduced
- E-flow is redefined as the flow regime sufficiently distant from a 'bad' e-flow
- Eco-Hydrological Distance from target ecological status of rivers is defined
- Restoration of natural flows is not enough when river quality is impaired

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Sergi Sabater

Keywords:
E-flow
Water resources management
Anthropogenic pressures
Ecological status

ABSTRACT

Achieving a good ecological status for rivers is a primary goal under European water protection legislation, and establishing suitable environmental flows (e-flows) is key to reach this objective. Typically, statistical hydrologic methods are used to determine e-flows at the river basin district scale; however, these often overlook water quality and critical flow-ecology relationships, i.e., models linking streamflow and ecological responses. This study integrates ecological status monitoring data with hydrologic models to address the limitations of hydrological methods for e-flow assessment. The new method developed in this study enables a more precise definition of e-flow thresholds and the development of an eco-hydrological distance index (EHDI). The EHDI indicates how closely a river's flow aligns with ecological targets, taking into account catchment pressures. The methodology involves: (i) a water balance simulation using a distributed hydrological model that accounts for human impacts, (ii) regression models to establish good and bad e-flow thresholds based on monitored data, and (iii) the EHDI, which compares actual flow with these thresholds to identify rivers where further water abstraction should be restricted. The application across 11,000 river reaches in Tuscany, (Italy) reveals that many rivers approach the bad e-flow threshold in summer. Instead only a few rivers deviate significantly from ecological targets according to mean annual flow. The findings underscore that statistical-hydrologic methods alone fail to capture the complex dynamics between flow regimes and ecological status, especially under high human pressure. In fact,

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https://doi.org/10.1016/j.scitotenv.2025.178961
Received 14 November 2024; Received in revised form 17 February 2025; Accepted 22 February 2025

when human pressures on water quality are significant, the restoration of natural flows would not be enough to achieve ecological status objectives.

1. Introduction

Freshwater is an essential natural resource that supports communities in diverse areas, including hygiene, agriculture, and industry. However, a growing population, climate change, and deteriorating water quality present significant risks to food and energy security (Food and Agriculture Organization of the United Nations (FAO), 2017). Sustainable water resource management is therefore critical for meeting human needs and maintaining ecological balance. The ecosystem services provided by rivers are highly vulnerable to changes in both water quality and availability (Grizzetti et al., 2019). To guide and support policies aimed at preserving water ecosystems, the concept of ecological flow or environmental flow (also known as e-flow, instream flow, and other terms) has been developed (Leone et al., 2023a). We will refer here mainly to the EU definition and use. *E*-flow is "the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon" (European Commission, 2015). The "amount of water" refers to quantity, timing (i.e., flow regime) and quality of water flows, with specific reference to the achievement of the environmental objectives, i.e., a good status of water bodies, of the European Water Framework Directive (WFD) (60/2000/EC). Ecological status is part of the overall river status and it is monitored by environment agencies accounting for (i) biological quality elements, such as macrophytes and benthic invertebrate fauna, (ii) hydromorphological (e.g., hydrological and sedimentological regimes) and (iii) the supporting physico-chemical parameters (e.g., nutrients, and dissolved oxygen)(EEA, 2018).

Three main methodologies are adopted in literature to set e-flows: (i) hydrological, (ii) hydraulic-habitat and (iii) holistic methods (WMO, 2019; European Commission, 2015). Hydrological methods are the most used approaches (Tharme, 2003; Prakasam and Saravanan, 2022). They rely on statistical analysis of river discharges (measured or simulated) and aim at identifying flow conditions which reflect the natural flow regime based on the assumption that native habitats evolved on such regimes (Acreman, 2016). Hydrological methods require limited need of on-site data collection and can be applied at large catchment/regional scale; however, they lack a direct ecological validity. Many works highlighted poor correlation between flow conditions and ecological indicators (Salmaso et al., 2018; Buffagni et al., 2006; Guareschi et al., 2017; Larsen et al., 2019).

Hydraulic-habitat methods instead are oriented to the definition and application of flow ecology-relationships for target species. They predict suitability of habitat species based on hydraulic parameters such as flow velocity, depth, and river morphology. Although flow-ecology relationships are rarely capable of capturing all taxonomic groups in a river (Tonkin et al., 2021), hydraulic-habitat methods are more accurate than hydrological ones. Nevertheless, they require a significant amount of fieldwork and expertise for studying a river reach and the results of this effort are not transferable to other rivers/catchments (Stein et al., 2021).

Holistic methods consider the riverine ecosystems as a whole (e.g., by including plant species in riparian habitats) and how different components of flow characteristics, e.g., peak flow, dry season low flow etc., support different ecosystems functions (Poff et al., 2010; Greco et al., 2021; Xing et al., 2018; Leone et al., 2023b; Yarnell et al., 2020). Indicators of hydrologic alterations are used to identify the acceptable levels of change at the provincial or catchment scale and the process involves different expertise. Holistic methods still require time for expert consultation, data collection and understanding of acceptable levels of hydrologic alteration based on local ecosystems. These methods are well represented by the Ecological Limits of Hydrologic Alteration (ELOHA) tool which aims at a more systematic approach at larger scale (Acreman and Dunbar, 2004). The ELOHA tool is based on 34 environmental flow components, e.g., magnitude and timing of high flow pulse, large flood, low flow, extreme low flow etc., and on the assessment of how these components have changed after a certain impact, e.g., dam construction.

In recent years many authors highlighted that imitating natural flow regimes in highly impaired rivers, for instance rivers with multiple pressures on physical habitat and water quality, has a limited effectiveness (Taniguchi-Quan et al., 2022; Stein et al., 2021; van Rees et al., 2021). The discussion on natural flow regimes or of acceptable ecological limits of hydrologic alteration still assumes the quantity of water as the main driver of ecosystem deterioration. This has an historical motivation because dams were the first responsible or river impairment and the need of determining a minimum vital flow was introduced to protect ecosystems downstream of dams (Tonkin et al., 2021). Today the concept has evolved into the more comprehensive e-flow recognizing the importance of supporting physical-chemical aspects, i.e., nutrients and dissolved oxygen, and biological indicators, which are only partly related to water quantity. A very recent work, in fact, considered also water quality for managing reservoir operations (Yu et al., 2023). According to the European Environment Agency 60 % of water bodies fails to achieve a good ecological status. Besides hydromorphological pressures, diffuse and point source pollution (e.g., agricultural surfaces wash-off and wastewater release) account for >56 % of ecological status failures (EEA, 2018). Clearly none of the method for e-flow determination described above can capture pollutants dynamics. Moreover, hydrologic alterations affect only 7 % of surface water bodies and physical alterations in channel and riparian zone affects 26 % of surface water bodies (EEA, 2018). Pressures in river catchments, on the other hand, have been found correlated to ecological status and might help predicting ecological status where onsite monitoring is not available (Arrighi and Castelli, 2023; Grizzetti et al., 2017).

In EU countries, the river basin district authorities responsible for water management and water abstraction authorization typically oversee large territories (such as regions or groups of catchments). They face the paradox of needing to make decisions based on existing methods for e-flow estimation that focus exclusively on hydrologic (quantity) alterations, even though the primary sources of anthropogenic pressures often impact water quality.

The primary objective of this work is to address the limitations of large-scale methods focused solely on analysing hydrologic regimes by combining flow statistics, indicators of anthropogenic pressures and monitored ecological status. We achieve this by developing a new diagnostic tool to assess the deviation from theoretical e-flow values on a regional scale, incorporating both hydrological and ecological indicators without explicitly analysing flow-ecology relationships and without modeling water quality. Additionally, we identify theoretical e-flow thresholds for ecological status, allowing us to measure how far the current flow regime deviates from theoretical values. Our approach should help determining under which conditions these targets could be met by mitigating quantitative pressures, i.e., by restoring hydrologically natural flows. The method introduced here is not intended to replace existing methods based on Indicators of Hydrologic Alteration (IHA) (Acreman and Dunbar, 2004; Acreman, 2016); rather, it offers an alternative tool for cases where ecological target failures are attributed to water quality impairments (EEA, 2018) rather than changes in hydrologic regimes. The specific objectives are: (i) to apply a data fusion approach where the officially monitored ecological status, obtained by combining several indicators (Arrighi et al., 2021; EEA, 2018), is combined with standard hydrologic statistics to establish theoretical thresholds for good and bad e-flow conditions; (ii) to adopt easily accessible geospatial proxies of ecological status to overcome the limited amount of available data and to transfer the model to unmonitored basins (all basins potentially); (iii) to determine a synthetic diagnostic tool named dimensionless index of Eco-Hydrological Distance of rivers which accounts for hydrology and water quality pressures; (iv) to compare the theoretical e-flow thresholds with natural flow regimes. The developed methodology can be applied to any river basin where anthropogenic pressures on water quality prevent the achievement of a good ecological status. In fact, a limited amount of data on ecological status for the full river network in the study area may suffice to calibrate and validate e-flow theoretical thresholds and calculate the Eco-Hydrological Distance Index. Moreover, although this methodological framework is designed to align with the objectives of the European (WFD), there are no constraints on the type of indicators used to assess ecological status. Therefore, it can potentially be applied to non-EU countries, provided that some ecological indicators are available.

