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Review

Hydrological Regime Alteration Assessment in the Context of WFD 2000/60: A European and Global Review

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Abstract: Although the impact of hydrology on the ecological status of surface water bodies has been highly recognised, the hydrological regime alteration assessment has proven to be a challenging task. In this context, an extensive structured review analysis was used as a research method to investigate the strength and limitations of the hydrological regime alteration assessment methods as adopted by each member of the European Environment Agency and the cooperating countries, according to the Water Framework Directive 2000/60, as well as to propose future directions. The review was also widened to include the methods currently used worldwide in the hydrological alteration studies and the supporting software tools developed. The implementation of a common methodology on a European scale is not applicable, since a single approach would not be able to cope with the regional needs and conditions. The main limitation in almost all the methods developed by European countries and worldwide is the need for a flow time series of high temporal resolution, so as to also capture the systems' extreme high and low flows. Automatic monitoring systems for rivers can provide a solution. Additionally, hydrological modelling may provide the necessary data for the definition of the reference conditions. Nevertheless, the main limitations of the methodologies reviewed and the challenge for future development are the incorporation of the groundwater contribution to the hydrological regime and the development of quantitative relationships between flow alteration and ecological response.

Keywords: rivers; water quality status; hydrological indicators; biological quality elements; groundwater–surface water interactions; flow alteration–ecological response relationships; software tools; WFD 2000/60

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1. Introduction

The Water Framework Directive (WFD) of the European Community introduced in 2000 [1] provides the legislative framework for the sustainable management and protection of freshwater resources. The WFD indicates that all Member States should aim for at least "good ecological status" of surface water bodies with catchment areas greater than 10 km^2 that are affected by human activities by 2015 [2], a deadline that can be extended up to 2027 [1,3]. This condition can be achieved when both its ecological and chemical status are characterised as at least "good" and by implementing the necessary measures within integrated Programmes of Measures (PoM), considering existing Community requirements [4].

In order to identify the ecological status or potential of surface water bodies, specific biological element criteria should be considered, e.g., the composition and abundance of aquatic flora and benthic invertebrate fauna and the composition, abundance and age of fish fauna. Additionally, chemical/physico-chemical and hydromorphological elements are being used to support the biological elements for the assessment of the ecological status/potential of surface water bodies. The chemical and physico-chemical status of surface water bodies can be specified using general condition information and specific pollutant concentrations. The hydromorphological elements comprise the hydrological regime, river continuity and morphological conditions of the river. Regarding the hydrological regime of the hydromorphological quality elements, high status is accomplished when "the quantity and dynamics of flow, and the resultant connection to groundwaters, reflect totally, or nearly totally, undisturbed conditions", while good and moderate status is achieved when the conditions are consistent with the achievement of the values specified for the biological quality elements [1]. Therefore, where hydromorphological pressures affect the ecological status of the surface water body and prevent the WFD's objectives of achieving "good water status" of surface water bodies from being met, actions are required [5]. According to the Guidance Document No. 13 concerning the overall approach for the classification of ecological status/potential of surface water bodies, hydromorphological quality elements are considered only when assigning water bodies to the "high" ecological status class (i.e., for distinguishing between high and good ecological status or maximum and good ecological potential) [2].

The development of the PoM for each river basin district must aim to address previously identified pressures and consider the results of the analysis related to the environmental impact of human activities and economic analysis of water use [1]. Based on the most recent WFD Reporting Guidance [6], hydrological alteration is examined as an impact/driver to the habitat alteration reported (HHYC—altered Habitats due to HYdrological Change). Pressures related to the hydrological regime and hydrological alteration are specifically identified in the list of pressures as presented in Table 1.

Table 1. Significant pressures associated with hydrological regime alteration that may cause failure to achieve the objectives of WFD [6].

Pressure	Main Driver(s)	Description	Indicators for Pressure
3.1—Abstraction or flow diversion—Agriculture	Agriculture	Includes irrigation and livestock breeding	Volume of water abstracted/diverted for agriculture (million m^3) to be reduced to achieve objectives
3.2—Abstraction or flow diversion—Public water supply	Urban development	Affection to TW and/or CW possible only in case of desalination plants	Volume of water abstracted/diverted for public water supply (million m^3) to be reduced to achieve objectives
3.3—Abstraction or flow diversion—Industry	Industry	Abstraction for industrial processes (cooling water is covered under the category "Abstraction—cooling water")	Volume of water abstracted/diverted for industry (million m^3) to be reduced to achieve objectives
3.4—Abstraction or flow diversion—Cooling water	Industry; Energy—non-hydropower	-	Volume of water abstracted/diverted for cooling water (million m^3) to be reduced to achieve objectives
3.5—Abstraction or flow diversion—Hydropower	Energy—hydropower	-	Volume of water abstracted/diverted (million m^3) to be reduced to achieve objectives
3.6—Abstraction or flow diversion—Fish farms	Fisheries and aquaculture	Typically, off-line fish farms	Volume of water abstracted/diverted for aquaculture (million m^3) to be reduced to achieve objectives

Table 1. *Cont.*

Pressure	Main Driver(s)	Description	Indicators for Pressure
3.7—Abstraction or flow diversion—Other	Tourism and recreation	Abstraction for any other purpose not listed above.	Volume of water abstracted/diverted for other purposes (such as recreation) (million m^3) to be reduced to achieve objectives
4.3.1—Hydrological alteration—Agriculture	Agriculture	A change in the flow regime (e.g., due to land drainage).	Length (km)/area (km^2) of water bodies where hydrological alterations for agricultural purposes are preventing the achievement of good ecological status/good ecological potential
4.3.2—Hydrological alteration—Transport	Transport	A change in the flow regime—typically due to inland navigation	Length (km)/area (km^2) of water bodies where hydrological alterations for transport purposes are preventing the achievement of good ecological status/good ecological potential
4.3.3—Hydrological alteration—Hydropower	Energy—hydropower	A change in the flow regime (e.g., hydropeaking)	Length (km)/area (km^2) of water bodies where hydrological alterations for hydropower production are preventing the achievement of good ecological status/good ecological potential
4.3.4—Hydrological alteration—Public water supply	Urban development	A change in the flow regime	Length (km)/area (km^2) of water bodies where hydrological alterations for public water supply purposes are preventing the achievement of good ecological status/good ecological potential
4.3.5—Hydrological alteration—Aquaculture	Fisheries and aquaculture	A change in the flow regime	Length (km)/area (km^2) of water bodies where hydrological alterations for aquaculture purposes are preventing the achievement of good ecological status/good ecological potential
4.3.6—Hydrological alteration—Other	-	-	Length (km)/area (km^2) of water bodies where hydrological alterations for other purposes are preventing the achievement of good ecological status/good ecological potential

Among the European Union (EU) Member States and river basin management authorities, different approaches have been developed so as to monitor, evaluate and assess the ecological status/potential of surface water bodies that will support the identification of pressures and the development of the appropriate PoM on a catchment scale. The implementation of a common methodological approach on a European scale is not applicable since existing national classification systems are potentially better adapted to the local needs, the catchments' characteristics and climate conditions and processes [7] (Figure 1) that subsequently affect the physicochemical conditions, sediment supply and hydrological regime of the rivers and eventually biological communities, chemical conditions and hydromorphological quality elements [8].