2. Materials and methods

2.1. Working hypothesis

Based on the agreed definition of e-flow as "the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon" (European Commission, 2015), it is necessary to identify statistical flow metrics that accurately describe the flow regime. Traditional statistics representing low flows, such as Q_{7_N} (the minimum flow not exceeded for seven consecutive days within a year with a return period of N years, often used to set minimum vital flow) (Stuckey, 2006) should therefore be supplemented or replaced by metrics that better represent average flow regimes, such as annual or seasonal averages. Once the reference statistic(s) is selected, corresponding values that, if maintained, could theoretically ensure a good ecological status should be quantified. These values are what we refer to as e-flows. The commonly accepted working hypothesis is that achieving good ecological status is possible by maintaining the flow regime at levels no lower than e-flows. From a practical standpoint, the significant variability and unpredictable effects of numerous anthropogenic pressures on water quality may lead to e-flow estimates that are excessively high compared to the actual natural hydrological capacities. For simplicity, we define this natural hydrological capacity as 'natural flow,' i.e., the flow in a stream without human interventions such as water abstraction and wastewater discharge. In some cases, it may be more practical to implement a complementary principle aimed at keeping the hydrological regime at a safe distance from values that would otherwise lead to bad ecological status. In the EU, the Water Framework Directive 60/2000 (EU Parliament, 2000) establishes normative definitions for ecological status classification. A good ecological status of rivers is defined as a level of the biological quality indicating low distortion due to human activities, meaning that the relevant biological communities display only a slight deviation from undisturbed conditions. A bad ecological status, on the other hand, is defined by the absence of large portions of biological communities typically associated with the surface water body type under undisturbed conditions(EU Parliament, 2000). Numerous studies have shown that some bioindicators used for ecological assessment, such as benthic invertebrates, are sensitive to pollution but have limited correlation with flow parameters (Larsen et al., 2019; Grizzetti et al., 2017; Salmaso et al., 2018).

In this work, we begin by redefining e-flow as the flow regime that maintains a sufficient safety margin—termed Eco-Hydrological Distance Index—from conditions associated with a bad ecological status (represented by the red flow in the bottom right panel of Fig. 1), based on both hydrology and pressures affecting the catchment. We will then analyse the relationship between the resulting e-flow values and flow estimates. This redefinition of e-flow implies the presence of a confidence band between the flow regimes that ensure good (if exceeded) and bad (if not reached) ecological statuses (depicted as green and red flow regimes in the bottom right panel of Fig. 1). This band could theoretically be eliminated if deterministic relationships between anthropogenic stressors, hydrological regime, and ecological status were available; however, this is currently unfeasible given the present state of

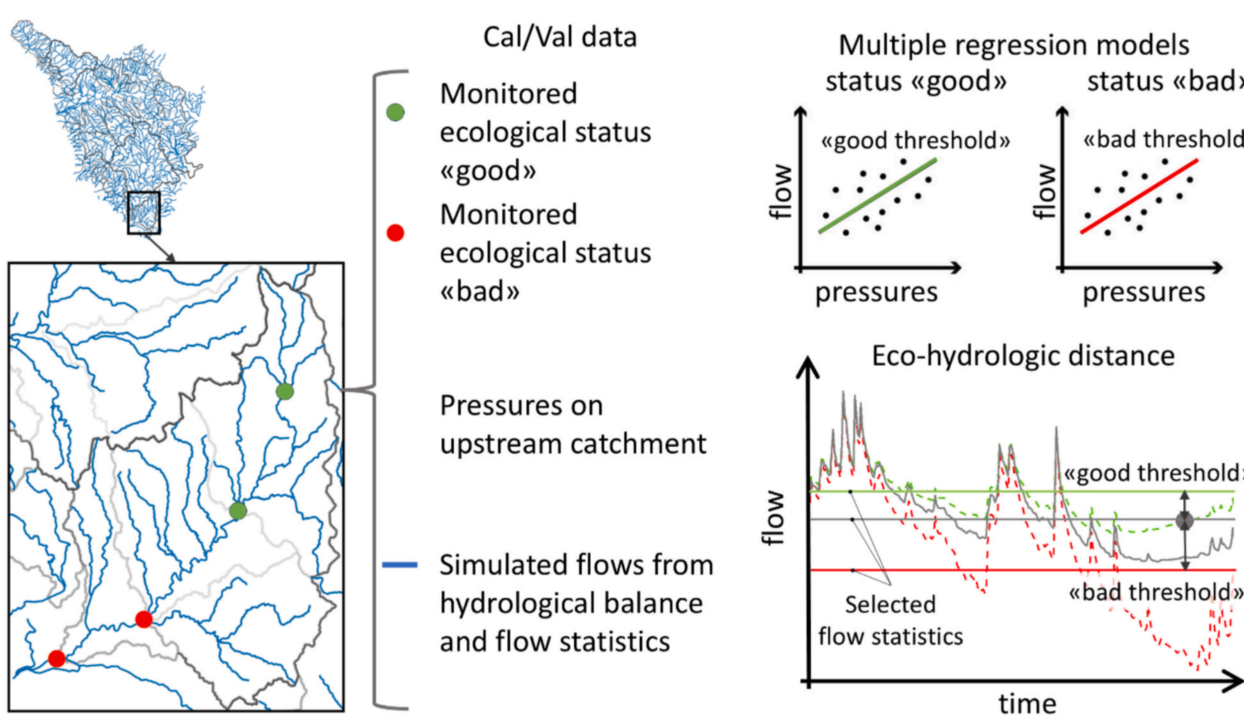

Fig. 1. Methodological scheme to determine the eco-hydrological distance of a river. On the left side we show an example of catchment with four ecological status monitoring points. Upstream of each monitoring point pressures are extracted, flow statistics are extracted on the respective river reach to proceed with the regression model. The bottom-right panel exemplifies the concept of eco-hydrological distance of the actual flow (grey line) from the good and bad theoretical thresholds (green and red lines respectively).

theoretical and experimental knowledge.

The determination of theoretical e-flows follows several steps, as summarized in the scheme in Fig. 1. First, two multiple regression models are defined to correlate specific flow statistics (representing the hydrological regime) and pressures in the catchment, which are assumed to influence ecological status (Arrighi and Castelli, 2023). The e-flow models are developed by dividing the dataset into two subsets: one that includes flow statistics and pressures in catchments classified with good ecological status, and another that includes the same flow statistics and pressures in catchments that do not meet the good ecological status, i.e., those classified as bad, in order to estimate the parameters of a Bivariate Constrained Mixture Regression Model (Ascari et al., 2024; Quandt, 1972). This approach simplifies ecological status classification into a binary framework of good/bad, though we acknowledge that there are actually five classes (1-high, 2-good, 3-moderate, 4-poor, and 5-bad). Model calibration and validation are performed on river reaches in the network where officially monitored ecological status data (good or bad) are available. These two calibrated models allow us to identify, for each river reach and its corresponding pressures in the upstream catchment, the theoretical e-flow threshold values: the flow regime below which a bad ecological status is expected and the flow regime above which a good ecological status is expected (see Fig. 1, right side, with green and red lines representing good and bad e-flows, respectively). Various representative statistics of the hydrological regime are used to assess model significance. Secondly, the models are applied across the entire river network—i.e., where data on pressures and hydrological regime statistics are available, but ecological status data are not—to define theoretical e-flow values.

Finally, a dimensionless index representing the ecohydrological distance (EHDI) of the actual hydrological regime, as determined by a water budget model (represented by the grey line and grey dot in Fig. 1, bottom-right panel), is calculated based on the e-flow threshold values. To complete this procedure, the same hydrological model is applied without abstraction and releases to estimate the natural flow regime, allowing comparison with the e-flow regime to assess the 'hydrological feasibility' of such a theoretical regime.

2.2. Water balance model

The water balance is simulated with the MOBIDIC model (Castelli et al., 2009; Yang et al., 2014; Castillo et al., 2015), a continuous, distributed, vector&raster-based model designed to simulate the energy and water fluxes within a watershed, including the effects of river regulations and the main quantitative anthropogenic pressures on hydrologic regimes. A distributed model divides the area of interest into a grid or sub-units, allowing spatial variability in inputs (e.g., rainfall, soil properties, vegetation) and outputs (e.g., runoff, infiltration, evaporation) within each sub-catchment. The model simulates various components of the hydrological cycle, based on historical records of precipitation, maximum and minimum temperature, humidity, wind velocity, and solar radiation. The balance simulation is here performed on a 20 years' time series, with a daily time step. MODIS data enables the calibration of evapotranspiration flux within the model, Sentinel-1C-SAR satellite data assists in calibrating model parameters controlling the soil moisture dynamics (De Simone et al., 2023). Parameters controlling surface runoff and percolation in soil are calibrated and validated by confronting modelled and measured streamflow at river gauges. Human impacts on water resources are described by means of georeferenced point data on water abstraction associated to the respective stream segment or groundwater body, including withdrawals for agriculture, industry, and municipal use with respective consumption patterns. Other anthropogenic components in the water balance model are wastewater treatment plants released discharges, and functioning of river regulating structures. The water balance simulation thus yields both actual and natural water flows statistics by simply 'turning on and off' the specific model components of water abstraction and water release.

2.3. Multiple constrained regression models

Low flows Q_{7_2} and Q_{7_10} (Stuckey, 2006), along with annual and seasonal averages, are calculated from water balance simulations as representative statistics of the actual river flow regime. These statistics are extracted at locations corresponding to ecological status monitoring stations. The dataset is divided into two subsets: river reaches with an ecological status that meets (i.e., good or high, hereinafter referred to as *good*) or does not meet (i.e., moderate, poor, or bad, hereinafter referred to as *bad*) the WFD objectives. For each subset, a model (good or bad status) is calibrated to estimate flow regime statistics (good/bad) based on certain pressures as in the general family of Mixture Regression Models (Quandt, 1972). The pressures included in both the good and bad regression models must be consistent, as ecological status is unknown a priori throughout the river network outside of monitored stations. The aim is to use this method as a diagnostic tool to estimate the eco-hydrological distance of any river reach based on flow and pressure data.

In each data subset, two-thirds of the data are used for model calibration and one-third for model validation. The model used is a multiple regression model with a double logarithmic transformation of the form:

$$log_{10}(Q) = b \bullet log_{10}(S) \tag{1}$$

Where Q is a flow regime statistics and S is the selected group of pressures, all positively definite. As previously mentioned, the selected group of pressures S should be consistent for both regression models. Needless to say, what can vary is the value of each pressure in the i-th catchment used for calibration that contributes to the calculation of the model parameters.

In the calibration step, model parameters are estimated separately for the dataset $\{Q_G, S_G\}$ related to rivers with good ecological status and for the dataset $\{Q_B, S_B\}$ related to those with bad ecological status, thus obtaining two different sets of calibrated parameters b_G and b_B. The calibrations are not independent; rather, the expectation that streams in good ecological status have higher flows, given the same pressures, must be satisfied. Therefore, a constrained regression algorithm is employed (Bjorck, 1996), which can be expressed mathematically through the following relationships between block matrices (where Eq. 2 represents the general linear model and Eq. 3 represents the constraint).

$$\begin{bmatrix} log_{10}S_G & 0 \\ 0 & log_{10}S_B \end{bmatrix} \begin{bmatrix} b_G \\ b_B \end{bmatrix} = \begin{bmatrix} log_{10}Q_B \\ log_{10}Q_G \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} -log_{10}S_B & 0 \\ 0 & log_{10}S_G \end{bmatrix} \begin{bmatrix} b_G \\ b_B \end{bmatrix} \leq \begin{bmatrix} -log_{10}Q_B \\ log_{10}Q_G \end{bmatrix} \tag{3}$$

Note that the constraint equation intersects the parameter set b_G (good status) with the dataset $\{Q_B, S_B\}$ (bad status) and vice versa. Without such a constraint, the calibrated parameters b_G and b_B would be independent and the hypothesis of having $Q_G > Q_B$ given the same pressures S would not necessarily hold. From a theoretical perspective, in a completely pristine catchment Q_G and Q_B could converge to a single theoretical value. The presence of the constraint (Eq. 3) prevents this from happening.

In the validation phase, the remaining third of the data is used to compare the simulated theoretical e-flows with the actual flow from the water budget. After successful validation, the models to predict Q_G and Q_B can be applied across the entire river network, also in areas where the official classification of ecological status is unavailable. This approach establishes the e-flow thresholds for good and bad ecological status based on the pressures (S) within each sub-catchment. Consequently, each stream segment is characterised by the pressures of its sub-catchment reflecting the spatial heterogeneity of ecological, hydrological and anthropogenic features.

The best choice for defining e-flow regime representative statistics is evaluated based on the models' ability to explain the variability of flow as a function of pressures (using R^2 statistic, RMSE, MAE). The multiple regression models of Eqs. 1–3 are tested on average annual flow, seasonal average flows, and low flows ($Q_{7,2}$, $Q_{7,10}$). Although in Europe the pressures responsible of the impairment of water ecology are known, (Grizzetti et al., 2017), the selection of pressures can be influenced by the geographic context; we describe our choice in the Section 2.5 (Study area).

2.4. Dimensionless index of eco-hydrological distance

The selection of Q_G values as e-flow values could potentially lead to an overly precautionary and unfeasible position in cases of high pressures on water quality. Therefore, e-flow values Q_{ECO} can be more appropriately defined as those that are sufficiently distant (in the sense of augmentation) from the bad ecological status regime values Q_B.

The method presented here allows for the coherent selection of a safety coefficient β for each river reach based on the distance between Q_G and Q_B of each river reach

$$Q_{ECO} = Q_B + \beta(Q_G - Q_B) \tag{4}$$

It also holds

$$\beta = \frac{Q_{ECO} - Q_B}{Q_G - Q_B} \tag{5}$$

From Eq. (5) we notice that if Q_{ECO} is set equal to the target value Q_G the value of β is equal to one, while if Q_{ECO} is set equal to the lower threshold value Q_G the value of β is zero.

To use this equation as a diagnostic tool to measure the distance from a flow condition which turns the river into a bad ecological status we substitute the actual flow Q, as obtained by hydrological balance, to Q_{ECO}

$$EHDI = \frac{Q - Q_B}{Q_G - Q_B} \tag{6}$$

The dimensionless parameter obtained is called Eco-Hydrological Distance Index (EHDI), and it provides a measure of the distance from a bad e-flow, relative to the distance between the good and the bad e-flows, as obtained by Eqs. 2–3. The calculation of EHDI can be based on different flow regime statistics Q, e.g., seasonal mean flow, annual mean flow, etc. If the representative flow statistic is larger than the upper theoretical threshold $Q > Q_G$ the value of the index is larger than one, i.e., the river has a very safe distance from the bad ecological status. If $Q < Q_B$ then EHDI becomes negative, and the river may be classified as in very critical eco-hydrological conditions, i.e. below the flow associated to a bad ecological status. The denominator of Eq. (6) is always positive since $Q_G > Q_B$ by definition (Eqs. 2–3) and it tends to zero in case the river catchment hasn't got any pressure, i.e., in nearly natural condition.

To measure the ability of EHDI to distinguish between good and bad ecological statuses the Cramér-Von Mises test of EHDI is performed on the calibration dataset. This test is widely used to compare two empirical distributions. In our analysis this test is used to ascertain that good and bad e-flow datasets are statistically independent.