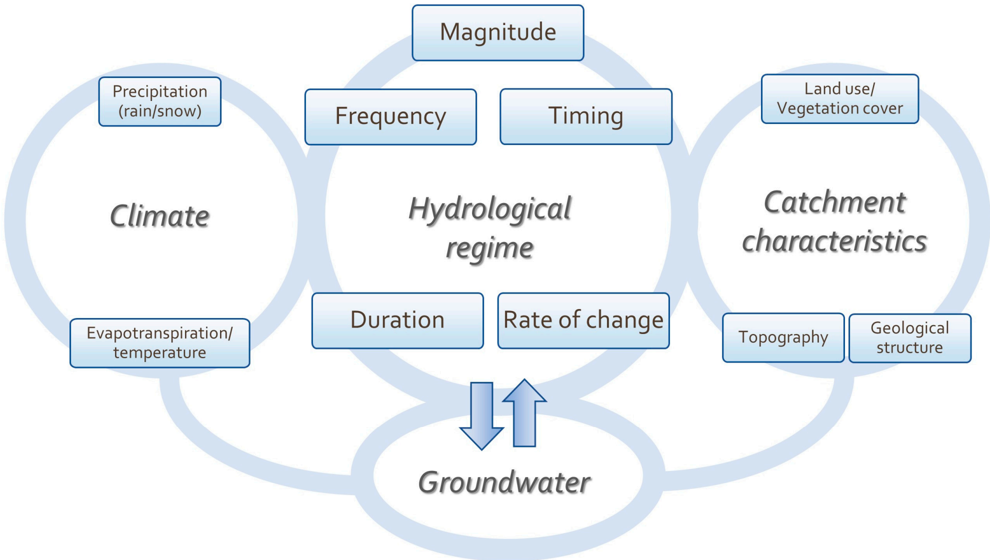

Figure 1. Factors affecting a river's hydrological regime and their interrelations.

Nevertheless, in Annex V of the WFD, it is recommended that the national methods adopted conform to the international standards, so as to ensure the provision of data of an equivalent scientific quality and comparability [9]. Regarding the hydromorphological quality element, the European Standard EN 14614:2020 "Water quality—Guidance standard for assessing the hydromorphological features of rivers" is currently in force [10]. Unlike EN 14614:2004, the updated EN 14614 also focuses on hydrological processes and how hydromorphological conditions are affected at each scale and provides examples of how river flow can be characterised using observations or modelled time series. Nevertheless, the related European Standard EN 15843 "Water quality—Guidance standard on determining the degree of modification of river hydromorphology" has not been updated yet. EN 15843:2010 [11], which is related to the old version of EN 14614, provides a protocol for the three-class characterization of river modification due to the effects of flow quality elements, e.g., the effect of artificial in-river structures or water abstractions on flow type diversity, discharge modification in relation to near natural flow characteristics due to catchment-wide pressures and daily flow alteration attributed to hydro-peaking [11].

The scope of the present paper is to review the methodological approaches adopted by each member of the European Environment Agency (EEA) of the European Union (EU) and the cooperating countries (CC) (Figure 2) for the assessment of the hydrological regime component of the hydromorphological quality element during ecological status/potential classification of surface water bodies for the implementation of the WFD 2000/60 under the 3rd Cycle of River Basin Management Plan (2021–2027). The review process was [1] widened also to include the methods currently used worldwide by non-European authorities and agencies in hydrological alteration studies or developed unofficially by European or non-European researchers, and to compare those to the ones developed for the implementation of the WFD. The software tools developed or used by the corresponding authorities and agencies for the hydrological regime alteration and classification are also presented.

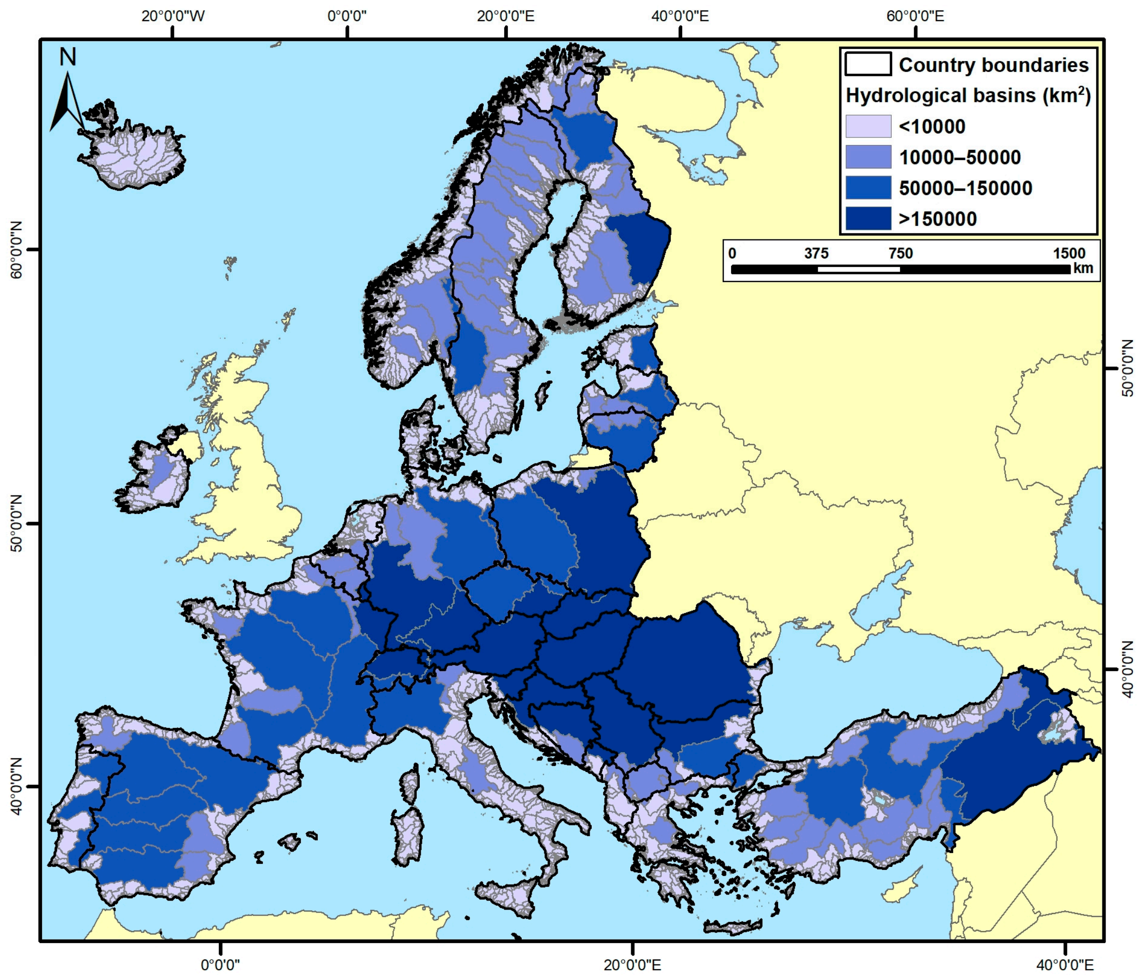

Figure 2. Member countries of the European Environment Agency (EEA) of the European Union (EU) and cooperating countries (CC) and classification of their major river basins based on the surface area [12].

So far, and to the best of our knowledge, research focusing specifically on the characterisation and assessment of the hydrological features and processes of flowing watercourses has not been conducted. Under the pan-European REFORM (REstoring rivers FOR effective catchment Management) project, 10 European and non-European hydrological regime alteration methods were reported in the deliverable concerning the literature review on existing eco-hydromorphological methods [13,14]. Likewise, under the river hydromorphological assessment and monitoring methodologies review conducted during the Common Implementation Strategy Ad-hoc Task Group on Hydromorphology 2016–2018 project, 41 hydromorphological methodologies used by EU Member States and EEA countries also covering, in some cases, the hydrological component of hydromorphological assessment were reported [15]. Finally, Jumani et al. [16] reviewed 13 methods to asses flow alteration and used them to develop decision-making trees to facilitate method selection. Therefore, this specific review analysis aims to fill this gap by comparing the existing hydrological regime alteration methods, highlighting the strengths and limitations and proposing directions for future development.