2.5. Study area

2.5.1. Geographic setting

The method is tested on the river network of the Tuscany Region (Central Italy) (Fig. 2, panel a). The region has a surface area of approximately 23,000 km^2 and a population of about 3.7 million inhabitants. The northern boundary of the region is characterised by terrain with an altitude above 1000 m a.s.l., while the western part is bounded by the Tyrrhenian Sea. Climatic conditions are semi-arid in the southern coastal areas and per-humid in the northern mountainous regions. Annual mean temperatures range from 8 °C in the northern mountain peaks to 17 °C in the southern coastal areas. Rainfall shows high seasonal and geographic variability, with mean annual precipitation of 1190 mm (minimum 618 mm, maximum 2748 mm at point rainfall gauges).

The river network simulated in the water balance consists of approximately 11,000 reaches. The most important river catchments are the Arno and the Ombrone (shown in blue and orange, respectively, in

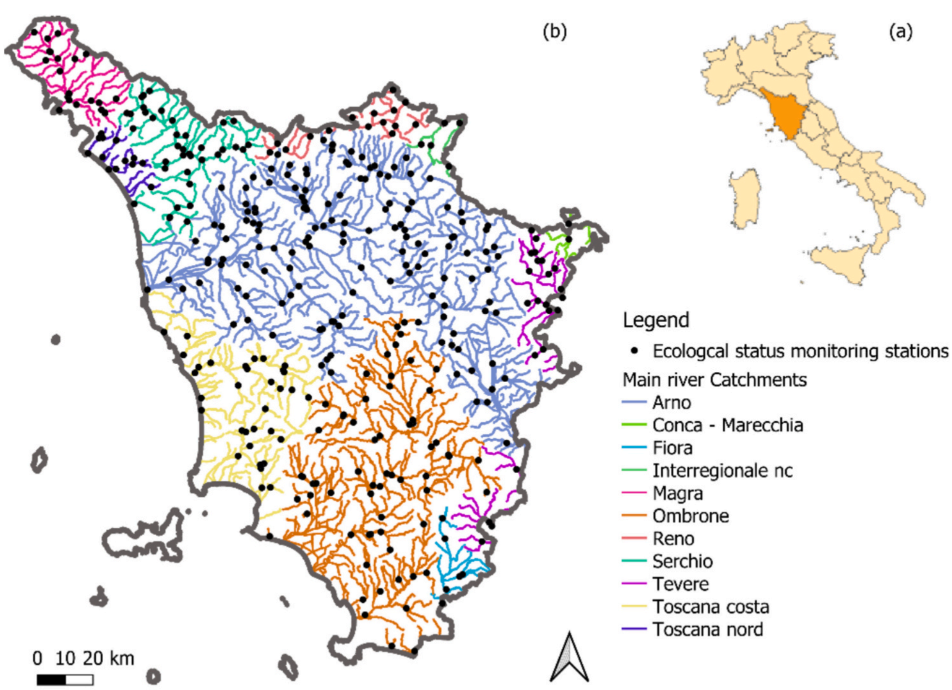

Fig. 2. Setting of the study area (a) river network of the main catchments simulated in the hydrological balance and ecological status monitoring sites (black points) (b).

Fig. 2, panel b). Hydro-meteorological data and water abstraction/release data for the water balance are obtained from the Regional Hydrologic Service and the Tuscan Water Authority respectively.

In Italy, the definition of e-flow coincided with the minimum vital flow (DMV), which is the minimum flow necessary to ensure a balance between resource availability and ecosystem needs. After 2017, the Ministry of Environment modified the definition to: "streamflow able to preserve morphological, chemical, and physical characteristics of the waters, and for the maintenance of the biocoenosis typical of natural conditions" (Leone et al., 2023a). The methods suggested by the Ministry of Environment are hydrologic or hydraulic-habitat methods (European Commission, 2015), and the decision on what to adopt is left to the District Authority.

In the study area, until the end of the current cycle of implementation of the WFD, e-flow is set to the minimum vital flow corresponding to the low flow statistic of the natural $Q_{7,2}$. This value is currently used to determine the authorization of new permitted water abstraction in rivers.

2.5.2. Data on ecological status and selection of indicators of pressures

The Regional Environment Agency (ARPAT, 2021) monitors the ecological status of ca. 400 points in the river network (black points in Fig. 2, panel b). The monitoring program is established by ARPAT and involves the periodic seasonal collection of water and biological samples, resulting in the assignment of an ecological status classification for each three-year period since the WFD came into effect. The five indicators used for ecological status classification are benthic macroinvertebrates, macrophytes, benthic diatoms, LIMeco (dissolved oxygen, phosphorus, ammonium, nitrate) and the concentration of selected hazardous substances (according to Italian Law *d.lgs. 172/2015* and WFD). About 50 % of rivers achieve the good ecological status objectives of the European WFD Directive.

In a previous work in the same study area (Arrighi and Castelli, 2023) the contribution of 14 different pressures on the ecological status of rivers was analysed, demonstrating that ecological status can be predicted with 80 % precision without considering river flow regimes and their alteration. The 14 pressure indicators were: (1) catchment area, (2) elevation of catchment outlet, (3) agricultural surface, (4) artificial surface, (5) forest and semi-natural areas surface, (6) mean annual precipitation, (7) minimum summer precipitation, (8) maximum summer temperature, (9) density of linear hydraulic structures, (10) density of point hydraulic structures, (11) density of combined sewer overflows, (12) ratio between permitted water abstraction and precipitation (annual), (13) ratio between permitted water abstraction and precipitation (summer), (14) treated water fraction. A standard single correlation analysis showed that ecological status in the area correlates well with the surface area of the catchment, land use (agricultural, forest and urban surfaces), summer precipitation, summer temperature and elevation, less well but significantly with the permitted water abstraction and discharged wastewaters. Limited or non-statistically significant correlation was found with the presence of point hydraulic structures (proxies of morphological alteration) and combined sewer overflows. The 14 pressure indicators also showed some correlations among them, e.g., summer temperature and catchment elevation (Spearman's correlation $r = -0.71$), or the fraction of agricultural surface and the fraction of forest surface (Spearman's correlation $r = -0.88$). The selection of stressors in this work goes in the direction of keeping a smaller number of pressures correlated to ecological status, e.g. by removing highly correlated pairs, based on this previous work (Arrighi and Castelli, 2023). The pressures should be also (i) easy to calculate in a GIS environment, e.g., elevation is preferred over temperature since it is available as a regional Digital Elevation Model rather than as a sparse point observation, and (ii) satisfy the expectations of the Hydrographic District Authority, i.e., be consistent with the WFD.

Therefore, eight pressures are used in this analysis to account for catchment size, land use, climate and water management characteristics, namely: (1) area of the catchment (km^2), (2) fraction of agricultural surface in the catchment, (3) fraction of urban surface in the catchment, (4) average summer precipitation (mm), (5) mean catchment elevation (m.a.s.l.), (6) summer water exploitation (i.e., permitted water abstraction divided by precipitation volume in summer), (7) riparian alteration, and (8) released wastewater discharge divided by average flow. Although the area of the catchment area is not strictly a pressure, it was found correlated to the ecological status in the study area (Arrighi and Castelli, 2023). It probably reflects a higher probability of finding largest urban and industrial settlements, and related pressures, as we proceed downstream in a river network. The summer water exploitation is an indicator for the hydrological alteration of low flows due to water abstraction. In fact, water abstraction in summer (i.e., the driest season) is considered the most important quantitative pressure in absence of flow regulation in the study area. Mean catchment elevation is adopted as a proxy of air and water temperatures (Navarro-Serrano et al., 2018; Shreve, 1924; Zhu et al., 2018; Chen and Fang, 2015), which are crucial for river self-purification capacity.

3. Results and discussion

3.1. Results

The validation of the models to set the theoretical e-flow values Q_G and Q_B which represent flows that allow for good and bad ecological status respectively, is performed on one-third of the data where the ecological status is monitored, as described in section 2.5.2. The e-flow models to estimate Q_G and Q_B are applied to the catchments classified as having good or bad status and then compared with the actual flow Q in the river. Fig. 3 shows four scatter plots that compare the estimated e-flows with the actual flows obtained from the hydrological balance. The top two panels of Fig. 3 represent the mean annual flow for the validation set in good (top left) and bad (top right) ecological statuses. The agreement between the estimated annual mean e-flow and the actual annual mean flow is very good with a $R^2 = 0.88$ and $R^2 = 0.96$ for good and bad statuses respectively (Table 1). RMSE is 6.4 and 0.8 m^3/s for Q_G and Q_B respectively (Table 1) that compared to the annual mean flow data of the validation set (mean is 2.7 and 5.9 for good and bad statuses respectively) can be considered acceptable, especially for the Q_B theoretical value used for the EHDI calculation. Mean Absolute Error (Table 1) is negative for Q_B (-1.2 m^3/s) and positive for Q_G (3.3 m^3/s) highlighting that the two estimated theoretical values for bad and good e-flows identify two thresholds. The catchments in a good status lie above the upper threshold Q_G and the catchments in a bad status lie under the lower threshold Q_B.