2. Methodological Approach

2.1. General Information

The main aim of the hydrological regime alteration assessment methods is to estimate the deviation of the current hydrologic regime in comparison to the natural one prior to human pressures and interventions. The magnitude of deviation is critical for the ecological functioning of the river and therefore for the capacity of the aquatic environment to provide its essential ecosystem services. Therefore, the appropriate hydrological alteration assessment method should consider both the hydrological and ecological characteristics of the study area in a relatively easy-to-apply approach in order for the methodology to be applicable to environmental engineers and managers. Moreover, the broad types of rivers and ecological characteristics existing worldwide make the selection of methods on a case-specific basis or at least per river typology a necessary approach for acquiring reliable assessment outputs.

A literature review as a research method provides a basis for advancing knowledge [17] and, if well conducted, can identify research gaps and limitations, develop precise research questions and set future directions [18,19]. In the specific structured review during which the relevant literature was identified using objective search criteria and the information was extracted in a structured fashion [18], the procedure described below was followed.

An extensive review analysis of the hydrological regime alteration assessment methods adopted firstly by the EEA members and the cooperating countries, and secondly worldwide, was performed. The main sources used were the protocols and background documents of each EEA country member and the cooperating countries, retrieved from the corresponding authority's official website and EIONET (European Environment Information and Observation Network) Central Data Repository. The EIONET consists of the EEA country members (the 27 EU Member States and the following five countries: Iceland, Liechtenstein, Norway, Switzerland and Turkey; EEA-MC) and the cooperating countries (the following six West Balkan countries: Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, Serbia, and Kosovo (this designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence); CC). It should be noted that the methodological approaches adopted by each EEA member for the implementation of the current 3rd Cycle of River Basin Management Plan (2022-27 RBMPs) were reviewed.

For non-EEA country members and the cooperating countries, the review process consisted of environmental agencies and ministries, official reports, scientific papers, and peer-reviewed journals, and technical resources screening. The research covered the last 35 years, which is considered sufficient [18]. The keywords used during the research were: hydrological/flow alteration/deviation/disturbance; flow stress; hydrological/flow index/indices; river/stream regulation; hydrological conditions; hydrological status; hydromorphological alteration/deviation/disturbance; hydropeaking; dam/reservoir disturbance; hydrological regime alteration/disturbance; quantity and dynamics of water flow; connection to groundwater bodies; and hydromorphological quality elements.

For each methodology reviewed, the following components were identified:

1. Methodology: the existence or not of a relevant methodology regarding the hydrological alteration assessment in the context of WFD for the EEA country members and the cooperating countries.
2. Type of methodology: index-based or descriptive.
3. Methodology components: whether both hydrological alteration components, as described in the WFD (e.g., (i) the quantity and dynamics of flow, and (ii) the resultant connection to groundwaters) have been included in the assessment.
4. Whether European Standard EN 14614 and/or EN 15843 were taken into consideration.
5. Whether the methodology has been updated for the 3rd RBMPs and whether further improvement is planned for the next cycle of RBMPs.
6. The temporary scale of the input data necessary for the assessment.
7. The minimum length of the time series necessary for the assessment.
8. Whether the river typology was taken into consideration during the development of the methodology.
9. The source of information proposed by the methodology (i.e., field data, modelled data, remote sensing, cartographic data or other).

10. How reference conditions are being assessed (i.e., based on historical data, based on reference sites, modelled, reconstructed or other).
11. The classification scheme used in the methodology.
12. Which components of the flow regime alterations are assessed, i.e., average flows, low flows (including extreme low flows—i.e., droughts) and/or high flows (i.e., small and large floods).
13. Information regarding the hydrological indicators and the corresponding indicator group used in the methodology.
14. The pressures identified by the methodology.
15. Whether during the development of the hydrological alteration methodology, the biological elements have been taken into consideration, and if yes, which one?
16. The software tools developed to support the methodology reviewed.

We would also like to note that during the review process, the related environmental (or ecological) flow (e-flow) methods were not taken into consideration. E-flow methods focus on estimating the flow requirements so as to ensure the maintenance of the biological integrity of the river ecosystems [20]; hydrological regime alteration methods aim to quantify the degree of river flow deviation between the current state and the unaltered/unimpacted conditions [14].

Finally, in order to identify the popularity of each method and its valuation as a scientific contribution [21], the primary reference citations in four electronic databases (Scopus, Web of Science, Google Scholar and ResearchGate) and the corresponding journal metrics when available are provided.

2.2. Hydrological Regime Indicators

Hydrologic indices (or indicators or metrics) are statistical parameters that characterise particular regions in terms of biologically relevant flow variables and quantify flow characteristics that are believed to be sensitive to various forms of human interventions [22]. Richter et al. [23] introduced 64 inter-annual statistics (32 measures of central tendency and 32 measures of dispersion) for the definition of the five main flow characteristics (magnitude, duration, timing of specific events, frequency and rate of change) (Figure 1) [24,25] and eventually the definition of the hydrological alteration. Although these statistics are the most commonly used in such assessments, other researchers or authorities have proposed different groups as indicators (e.g., [22,26,27]).

In EN 14614:2020, the proposed indicators related to the river flow regime and extremes are flow regime type; annual floods of hydromorphological significance ($m^3\ s^{-1}$): Q_{median}, Q_{2year}, Q_{10year}; specific stream power at contemporary bank full width (based on, e.g., Q_{median}, Q_{2year}, Q_{10year}); average annual flow; baseflow index; short-term rate of flow or water level change; flow duration curve and low flow frequency indicators; and timing of maximum and minimum flows [10].

It should be noted that a dataset of pressure quantitative indicators has been proposed by the Joint Research Centre (JRC) for the provision of a consistent view of anthropogenic pressures on surface water bodies of Europe. The pressures identified using the JRC Water Pressure Indicators can be compared to the pressure and status information reported by Member States under the WFD. Among the pressure indicators developed by JRC are two related to flow regime alteration: (a) the ratio of the volume of consumptive water use to the volume of annual available flow under natural conditions; and (b) the reduction of low flow durations or the number of additional days in the year when a given threshold discharge is not exceeded or equalled in the river due to abstractions in comparison to natural conditions [28].

3. Methods Reviewed

3.1. Methods Adopted by the EEA Members and the Cooperating Countries in the Context of the WFD

Based on the results of the review process, of the 38 EEA country members and the cooperating countries, 28 have developed methods for the assessment of hydrological regime alteration (Table 2 and Table S1a,b). In the case of France and Belgium, more than one methodology has been adopted by the corresponding province or region (metropolitan France and overseas regions of France; Brussels, Flanders and Wallonia, respectively), therefore overall 30 methodologies related to hydrological regime alteration have been reviewed. Of these 30 methodologies, 26 are index-based, while the other 4 are descriptive or the hydrological component is assessed only in relation to morphological alteration of the river waterbody. In 26 of the 30 methodologies reviewed, the "quantity and dynamics of flow" component of the hydrological regime alteration is assessed quantitively, and in 4, qualitatively. In 12 and 9 methods, the European Standards EN 14614 and EN 15843 recommended by the WFD were taken into consideration, respectively. In 10 cases, the methods were recently updated for the implementation of the 3rd RBMPs and in 9 cases it is stated that further development and improvements will be carried out for the next RBMP.

Table 2. Hydrological regime alteration assessment methods as component of the hydromorphological quality assessment for the WFD implementation adopted by the 32 EEA member countries and the cooperating countries (EEA-MC: EEA member countries; CC: cooperating countries; IN: index based on flow indicators; D: descriptive; M: hydrological component only in relation to morphological alteration; Ql: Qualitative; Qn: Quantitative).

a/a	Country		Method (or Part of)	Hydrological Regime Alteration Assessment	Quantity and Dynamics of Flow	Connection to Groundwaters	Reference
1	Albania	CC	-	-	-	-	[29]
2	Austria	EEA-MC	Austrian Guidance on hydromorphological assessment of rivers	IN	Qn	Qn	[30–32]
3	Belgium	EEA-MC					
	Brussels		évaluation de la QUALité du milieu PHYsique des cours d'eau/assessment of the quality of the physical environment of watercourses) (QUALPHY)	D	Ql	Ql	[33–35]
	Flanders		meetnet Hydromorfologie	M	Ql	-	[36,37]
	Wallonia		évaluation de la QUALité du milieu PHYsique des cours d'eau/assessment of the quality of the physical environment of watercourses) (QUALPHY)	IN	Qn	Qn	[38]
4	Bosnia and Herzegovina	CC	Hydromorphological assessment	IN	Qn	-	[39,40]
5	Bulgaria	EEA-MC	Flood Attenuation from Reservoirs and Lakes (FARL)	M	Qn	-	[41,42]
6	Croatia	EEA-MC	Methodology of monitoring and assessment of hydromorphological indicators	IN	Qn	-	[43]
7	Cyprus	EEA-MC	-	-	-	-	[44]

Table 2. *Cont.*

a/a	Country		Method (or Part of)	Hydrological Regime Alteration Assessment	Quantity and Dynamics of Flow	Connection to Groundwaters	Reference
8	Czech Republic	EEA-MC	Work procedure for the determination of significant effects on morphology and hydrological regime	IN	Qn	-	[45,46]
9	Denmark	EEA-MC	Dansk fysisk indeks/Danish Physical Index (DFI)	-	-	-	[47–49]
10	Estonia	EEA-MC	Part of the HM assessment (HYMO EST)	IN	Qn	-	[50]
11	Finland	EEA-MC	HyMo method (Kevomu-menetelmä)	IN	Qn	-	[51,52]
12	France	EEA-MC					
	Metropolitan France		SYstème Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau/Relational System of watercourse Hydromorphology Auditing (SYRAH-CE)	IN	Qn	Ql	[53,54]
	Overseas regions of France		Référentiel hydromorphologique ultra-marin/Overseas hydromorphological repository (RHUM)	IN	Qn	Ql	[55]
13	Germany	EEA-MC	LAWA-Klassifizierung des Wasserhaushalts von Einzugsgebieten und Wasserkφrpern/Classification of the water balance of catchment areas and water bodies	IN	Qn	Qn	[56]
14	Greece	EEA-MC	Methodology for the determination and the assessment of hydromorphological alteration	IN	Qn	-	[57,58]
15	Hungary	EEA-MC	Assessment of the hydromorphological condition of watercourses and standing waters	IN	Qn	-	[59]
16	Iceland	EEA-MC	Hydromorphological quality factors of streams and lakes	IN	Qn	-	[60,61]
17	Republic of Ireland	EEA-MC	Morphological Quality Index-Ireland (MQI-Ireland)	D	Ql	-	[62,63]
18	Italy	EEA-MC	Indice di Alterazione del Regime Idrologico/Hydrological Regime Alteration Index (IARI)	IN	Qn	-	[64,65]
19	Kosovo	CC	-	-	-	-	[66]

Table 2. *Cont.*

a/a	Country		Method (or Part of)	Hydrological Regime Alteration Assessment	Quantity and Dynamics of Flow	Connection to Groundwaters	Reference
20	Latvia	EEA-MC	Summary of methods for determining the significance of loads	IN	Qn	-	[67]
21	Liechtenstein	EEA-MC	Management plan and program of measures according to the Water Framework Directive	-	-	-	[68]
22	Lithuania	EEA-MC	Upės Hidromorfologinis Indeksas/River Hydromorphological index (UHMI-RHMI)	IN	Qn	-	[69]
23	Luxembourg	EEA-MC	OWK water balance	IN	Qn	Qn	[56,70]
24	Malta	EEA-MC	-	-	-	-	[71,72]
25	Montenegro	CC	\hydromorphological assessment	IN	Qn	-	[73]
26	Netherlands	EEA-MC	Handboek hydromorfologie 2.0/Handbook of hydromorphology 2.0	IN	Ql	Ql	[74]
27	North Macedonia	CC	-	-	-	-	[75]
28	Norway	EEA-MC	Forslag til metode for klassifisering av hydromorfologisk tilstand i norske elver/Proposal for a method for classifying hydromorphological conditions in Norwegian rivers	IN	Qn	-	[76]
29	Poland	EEA-MC	-	-	-	-	[77]
30	Portugal	EEA-MC	River Habitat Survey/Hydromorphological Quality Index for Large Rivers (RHS/IQHGR)	-	-	-	[78,79]
31	Romania	EEA-MC	Romanian Hydromorphological Assessment Methodology (HYMO_RO)	IN	Qn	Qn	[80]
32	Serbia	CC	-	-	-	-	[81]
33	Slovakia	EEA-MC	Hodnotenie hydromorfologickej kvality tokov/Evaluation of the hydromorphological quality of streams (HYMOK)	IN	Qn	-	[82,83]
34	Slovenia	EEA-MC	-	-	-	-	[84,85]

Table 2. *Cont.*

a/a	Country		Method (or Part of)	Hydrological Regime Alteration Assessment	Quantity and Dynamics of Flow	Connection to Groundwaters	Reference
35	Spain	EEA-MC	Protocol for the hydromorphological characterization of water bodies	IN	Qn	Ql	[86,87]
36	Sweden	EEA-MC	The Swedish Agency for Marine and Water Management regulations on classification and environmental quality standards regarding surface water	IN	Qn	-	[88]
37	Switzerland	EEA-MC	"Hydrology—flow regime" module at level R (region) (HYDMOD-R)	IN	Qn	-	[89]
38	Turkey	EEA-MC	hydromorphological assessment	IN	Qn	Ql	[90–92]

Although in most cases the contribution of the groundwater to the hydrological regime alteration assessment has been acknowledged, especially in the southern European countries, only 11 methodologies assess the "connection to groundwaters" component. The connection to groundwater is assessed in 5 cases quantitively using river discharge base flow or minimum/low flow, groundwater level measurements or spring discharge alteration, and in 6 cases qualitatively using lithological and geological maps and information regarding riverbed interventions, dam existence, catchment land use alteration and topography alteration, or a combination of the above.

Most methods require daily time series to assess the flow regime characteristics (N = 7), 6 methods use hourly time resolution, and 5 and 2 methods require monthly and annual time series, respectively. In 10 methods, the time resolution was not determined (Figure 3a). Additionally, only in 11 methods is the optimum minimum period of records stated, which ranges from 1 year minimum to 30 years.

The river typology is only considered in 9 methods. In the majority of methods (23), field measurements are used for the hydrological regime alteration assessment, while in 17 cases, additionally modelled time series, cartographic information and remote sensing data are used.

Reference conditions are being assessed based on the available information, and in most methods, more than one approach is proposed. In 8 cases, historical data are necessary (pre-impacted period), in 4 cases reference conditions are estimated based on reference sites, in 5 cases alternatively modelled time series are employed, in 2 cases the time series can be reconstructed by omitting the pressures identified and in 3 cases, the reference conditions are available in the form of maps (Figure 3b).