The two bottom panels of Fig. 3 represent the mean summer flow for the validation set in good (bottom left) and bad (bottom right) ecological status. The agreement between estimated summer mean e-flow and actual summer mean flow is good with a $R^2 = 0.75$ and $R^2 = 0.84$ for good and bad statuses respectively. RMSE is 4.9 and 0.2 m^3/s Q_G and Q_B respectively (Table 1) that compared to the summer mean flow data of the validation set (mean is 0.6 and 1.3 for good and bad statuses respectively) is acceptable for the Q_B theoretical value and quite high for Q_G. Mean Absolute Error (Table 1) is negative for Q_B (-0.54 m^3/s) and positive for Q_G (2 m^3/s) confirming the same threshold behaviour observed for mean annual flows. Again, the catchments in a good status lie above the upper threshold for summer mean flow Q_G and the catchments in a bad status lie under the lower threshold for summer mean flow Q_B.

Both when considering annual or summer mean flow the R^2 appears larger and the RMSE smaller for the bad status threshold Q_B. This can mean that the theoretical threshold for the bad status is clearer while the good theoretical threshold is more uncertain. It is worth remembering that due to the transformation into a binary problem the "good" dataset includes high and good statuses, and the "bad" dataset includes moderate, poor, bad statuses. However, this supports the idea of using the

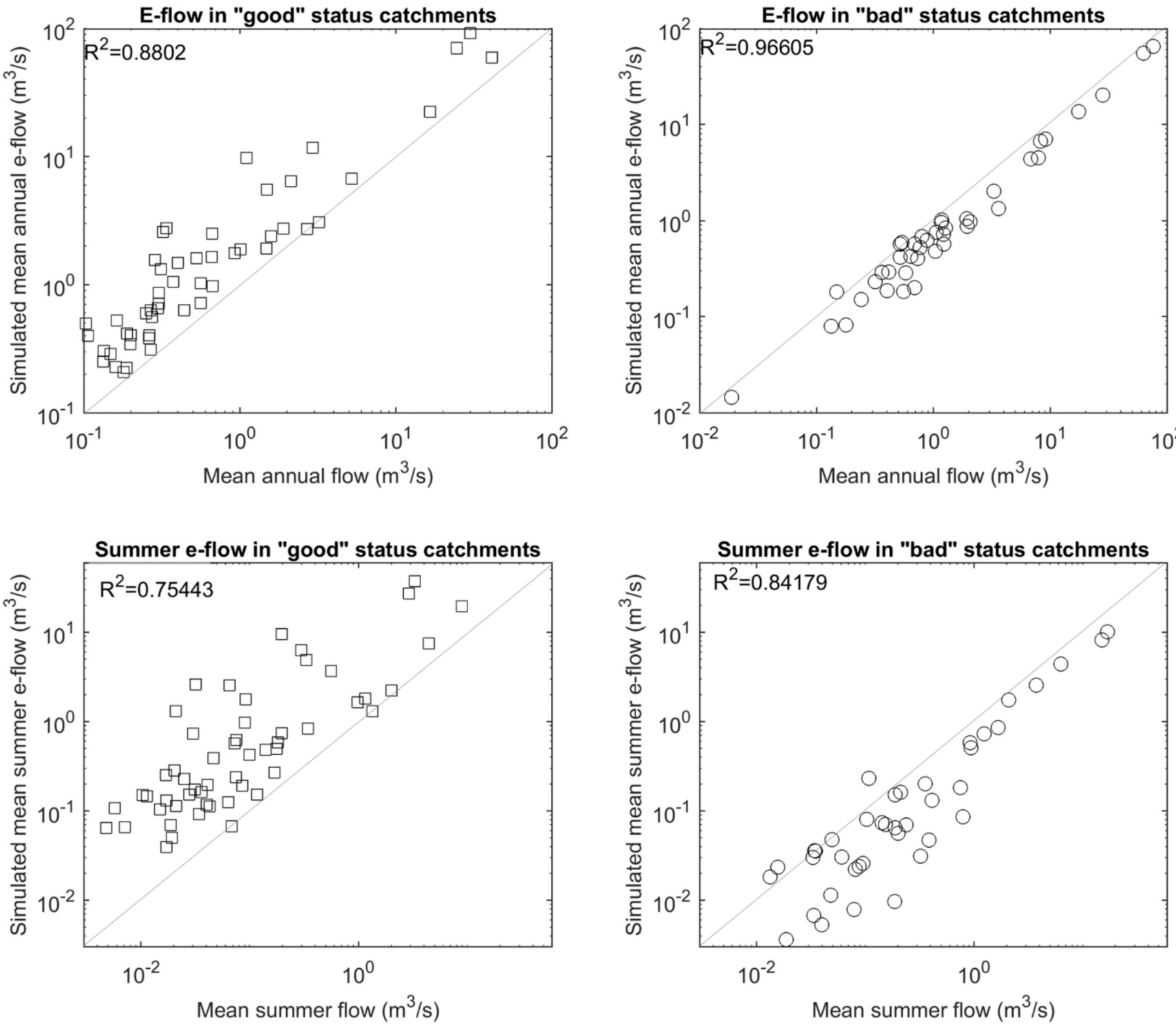

Fig. 3. Validation of the estimated e-flow for ensuring a good (left) or bad (right) ecological status for mean annual flow (top) and mean summer flow (bottom). The validation set for "good" status includes also rivers in high ecological status, while the validation set for "bad status" includes moderate, poor, bad statuses according to our transformation into a binary problem.

Table 1
Determination coefficients R^2, RMSE and MAE of the e-flow theoretical thresholds models tested on different flow regime statistics.

	Low flow statistics		Average flow statistics				
	$Q_{7,10}$	$Q_{7,2}$	Q_{winter}	Q_{spring}	Q_{summer}	Q_{autumn}	Q_{year}
R^2 good status threshold Q_G	0.57	0.50	0.91	0.77	0.75	0.91	0.88
R^2 bad status threshold Q_B	0.70	0.63	0.96	0.93	0.84	0.93	0.97
RMSE good status threshold Q_G	3.7	6.3	6.9	6.5	4.9	7.3	6.4
RMSE good status threshold Q_B	0.05	0.05	0.98	0.76	0.2	1.1	0.8
MAE good status threshold Q_G	1.4	2.4	4.5	2.6	2.0	4.3	3.3
MAE good status threshold Q_B	−0.36	−0.5	−1.6	−1.0	−0.54	−6.2	−1.2

concept of *safe distance EHDI* from a bad ecological status Q_B as a diagnostic tool for water management purposes, i.e. to evaluate new permitted water abstractions.

Other representative statistics of the flow regime have been tested, namely winter, spring and autumn mean flows, $Q_{7,2}$ and $Q_{7,10}$. Table 1 shows R^2, RMSE and MAE values obtained for each of the tested statistics of flow regime. According to the analysis (Table 1), all seasonal average flows perform very well in terms of R^2, especially autumn and winter season with values above 0.9. Also spring and summer e-flow models perform well with R^2 values above 0.8 and above 0.75 for bad and good ecological statuses, respectively. Low flows statistics instead have a much lower performance with R^2 values around 0.5–0.6. For the good status, RMSE and MAE of $Q_{7,2}$ and $Q_{7,10}$ (Table 1) are an order of magnitude larger than the mean of the validation set (0.19 m^3/s and 0.12 m^3/s respectively). For the bad status, RMSE and MAE of $Q_{7,2}$ and $Q_{7,10}$ (Table 1) are instead quite small with respect to the mean of the validation set (0.54 m^3/s and 0. 4 m^3/s respectively).

This behaviour suggests that ecological status is more sensitive to average flow conditions rather than on occasional extreme unfavourable conditions, i.e., low flows, however this aspect should be better analysed in further research. In all cases, the validation performs better in identifying the bad theoretical thresholds Q_B based on R^2, RMSE and MAE. The vectors of the coefficients b (eqs. 2–3) are available as supplementary material.