The alteration of the hydrological regime is estimated using the average flow component of the hydrological regime in 24 cases, low flows in 17 cases and high flows in 14 cases. In 5 cases, the hydrological regime component is not determined (Figure 3c). In many cases, a variation in hydrological indicators is used. In some cases (N = 12), the determination of the hydrological regime alteration takes into consideration almost all aspects of the 5 main flow characteristics (magnitude, duration, timing of specific events, frequency and rate of change) [24]. Nevertheless, in 14 cases, only magnitude is used to evaluate river conditions (Figure 3d).

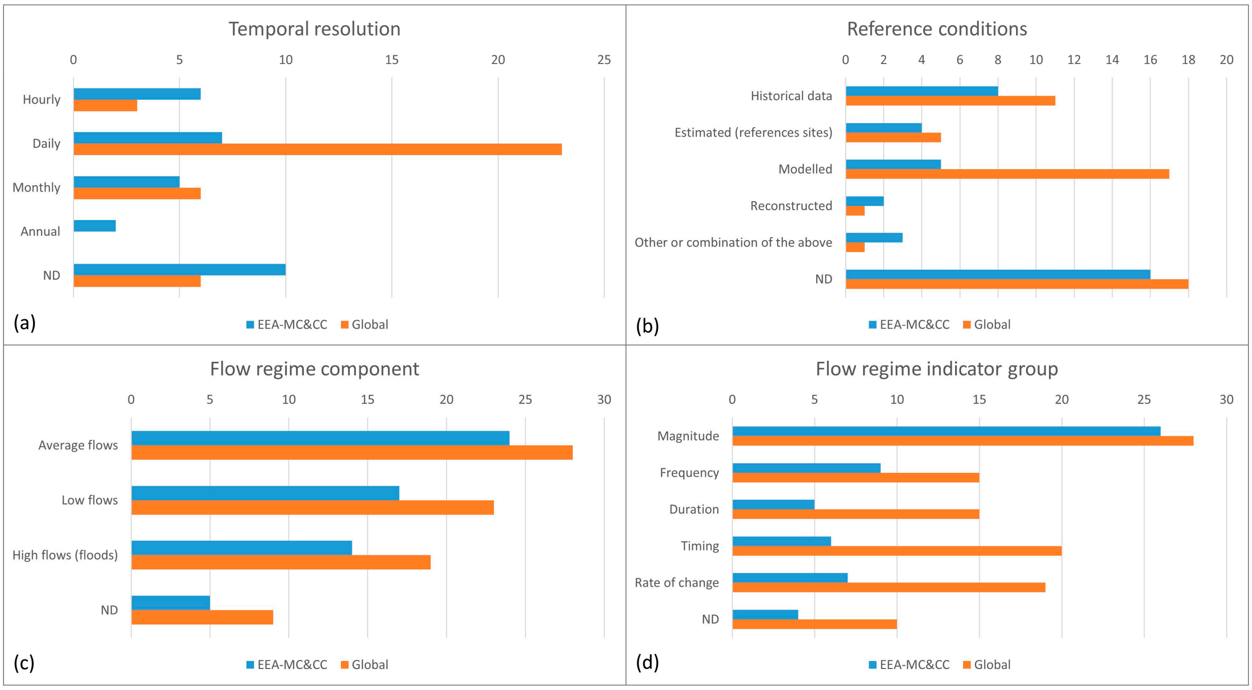

Figure 3. Number of reviewed methods for EEA-MC and CC, and globally, by their (**a**) temporal resolution; (**b**) reference conditions; (**c**) flow regime components; and (**d**) flow regime indicator group.

In 21 methods, a detailed description of the hydrological indicators needed for the assessment of the hydrological alteration is provided, in 1 method, the assessment is accomplished in a descriptive way, while in 8 methods, no information is provided. The most commonly used hydrological indicators for the assessment of hydrological alteration are the average annual flow, Q_a; the average daily flow, Q_d; the average monthly flow, Q_m; the average annual low flow, Q_{al}; and the average daily low flow, Q_{dl}. Not so common is the use of the median instead of the average flow of the above-mentioned indicators. Finally, in some cases (10), more sophisticated indicators are used, such as the change in mean flow, MQ, and 80% of the average flow in August, $Q_{aug80\%}$. Regarding high flow, the most common hydrological indicators used are the average level of peaking, La, and the length of effect of peaking, Ld, and the flood of 2-year/10-year/33-year return periods.

In 26 methods, the classification scheme is determined. A total of 16 methods use a 5-class system, 3 of which also use a 3-class system in some of the hydrological regime components. A 4-class system is only used in 2 methods, 3-class in 6 methods, and 2-class in 2 methods.

Although in all the 30 methodologies reviewed the effect of hydrological alteration on the biological elements has been highly acknowledged, only in 7 methods was a direct link accomplished. In 4 of these methods, the biological element that is specifically associated is mentioned (ichthyofauna in 4 cases, macrozoobenthos/benthic fauna in 3 cases, and macrophytes in 1 case), while in 3 cases, although mentioned, it has not been determined.

3.2. Other Methods Used Globally

Since the Indicators of Hydrological Alteration (IHA) were introduced to characterise the five groups of hydrological features (flow magnitude, duration, timing, frequency and rate of change) using 32 ecologically relevant parameters [23], numerous hydrological alteration assessment methodologies have been proposed. It is noted that daily discharge data are required for the assessment.

In Figure 4, the primary reference citations in four electronic databases (Scopus, Web of Science, Google Scholar and ResearchGate) and the corresponding journal metrics of each methodology listed in Table 3 are provided (see also Table S3). Based on the analysis, the most cited method used for hydrological alteration studies is the Range of Variability Approach (RVA; 396 median citations) followed by the Flow Duration Curves (FDC; 385 median citations), the Index of Stream Condition (ISC; 256 median citations) and the lotic-invertebrate Index for Flow Evaluation (LIFE; 241 median citations). The least cited methods were the ones referenced by technical reports and manuals instead of journal articles, book chapters or conference papers, indicating the possibly small penetration rate to the scientific community. Finally, it should be noted that there is a high negative correlation (−0.70) between the median citations and the year of publication.

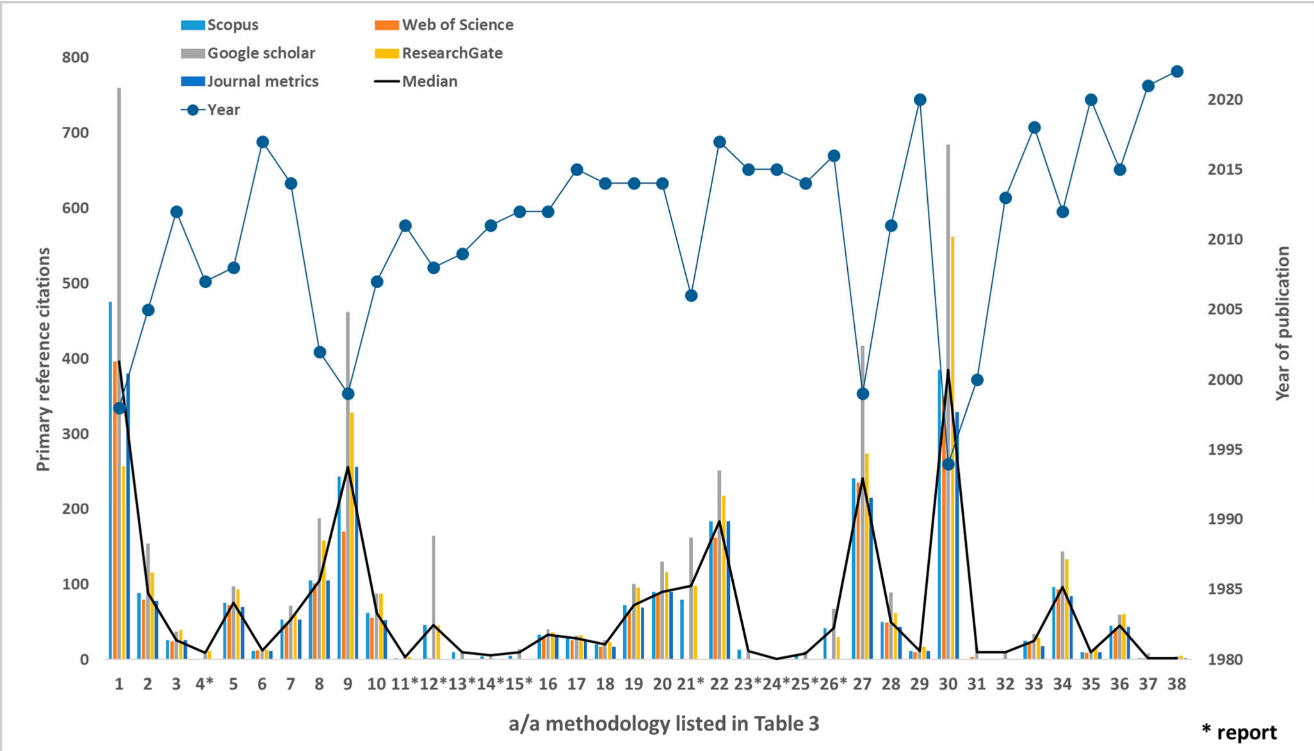

Figure 4. Primary reference citations per methodology listed in Table 3.

The range of variability approach (RVA) is a multivariable approach developed for the assessment of the degree of hydrological alteration of river ecosystems due to hydrometeorological and anthropogenic imposed pressures [93,94]. This approach, which employs the IHA parameters, suggests assessing hydrologic alteration based on the differences in streamflow regime characteristics between two defined time periods at a given stream gauge, a natural or unimpacted (e.g., predevelopment) and impacted (postdevelopment) condition. The final quantification of the overall degree of hydrologic alteration has been a challenge for all researchers. The RVA approach uses a simple three-class system of equal range of hydrologic alteration: low 0–33%, moderate 33–67% and high 67–100%. Other pieces of research have proposed a different classification scheme, such as the approach introduced by Shiau and Wu [95] that gives more weight to the high alteration category, allowing a highly altered IHA parameter to classify the overall degree of hydrologic alteration as high, the revised IHA method proposed by Zhou et al. [96] that gives each parameter its own weight by applying a projection pursuit (PP) and real-coded accelerated genetic algorithm (RAGA) or the fuzzy-based approach that uses the trapezoidal membership functions to quantify the belongingness of RVA into low, moderate and high alteration categories [97]. Other pieces of research have aimed at the simplification of the hydrological regime alteration procedure by minimising the number of IHA parameters used in the assessment. Since most IHA indicators have a strong correlation with one or two eco-flow metrics [98], many attempts have been made to eliminate intercorrelations and remove repetition by identifying dominant IHAs from 32 IHA indicators [99]. Finally, other have been attempts aimed at applications where only monthly time series datasets are available [100].

Apart from RVA, numerous methodologies developed utilise the IHA to assess hydrological alteration (Tables 3 and S2a,b). Overall, 38 methodologies have been reviewed that have been developed specifically for the assessment of hydrological regime alteration of rivers by various global environmental agencies, ministries, universities or individual researchers. In total, 36 of these methods are index-based and only 2 of them assess hydrological alteration qualitatively.

The majority of the methods reviewed require daily time series to assess flow regime characteristics (N = 26), 3 methods require hourly time series and 6 require monthly (Figure 3a). In 17 methods, the minimum period of measurements is stated and it ranges between 3 and 20–25 years.

Table 3. Hydrological regime alteration assessment methods reviewed apart from EEA members and the cooperating countries (IN: index based on flow indicators; D: descriptive; M: hydrological component only in relation to morphological alteration; Ql: Qualitative; Qn: Quantitative).

a/a	Methodology	Acronym	Country	Hydrological Regime Alteration Assessment	Reference
1	Range of Variability Approach	RVA	USA	IN/Qn	[23,93,94]
2	Dundee Hydrological Regime Alteration Method	DHRAM	Scotland	IN/Qn	[101,102]
3	Index of Global Alteration	IGA	Spain	IN/Qn	[103,104]
4	Hydrological Driver Assessment Index	HAI	South Africa	IN/Qn	[105]
5	Histogram Matching Approach	HMA	Taiwan	IN/Qn	[106]
6	Histogram Comparison Approach	HCA	China	IN/Qn	[107]
7	River Impact Index	IR	Finland	IN/Qn	[108]
8	River Disturbance Index	RDI	Australia	IN/Qn	[109]
9	Index of Stream Condition	ISC	Victoria, Australia	IN/Qn	[110,111]
10	Hydrological Disturbance Index	HDI	Australia	IN/Qn	[112,113]
11	Flow Stress Ranking	FSR	Victoria, Australia	IN/Qn	[114,115]
12	Sustainable Rivers Hydrology Index	SR-HI	Murray-Darling Basin, Australia	IN/Qn	[116]
13	Hydrology Sub-index Tasmanian River Condition Index	HSI-TRCI	Tasmania, Australia	IN/Qn	[117]
14	Chinese Hydrology and Water Resources Index	HD	China	IN/Qn	[118]
15	Index of Flow Health	IFH	China	IN/Qn	[119]
16	Index of Daily Hydrological Alteration	IDHA	Italy	IN/Qn	[120]
17	Alteration of the HYT (Hydrologic Year Types) Order	HYT	China	IN/Qn	[121]
18	Eco-Index	-	South Korea	IN/Qn	[122]
19	Ecological Risk due to Flow Alteration	ERFA	Pan-European	IN/Qn	[100]

Table 3. *Cont.*

a/a	Methodology	Acronym	Country	Hydrological Regime Alteration Assessment	Reference
20	River Regulation Index	RRI	-	IN/Qn	[123,124]
21	Hydroecological Integrity Assessment Process	HIP	USA	IN/Qn	[125]
22	Effective Degree of Regulation	EDOR	USA	IN/Qn	[126]
23	The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015	-	England and Wales	IN/Qn	[127,128]
24	The Water Framework Directive (Classification, Priority Substances and Shellfish Waters) Regulations (Northern Ireland) 2015	-	North Ireland	IN/Qn	[129]
25	The Scotland River Basin District (Standards) Directions 2014	-	Scotland	IN/Qn	[130]
26	Hydro-Morphological Quality Index	HMQI	-	IN/Qn-Ql	[131]
27	Lotic-invertebrate Index for Flow Evaluation	LIFE	United Kingdom	IN/Qn	[132]
28	Canadian Ecological Flow Index	CEFI	Canada	IN/Qn	[133,134]
29	Hellenic Flow Index	ELF	Greece	IN/Qn	[135]
30	Flow duration curves	FDC	USA	IN/Ql	[136–138]
31	Hydrologic Condition Assessment	HCA	USA	IN/Ql	[139]
32	Flow Duration Curve Index	FDCI	Canada	IN/Qn	[140,141]
33	Hydrologic Alteration Index	HAI	Southern California, USA	IN/Qn	[142,143]
34	Hydrological Status	HS	EU	IN/Qn	[144,145]
35	Mexican Standard-Hydrologic Alteration Indexes	HAI	Mexico	IN/Qn	[146,147]
36	Hydropeaking	HP	-	IN/Qn	[148,149]
37	Hydrology sub-index	HI	Turkey	IN/Qn	[150]
38	Dynamic Flow Alteration Indices	DFAI	-	IN/Qn	[151]

River typology is taken into consideration only in 5 methods. In the majority of methods (N = 30), field measurements are used for the hydrological regime alteration assessment, while in 19 cases, modelled time series are also employed. Finally, in 3 methods, cartographic information and remote sensing data are additionally used.