The models for e-flow theoretical thresholds are then applied to all river catchments where the hydrological balance and pressures are available in order to identify Q_G and Q_B in all catchments and calculate EHDI.

Fig. 4 shows the values obtained for annual mean flow (top) and summer mean flow (bottom) here ordered by increasing catchment area (one of the 7 indicators of pressure included in the regression) in the 11,135 river reaches of the study area.

From Fig. 4 it is possible to notice that good e-flows (blue) are larger than bad e-flows (orange) by construction, but also that for larger catchments (top right of both panels in Fig. 4), which are characterised by significant cumulative pressures, the two e-flow thresholds are significantly far from each other and their distance increases in summer. Moreover, the black dots which represent the flow appear in a very few cases larger than the good e-flow or lower than bad e-flow depicting very peculiar conditions. Flows are also very similar to bad e-flows for the largest catchments in the study area (top right part of both panels). The large spread should be also noted, confirming the need to consider a variety of pressure variables.

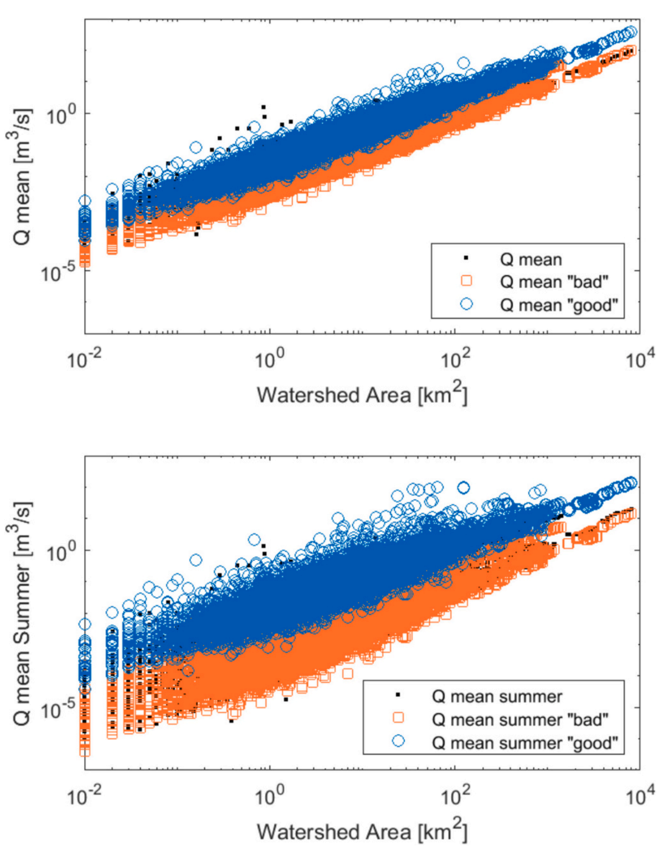

Fig. 4. *E*-flows theoretical thresholds for good (blue) and bad (orange) ecological status referring to mean annual flow (top) and mean summer flow (bottom).

The maps of Fig. 5 show the e-flow results for mean annual flow for good Q_G and bad Q_B thresholds in the top-right and top left panels respectively. The color scale has been adjusted to highlight the smaller streams which are characterised by mean annual flows of the order of 0.005–0.1 m^3/s. In the study area in fact only the Arno river (panel a, dark green color, center of the region) has a mean annual flow of the order of 40 m^3/s in its mid-course and of the order of 85 m^3/s close to the mouth. The Ombrone river (panel a, dark green color, South of the region) has a mean annual flow of the order of 30 m^3/s close to the mouth.

The results show a change in the order of magnitude of average flow from the bad threshold (panel a, Fig. 5) to the good threshold (panel b, Fig. 5). For the Arno river at the mouth Q_B is ca. 80 m^3/s (close to the actual mean annual flow) and Q_G is ca. 260 m^3/s, this witnesses one of the most critical situations in terms of pressures acting ecological status in the region.

For the Ombrone river at the mouth Q_B is ca. 26 m^3/s (slightly below the actual mean flow equal to 30 m^3/s) and Q_G is ca. 86 m^3/s, highlighting another critical river reach in the region.

The maps of Fig. 5 show the e-flow results for mean summer flow for good Q_G and bad Q_B thresholds in the bottom-right and bottom-left panels respectively. The maps show that summer bad e-flow thresholds Q_B are of the order of 0.005–0.01 m^3/s in the majority of the river network (panel c, Fig. 5) and these values should be on average doubled to get closer to the good ecological threshold Q_G in summer (panel d, Fig. 5).

For the Arno river at the mouth the summer Q_B is ca. 13 m^3/s (slightly below the actual mean summer flow ca. 20 m^3/s) and Q_G is ca. 120 m^3/s, this witnesses an exacerbated critical situation in summer with respect to annual average conditions because the flow is very close to the bad ecological threshold in summer.

For the Ombrone river at the mouth the summer Q_B is ca. 2 m^3/s (slightly below the actual mean summer flow ca. 3 m^3/s) and Q_G is ca. 30 m^3/s, showing a significant spread between Q_B and Q_G with respect to average annual conditions, but with an actual flow still above the bad ecological threshold.

The index EHDI allows to represent at regional scale the most critical situations in terms of eco-hydrological distance as shown in the maps of Fig. 6 for annual (panel a) and summer conditions (panel b). For the mean annual conditions (panel a) there are clearly two catchments which are distant from eco-hydrological targets. They are the Arno and Ombrone rivers which are represented in purple (flow lower than the annual Q_B) and red (flow slightly above annual Q_B). Rivers represented in blue and green are above or very close to Q_G respectively and are placed in the northern boundary of the region (Apuan and Appennines mountains, low anthropic activities), in some areas in the center and in the southern boundary of the region (low population density, presence of wild areas but also presence of springs which sustain the river flow throughout the year). In summer the situation is worse with EHDI lowering down to values close to Q_B in almost all the river network and with a reduction of streams close to Q_G which are limited to Apuan Alps and the center of the region due to very limited anthropogenic pressures and the presence of springs. Surprisingly a few river segments improve their EHDI value in summer. At a closer inspection these rivers are characterised by upstream reservoirs which ensure a flow much larger than the natural one in summer (Sieve river). Panel (c) of Fig. 6 represents the ecological status of rivers according to the WFD classification from high (green) to poor (purple) and shows a very good match between the outcome of the ecological monitoring by the regional authority (ARPAT) and the index EHDI. In fact, EHDI has negative values, i.e., flows lower than Q_B, where the ecological status is poor or bad and values above 1 when the ecological status is high, although the e-flow model was calibrated only on two subsets of data, i.e., at least good