In 21 methods, details concerning the reference condition assessment are provided. In 11 methods, reference conditions are determined based on historical data, in 5, they are estimated based on reference sites, in 17, they are based on modelled datasets, and in 1 method, other data sources that are not determined are proposed (Figure 3b).

Alteration of the hydrological regime is estimated using the average flow component of the hydrological regime in 28 cases, low flows in 23 cases and high flows in 19 cases. In 9 cases, the hydrological regime component is not determined (Figure 3c). Out of the 5 main flow characteristics that are used to describe the river flow regime, magnitude is the one recorded and used most (N = 28). The timing and rate of change are also used in the majority of methods (20 and 19, respectively), while the frequency and duration are used by 15 methods (Figure 3d).

Regarding the hydrological indicators used for the evaluation of hydrological alteration, a variety of statistics are employed. In 10 methods, numerous indicators ranging between 32 and 171 are used to describe the 5 groups of hydrological features. Other methods are simpler in usage and require a smaller number of indicators (N = 24).

Finally, only 5 methods reviewed were associated with a biological element (1 with ichthyofauna, and 4 with macrozoobenthos) regarding the classification into environmental standards for river flows.

3.3. *Software Tools*

Due to the complexity and high computational demands of most methods in estimating the hydrological indicators that support the assessment of the hydrological regime alteration indexes, many software tools have been developed by authorities or research institutes and universities.

Overall, 13 software tools used in hydrological regime alteration studies have been reviewed (Table 4 and Table S4a,b). It should be noted that only software tools that, apart from the hydrological indicators calculation, also provide an estimation of the disturbance of the hydrological regime have been reviewed in this study.

The most famous is the Indicators of Hydrologic Alteration—IHA software version 7.1 developed by The Nature Conservancy, which is associated with the RVA method. Additionally, a package that implements The Nature Conservancy's Indicators of Hydrologic Alteration software in R [152] and in Python [153] has been developed. Indicators of Hydrologic Alteration in RIverS-IAHRIS version 3.0 is a software designed to obtain parameters that characterise the flow regime, both the natural and the regulated regime, and it also calculates a set of indicators that evaluate the degree of alteration of the most relevant environmental aspects of the flow regime and assess the condition of high alteration according to two criteria. The Hydrologic Index Tool (HIT) calculates 171 biologically relevant hydrologic indices using daily and peak flow records to be used for a regional stream classification analysis. The National Hydrologic Assessment Tool (NATHAT) program can be used to establish a hydrologic baseline (reference time period), to establish environmental flow standards and to evaluate past and proposed hydrologic modification. In addition to these two tools, the R package called EflowStats [154] and the MATLAB Hydrological Index Tool (MHIT) [155] were developed.

Table 4. Software tools used in hydrological regime alteration studies (for methods associated see Tables 2 and 3; see also Table S4a,b).

a/a	Name	Acronym	Developer	Method Associated	Reference
1	Indicators of Hydrologic Alteration	IHA	The Nature Conservancy (TNC)	RVA	[94,152,153,156]
2	Indicators of Hydrologic Alteration in RIverS	IAHRIS	Spanish Ministry of the Environment/Polytechnic University of Madrid	IGA	[104]
3	Hydrologic Index Tool	HIT	USGS	HIP	[22,125,154,155]
4	National Hydroecological Integrity Assessment Software	NATHAT			
5	Flow Health	FH	International WaterCentre, Fluvial Systems Pty and Yorb Pty Ltd.	IFH	[119]
6	River Analysis Package	RAP	eWater CRC	FDC	[157]

Table 4. *Cont.*

a/a	Name	Acronym	Developer	Method Associated	Reference
7	Streamflow Analysis and Assessment Software	SAAS	Ministry of Natural Resources and Forestry of Canada	FDCI	[140]
8	Temporary Rivers Ecological and Hydrological Status	TREHS	IDAEA-CSIC	HS	[158,159]
9	Hydrology—Flow Regime Module-FIT	HYDMOD-FIT	Hydrology-Flow Regime Module for the So-Called Spatial Step R (Regional Scale)	HYDMOD	[89]
10	COSH-Tool	-	SINTEF Energy	hydropeaking	[160]
11	Indicators of Short-Term Hydrological Alteration	InSTHAn	Universidad Politécnica de Madrid, Umeå University	hydropeaking	[161]
12	-	GeoTools	Engineering Research Center at Colorado State University	-	[162]
13	Hydrologic Alteration and Environmental Flow Assessment	Hydra-Eflow	Instituto Interamericano de Tecnología y Ciencias del Agua (IITCA); Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (Inrae)	IAHRIS/IGA or Mexican standard Hydrologic alteration indexes/HAI	[163]

Likewise, other software tools in Table 4 aim to quantify the disturbance of flow regime characteristics by calculating the relevant hydrological indicators and evaluating the degree of hydrological alteration. Only 2 of the total software tools reviewed are related to the WFD implementation, while the other 11 were developed to support similar water management strategies worldwide. All software tools except one are free to use, and all are provided in Windows executables, although in some cases, the alternative of using R, Python or Matlab is provided.

4. Discussion

Hydrological regime alteration assessment has proven to be a challenging task. For the implementation of the objectives set by WFD, various methodologies and approaches have been adopted by the EEA members and the cooperating countries and adjusted to the local needs and data availability. Although the effect of the hydrological component on the state of riverine systems has been acknowledged, the incorporation in the estimation procedure for the ecological status or potential of surface water bodies is usually incomplete. Nevertheless, it should be noted that many member countries have managed to assess the hydrological regime alteration successfully (e.g., Austria [29–31], Italy [64,65], Norway [76], Spain [85,86], Switzerland [89]), while in relation to the 2nd RBMPs, a considerable improvement has been reported and the gap among the countries tends to be narrower.

In most cases, the methodologies manage to characterise only part of the five hydrological features (flow magnitude, duration, timing, frequency and rate of change) [24] and usually focus on identifying the magnitude alteration. This is in agreement with the main finding of the Common Implementation Strategy Ad-hoc Task Group on Hydromorphology 2016–2018 project report [15] that concluded that both magnitude and duration are two of the flow characteristics used most. Generally, in most methods reviewed, some flexibility and adjustments based on the dataset availability are allowed. As a general rule, simple approaches are preferable by the EEA country members and the cooperative countries. Sophisticated indicators are usually not used, and rather simple and easily applied indicators are preferable.

The need for long and high-resolution flow time series is in many cases the main obstacle to the reliable assessment of hydrological alteration of a specific river waterbody. Most methods require daily flow datasets, which are not always available since usually field flow measurements are conducted seasonally. Additionally, high-temporal-resolution data obtained from automatic stations are usually sparse or are not always considered to be representative of a specific river waterbody (e.g., Greece [164]). Another challenge is the definition of the reference (unimpacted) conditions, which require either long natural (e.g., predevelopment) time series or the development of hydrological models for the specific location as also described by Hawkins et al. [165].