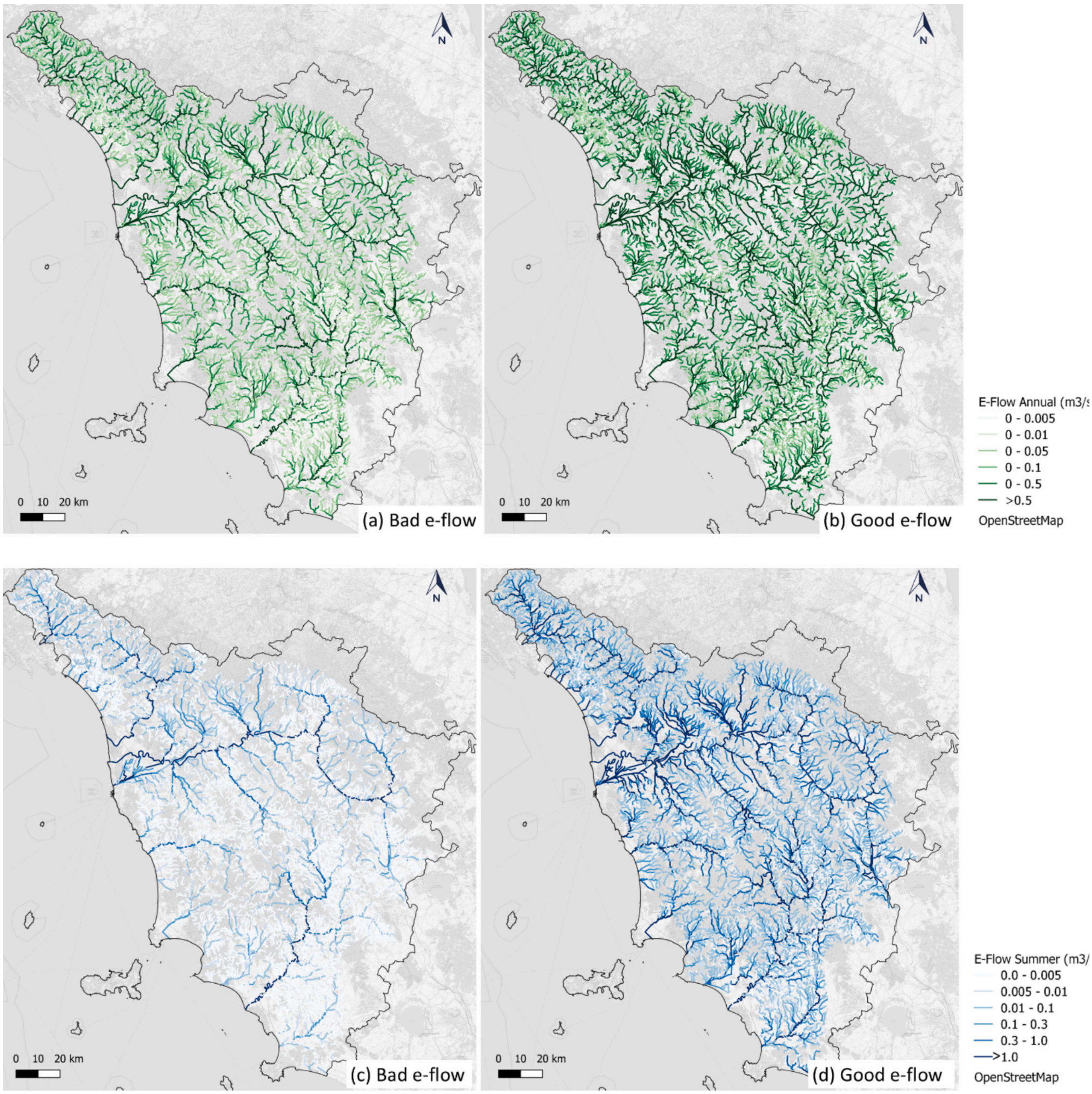

Fig. 5. *E*-flows theoretical thresholds for good Q_G (right panel) and bad Q_B (left panel) ecological status referring to mean annual flow (top) and mean summer flow (bottom) in the study area.

(good and high status) and less than good (moderate, bad and poor status). Panels d, e (Fig. 6) show a more dynamic view of two stream conditions taken as example. In panel (d) the river R653 has an annual EHDI that is not critical (quite distant from Q_B). However, during the summer season its EHDI becomes very close to zero. This means that further water abstraction in summer should not be allowed (mean summer flow is lower than summer Q_B). New abstractions would be possible in other seasons pending the verification of the new annual mean flow with respect to annual EHDI. In panel (e) the river R1272 is well above the thresholds Q_G for both the annual and summer conditions (EHDI>1). Thus, new water abstraction would be possible.

To test the model's ability to correctly discriminate between good and bad ecological status, we study the probability distributions of the EHDI estimated separately on the training set in good status and in bad status and evaluate the difference of these distributions using the Cramér - Von Mises test. The test is evaluated as passed with respect to a very restrictive probability on the null hypothesis ($\alpha = 0.5$ % instead of the usual 5 %). The Cramér-Von Mises test of EHDI confirms that the good and bad datasets are statistically independent when calculated with annual and seasonal average flows (values equal to 1), but not with low flows. This confirms that the tested low flow statistics $Q_{7,2}$ and $Q_{7,10}$ are not adequate to determine ecological status conditions in rivers, although they are currently in use to authorise new water abstraction in the study area. According to our methodology, new water abstraction should be avoided where the eco-hydrological distance index EHDI is negative, i.e., although freshwater is available its quality could be so impaired to require a larger dilution of pressures.

As described in the methodology, the e-flow theoretical thresholds, especially Q_G cannot be directly used to define e-flows because they can be larger than natural hydrological capabilities. However, the index EHDI allows to set a more coherent safety distance from Q_B (Eq.4) by selecting a value for the coefficient β. The selection of β can be seen as

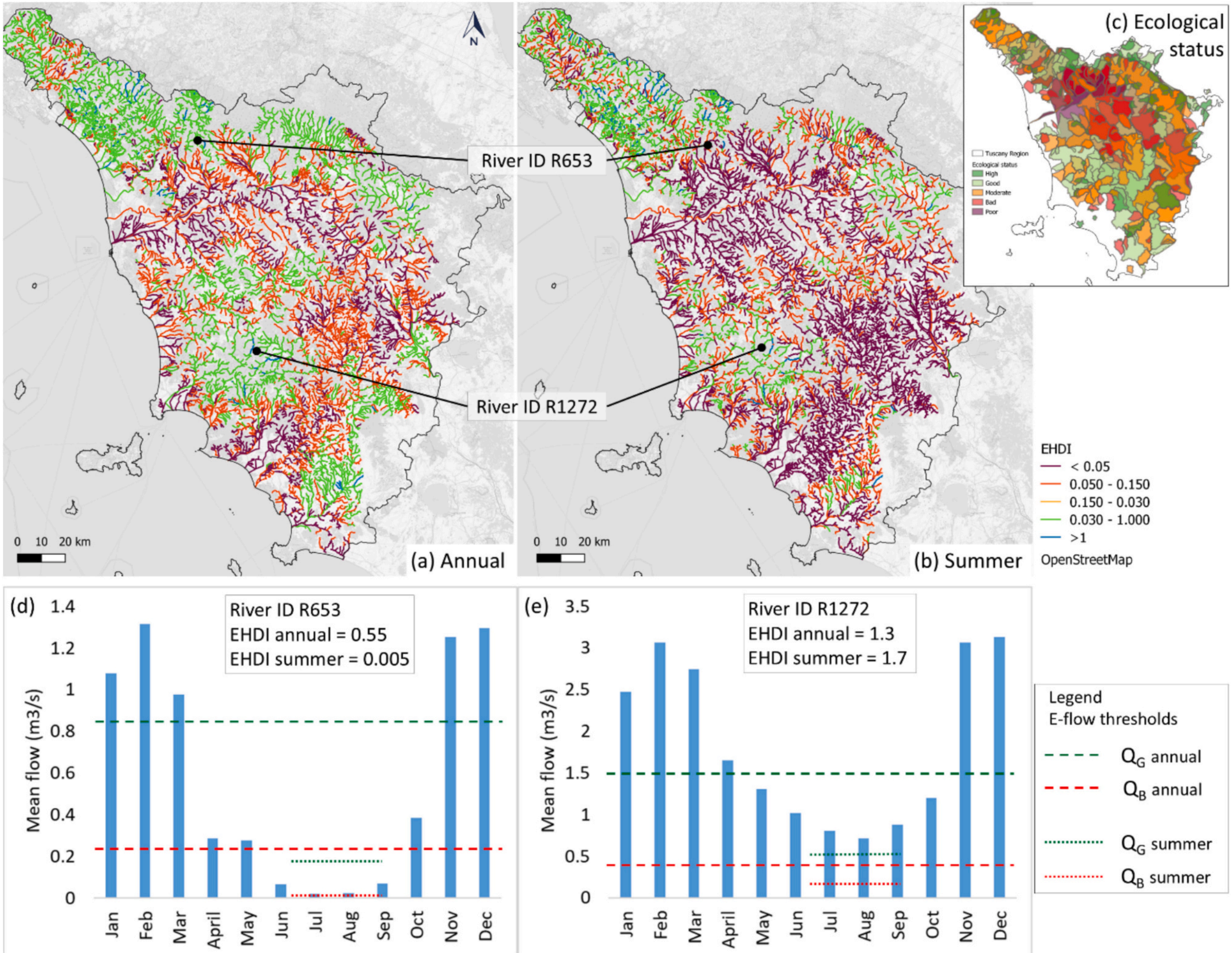

Fig. 6. EHDI referring to mean annual flow (a) and mean summer flow (b) in the study area. Ecological status of rivers as monitored by the environmental agency ARPAT (c). Two examples of streams where EHDI method finds practical application for authorizing new water abstraction. Possible further abstraction from autumn to spring (e) or all the year (d).

the decision to be implemented by the water authority in the phase of allowing or not new water abstraction in a stream, i.e., by selecting β, the e-flow Q_{ECO}, (Eq.4) is then obtained. The panels a and b of supplementary Fig. 7 show an example of selection of the coefficient β to determine the summer e-flow in study area for $\beta = 0.1$ and $\beta = 0.05$ respectively. The selection of a higher safety distance from Q_B yields a larger e-flows in the streams as can be noticed by comparing the blue shades in the two top panels of supplementary Fig. 7, i.e., darker blue colors are visible in panel a with respect to panel b. The actual feasibility of implementing summer ecological flow for $\beta = 0.1$ and $\beta = 0.05$ is shown in supplementary Fig. 7 panels c and d respectively. Summer e-flow is considered feasible if lower than the natural flow of the river segment. For the Arno and Ombrone rivers at the mouth, the summer e-flows for $\beta = 0.1$ are equal ca. to 24 m^3/s and 5m^3/s respectively. These values are slightly higher than natural flows which are 18 m^3/s and 3.5 m^3/s respectively. This means that also with a small value of β some rivers cannot achieve a sufficient distance from Q_B. For $\beta = 0.05$ the summer e-flows are equal ca. to 19 m^3/s and 4 m^3/s for the Arno and Ombrone river at the mouth respectively, thus again not applicable by restoring natural summer flow. Supplementary Fig. 7 (panels c, d) represents in green the river reaches whose summer e-flow is lower than natural flow and in blue the river reaches whose summer e-flow is larger than natural flow, i.e., reaching a good ecological status by means of e-flow is hydrologically unfeasible. For $\beta = 0.1$ (Fig. 7, panel c) the application of the summer e-flow is feasible only in 35 % of the river network. For $\beta = 0.05$ (Fig. 7, panel d) the feasibility of application of the summer e-flow increases up to 50 % of the river network.

The river reaches which cannot achieve a good ecological status with e-flow obtained by small values of β are those characterised by high human pressures as described by the negative or very small EHDI values (see Fig. 6, panel d). In these catchments only integrated actions aiming at a better management of water abstraction and diffuse and point source pollution might contribute to the achievement of European objectives of the WFD.

In supplementary Fig. 8 e-flow thresholds for good and bad statuses are compared to natural flows for the annual mean (top panel) and summer mean (bottom panel). In both panels the blue dots represent the good threshold Q_G and the orange dots the bad threshold Q_B. The black dots are the natural flows, i.e., the flows without the simulation of abstraction and release components. The transparency of the black symbols allows to see that in the whole river network the natural flows are usually placed between the e-flow thresholds. For the annual mean (top panel) we observe that for the larger catchments (watershed area > 10^3 km^2) natural mean annual flows are very close to Q_B. The summer season is confirmed to be the most critical for the study area. In fact, natural flows appear more frequently closer to Q_B or even lower (bottom panel). It should be noticed that in some cases natural flows can be also lower than actual flows, i.e., when the water discharged from wastewater treatment plant is significant.

3.2. Discussion

The identification of e-flows is crucial to satisfy human needs while respecting the health of ecosystems. The European WFD sets the objective of achieving a good ecological status of rivers partly through the assignment of an appropriate e-flow. The river basin district authorities manage large territories where typically pure hydrologic methods are applied (European Commission, 2015). However, the complexity of pressures acting on rivers (Grizzetti et al., 2017), makes hydrologic methods inadequate for addressing water quality alterations, such as the nutrient loads due to wastewater or agricultural runoff (Taniguchi-Quan et al., 2022; Yarnell et al., 2020; Stein et al., 2021). The application of our method to identify e-flow thresholds and calculate EHDI demonstrates that, when significant quality pressures are present in catchments, natural flows alone are insufficient to achieve a good ecological status. With respect to existing approaches at regional scale, which are only based on statistical analysis of flow or hydrological alteration (measured or simulated) (Leone et al., 2023b; Dalcin et al., 2022; Zhao et al., 2021), the method adopted in this work allows to embrace indirectly, i.e., through pressures, the ecological information to reflect the complexity of ecosystems with water quantity and quality alterations. There are examples of adjusting hydrological statistic values through the application of multiplicative coefficients in simple formulas to account, for instance, for agricultural land use in upstream catchments (Greco et al., 2021). This reflects the perceived need to refine hydrological methods by incorporating pressures; however, such adjustments have so far been carried out empirically. The regression models adopted in this work address the need to adjust pure hydrological statistics using a more quantitative approach grounded in ecological status classification.

The approach of EHDI allows to advance the understanding of e-flows with respect to the indicators of hydrologic alteration (Poff et al., 2010; Acreman and Dunbar, 2004), which was conceived to describe one main source of quantitative alteration of flow regimes which is the presence of dams and is not suitable when river hydrology is almost natural but rivers are impaired by pollution (Taniguchi-Quan et al., 2022; Tonkin et al., 2021). Therefore, the EHDI method complements the hydrologic alteration methods in situations where the water quality alteration is the main responsible of ecosystem deterioration.

The failure of WFD objectives has important consequences on biodiversity and river ecosystems services. In fact, river ecosystem services are affected by the deterioration of water quality (Grizzetti et al., 2019) and poor ecological status of rivers could prevent the use of water resources for human needs. The EHDI method could be also used to assess the effects of climate change by confronting flow statistics in a future climate with the thresholds Q_B and Q_G for present climate.

EHDI is a simple metric that could be used to discuss the effects of potential interventions to achieve the WFD objective. The selection of the coefficient β allows the authorities to set the safety distance from Q_B. Therefore, annual or seasonal e-flows can be identified starting from the theoretical thresholds and the sustainability of further water abstraction can be evaluated. Among the possible interventions are changes in water allocation strategies, improvements in wastewater treatments, land use planning. The effectiveness of these measures could be calculated in a catchment by modifying actual flows and pressures in the model (i.e., decrease of agricultural land use or decrease of released wastewater).

4. Conclusions

The newly defined Index of Eco-Hydrological Distance (EHDI) for rivers, based on theoretical e-flow regime thresholds for good and bad ecological status, effectively depicts the situation regarding anthropogenic pressures acting on river catchments. EHDI can be used as a diagnostic tool to assess the position of the actual river flow in relation to the bad and good thresholds and may support decisions on new water abstraction based on pressures affecting water quality, rather than solely relying on flow statistics. As EHDI can be calculated using any flow statistics, such as annual average or summer average flows, it highlights the most critical seasons that push rivers far from their ecological needs. EHDI can also be adopted to calculate eco-hydrological distance for future climate or in case of droughts. The method highlights that a good ecological status in rivers cannot be achieved through the sole identification of e-flows, which might be larger than the natural hydrologic capacity, in case the catchment is affected by significant quality pressures.

The low flow indices tested in this work are less capable than seasonal or annual mean flows in distinguishing between good and bad ecological statuses, as demonstrated by the Cramér-von Mises test and goodness-of-fit measures. The e-flow threshold Q_B calculated for seasonal and annual mean flows appears as the most reliable indicator to describe eco-hydrological characteristics (larger R^2 and lower RMSE with respect to Q_G). Obviously ecological phenomena in rivers are complex and involve small-scale aspects which are hardly tackled at regional scale, which is the scale of water management decisions.

Integrated actions towards a general reduction of diffuse and point source pollution together with a more sensible water abstraction management remains the only way to achieve the WFD objectives. Further research should better investigate the sensitivity of e-flow thresholds with respect to different pressure indicators and with respect to the single components making the ecological status. Moreover, a reduced number of pressures or different pressures could be tested in other study areas with similar environmental characteristics. A further application of EHDI method to future climate scenarios could also provide insights on future ecological status with present water exploitation.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178961.

CRediT authorship contribution statement

Chiara Arrighi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco De Simone:** Data curation. **Gaia Checcucci:** Project administration, Funding acquisition. **Isabella Bonamini:** Project administration. **Stefano Bartalesi:** Supervision, Project administration. **Cristina Simoncini:** Project administration. **Fabio Castelli:** Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fabio Castelli reports financial support was provided by Ministry of the Environment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work has been funded by FSC (Fondo Sviluppo e Coesione) Ministero dell'Ambiente e della tutela del territorio e del mare.

Data availability

Data will be made available on request.

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