Although in most cases, the contribution of the groundwater to the hydrological regime alteration assessment has been acknowledged, especially in the southern European countries, only 11 methodologies assess the "connection to groundwaters" component, and in most cases qualitatively. This was also concluded by Belletti et al. [14], who mentioned that groundwater alteration is neglected and only assessed indirectly through low-flow analysis. Finally, although the effect of hydrological alteration on the biological elements has been highly acknowledged, only in seven methods has a direct link been accomplished.

Regarding the hydrological regime alteration methods reviewed globally, based on the results of the current review, the requirements for detailed datasets are even higher. The majority of the methods use daily flow time series and, in most cases, modelled time series is proposed to be used for the estimation of the reference conditions so as to overcome the lack of field measurements. Flow regime indicators proposed are more complicated and manage to cover almost all of the five hydrological features (flow magnitude, duration, timing, frequency and rate of change). Nevertheless, the implementation of these methods requires experienced personnel and is more time-consuming. Finally, although all research worldwide highlights the impact of hydrological alteration on biological elements of the riverine systems, few manages to directly link the classification of hydrological alteration to the biological quality of river water bodies.

Due to the complexity and high computational demands of most methods in estimating the hydrological indicators that support the assessment of the hydrological regime alteration indexes, many software tools have been developed by authorities or research institutes and universities globally. These tools, although developed to meet the needs of different and usually local needs, aim to support similar water management strategies in the context of Integrated Water Resources Management (IWRM), such as the WFD, the Australian National Water Initiative (NWI), the Clean Water Act in the United States or the National Water Act of South Africa [141]. The vast majority of these tools are free to use and are available in a Windows-executable format.

5. Conclusions and Future Directions

The scope of the present review was to report the current state of the art concerning the assessment of hydrological regime alteration in the context of the WFD by each member of the European Environment Agency (EEA) of the European Union (EU) and the cooperating countries, as well as worldwide. It should be noted that during this review procedure, in some cases, the original reference could not be identified or was not reported; therefore, in these cases, some inaccuracies in the description of the hydrological regime alteration assessment that cannot be determined may occur. Additionally, in many cases, the hydrological regime alteration assessment was described in a non-English language. Although every effort was made to ensure the accuracy of the information retrieved, some details may elude us. Finally, it should be noted that in many cases, hydrological regime alteration methods are being developed operationally by local environmental agencies, research institutes and consultant organizations; therefore, some methodologies and related protocols may have not been detected during the current review procedure, especially in the case of non-English language speaking countries.

The development of a global hydrological regime alteration assessment method cannot be supported, since a single approach would not be able to capture the regional needs and distinctiveness.

The main limitation in almost all the methods developed for hydrological alteration assessment is the need for flow time series of a high temporal resolution, so as to also capture the systems' extreme high and low flows. It is generally accepted that daily hydrologic data provide the appropriate temporal resolution for understanding many ecological responses and, thus, developing hydrological classifications [166]. Automatic monitoring systems for rivers can provide a solution since they can supply continuous, reliable and low-cost flow measurements [167] for the assessment of the current hydrological regime after proper monitoring program planning.

Additionally, the assessment of the hydrological alteration requires the definition of the reference conditions. The advances in hydrological modelling may provide the necessary input for such analysis in an efficient and cost-effective way, although their development can sometimes be time-consuming and require expertise [168].

Although the contribution of groundwater to the hydrological regime alteration assessment has been highly acknowledged, especially in southern European countries, few methods manage to include the groundwater component in the hydrological regime assessment. An insight regarding the multifactor and interconnected process between surface-groundwater interactions can be provided using new advancements, such as isotope analysis and element speciation, statistical analysis and modelling, thermal approach and geophysical techniques such as electrical resistivity tomography and airborne electromagnetic surveys [169,170].

Finally, the main limitation of the current methodologies developed and the challenge for future development is the link of ecological response to flow regime alteration. The development of quantitative relationships between flow alteration in terms of magnitude, frequency, duration, timing and rate of change, and ecological responses according to taxonomic identity (macroinvertebrates, fish, riparian vegetation) and type of response (abundance, diversity, demographic parameters) are needed [171]. Despite the progress in hydroecological research regarding the understanding of how flow regimes affect biota and ecosystem processes, major challenges persist that prevent a complete understanding of the flow-biota-ecosystem processes' nexus [172]. Research should focus on manipulative or experimental design supported by modelling tools, with the scope to advance knowledge on the ecological response to multiple stressors such as flow alteration [172,173] (Figure 5).

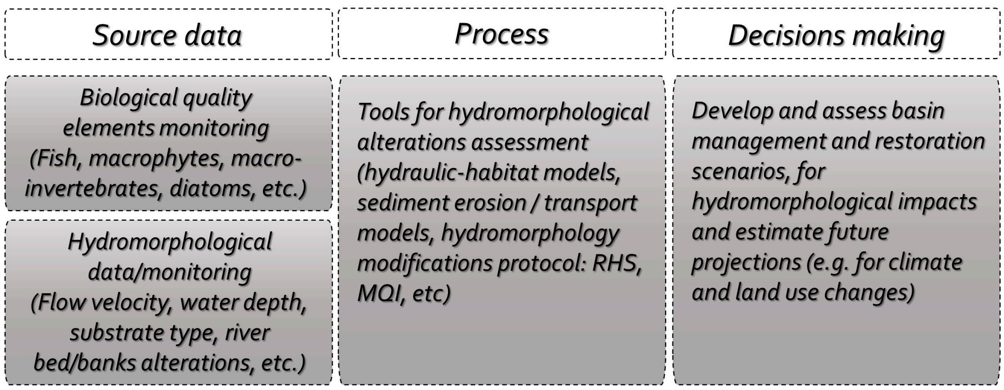

Figure 5. Procedure of river water quality status identification and management regarding hydromorphology and the hydrological regime component.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152215704/s1, Table S1a. Reviewed hydrological regime alteration assessment methods adopted by the 32 EEA member countries and the cooperating countries and their main characteristics (IN: index based on flow indicators; D: descriptive; M: hydrological component only in relation to morphological alteration; Ql, qualitative; Qn, quantitative); Table S1b. Reviewed hydrological regime alteration assessment methods adopted by the 32 EEA member countries and the cooperating countries and their main characteristics (ND: not determined; IN: index based on flow indicators; D: descriptive; M: hydrological component only in relation to morphological alteration; Ql, qualitative; Qn, quantitative; component: 1: average flows, 2: low flows, 3: high flows; indicators: see footnote; indicator group: 1: magnitude, 2: frequency, 3: duration, 4: timing, 5: rate of change; pressures identified: 1: flow diversion, 2: abstractions, 3: hydropeaking, 4: channel interventions, 5: large scale interventions; biological element: 1: ichthyofauna, 2: macrozoobenthos/benthic fauna, 3: macrophytes); Table S2a. Reviewed global hydrological regime alteration assessment methods (IN: index based on flow indicators; D: descriptive; M: hydrological component only in relation to morphological alteration; Ql, qualitative; Qn, quantitative); Table S2b. Reviewed global hydrological regime alteration assessment methods (ND: not determined; component: 1: average flows, 2: low flows, 3: high flows; indicator group: 1: magnitude, 2: frequency, 3: duration, 4: timing, 5: rate of change; pressures identified: 1: flow diversion, 2: abstractions, 3: hydropeaking, 4: channel interventions, 5: large scale interventions; biological element: 1: ichthyofauna, 2: macrozoobenthos/benthic fauna, 3: macrophytes); Table S3. Reviewed global hydrological regime alteration assessment methods—number of primary reference citations; Table S4a. Software tools used in hydrological regime alteration studies; Table S4b. Software tools used in hydrological regime alteration studies (continued).

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