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Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants

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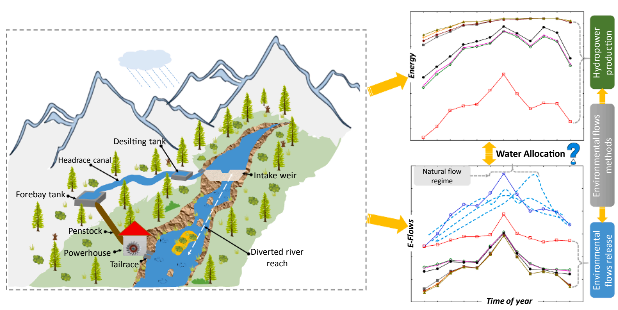
HIGHLIGHTS

- Pluvial stable hydro-sites resulted in stable hydropower production.
- Pluvial highly fluctuating hydro-sites showed impulsive hydropower production.
- Pluvial-nival hydro-sites indicated unstable hydropower production.
- Minimum EFMs compromised the trade-off between hydropower production and e-flows.
- Dynamic EFMs enhanced e-flows and maximised the hydropower production.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigates the influence of the river flow regime type on the e-flows releases and hydropower production, constrained by eight hydrologically-based e-flows methods. For this purpose, 20 run-of-river hydropower plants up to 10 MW, from five Iberian Peninsula basins, located in regions with pluvial highly fluctuating, pluvial stable, pluvial winter, and pluvio-nival flow regimes were analysed. We integrated a hydropower model with a hydrological model, and eight e-flows methods to estimate mean daily hydropower production, e-flows, and hydrologic alteration. The results demonstrate little influence on hydropower production and e-flows releases for the pluvial regime type, notably, pluvial stable regime river reaches. Pluvio-nival regime provides unstable hydropower production and comparatively high e-flows alteration. Overall, hydrologic parameters represented by five global indices derived from Indicators of Hydrologic Alteration were affected differently for the e-flows releases regime induced by tested e-flows methods. In general, e-flows methods that involve annual minimum flow and indices of flow duration curve show inconsistent results among all study cases and hydrological regimes types; either they result in high e-flows releases while sharply reducing hydropower production or vice versa. However, so-called dynamic approaches demonstrate consistent results and are more suitable, both in terms of hydropower production and e-flows releases by therefore providing 10–35% more energy production while having little impact in several hydrological parameters. The findings of this study may serve as a starting point to initiate a new discussion on the methods and criteria that should be established regarding e-flows determination at run-of-river hydropower plants.

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Nomenclature

Abbreviations and acronyms

RoR	Run-of-River hydropower plant
SHP	Small Hydropower Plant
HPP/HP	Hydropower Plant
LHP	Large Hydropower Plant
EFM	Environmental Flow Method
NFR	Natural Flow Regime [$m^3 s^{-1}$]
e-flows	Environmental Flows [$m^3 s^{-1}$]
ELOHA	Ecological Limits of Hydrologic Alteration
IHA	Indicators of Hydrological Alteration
FDC	Flow Duration Curve
1/3 ASF	1/3 of the Average Summer Flow [$m^3 s^{-1}$]
10% and 25%MAF	10% and 25% of Mean Annual Flow [$m^3 s^{-1}$]
%Q-Daily	% of Mean Daily Flow [$m^3 s^{-1}$]
MMQ	Annual Minimum Flow [$m^3 s^{-1}$]
T	Turbine

Parameters

A	basin area [km^2]
Q_{min}	minimum flow [$m^3 s^{-1}$]
Q_{mean}	mean flow [$m^3 s^{-1}$]
Q_{max}	maximum flow [$m^3 s^{-1}$]
H_g	gross head [m]
H_{net}	net head [m]
L	diversion length [m]
P	installed power capacity [MW]
η_{T_j}	turbine efficiency [%]
η_G	generator efficiency
γ	the unit weight of water [Nm^{-3}]
τ_h	operating hours [h]
Δt	time (days)
d_y	number of days in a year (365)

Indices

Q_{75}, Q_{95}	percentiles exceedance of FDC [$m^3 s^{-1}$]
DDI	Downstream Diversion Index [–]
$I_{i,j}$	alteration index regarding hydrological indicators i for each group j [–]
$HI_{i,j}nfr$	hydrological indicator related to the natural flow regime [–]
$HI_{i,j}afr$	hydrological indicator related to the altered flow regime [–]
$\#HI_{i,j}$	number of hydrological indicators for each group [–]
I_{MM}	mean monthly flow alteration index [–]
I_{MDE}	magnitude and duration of extreme flow alteration Index [–]
I_{TE}	timing of extreme flow alteration index [–]
I_{FD}	frequency and duration alteration index [–]
I_{RF}	rate and frequency alteration index [–]

Variables

Q_{nfr} (t)	natural flow regime [$m^3 s^{-1}$]
Q_{mfr} (t)	minimum flow regime [$m^3 s^{-1}$]
Q_{env} (t)	environmental flows [$m^3 s^{-1}$]
Q_{afr} (t)	altered flow regime [$m^3 s^{-1}$]
Q_d	design discharge [$m^3 s^{-1}$]
$q_d(t)$	mean daily turbine inflow [$m^3 s^{-1}$]
Q_{tech}	minimum technical operation flow [$m^3 s^{-1}$]
Q_{hydro} (t)	available flow for energy production [$m^3 s^{-1}$]
q_j (t)	turbine inflow [$m^3 s^{-1}$]
E (t)	energy production [GWh]

1. Introduction

The rapid growth of population and industry has sharply increased the energy demand on a global scale. In many countries, particularly in developing countries, energy consumption is growing much faster than domestic energy production [1]. Drastic depletion of fossil fuels, and other non-renewable energy sources as well, and also increasing awareness towards global warming has already shifted many countries' focus on the exploitation of renewable energy sources [2]. Among renewable energy sources (i.e., hydro, wind, solar, tides, biomass, biofuels and geothermal), hydropower is the most common and represents the highest share, accounting for 83.6% of overall renewable energy sources and more than 16.4% of global electricity production [3,4]. Hydropower is an important renewable energy resource to respond to the load change of the power system [5]. Hydropower installed capacity at the global scale has reached up to 1267 GW, while net electricity production is about 4185 TWh, which account for about 48% of potential electricity production (i.e., 8721 TWh) from hydropower plants [6]. At this time, the amount of electricity generated from hydropower plants is enough for supplying only one billion people [3]. The hydropower installed capacity is predicted to increase by 35% within the next two decades [3]. Hydropower development is gaining more and more interest mainly because of the less carbon dioxide and other gasses emissions, efficiency, operation flexibility, low operation and maintenance cost, and economic benefit among others [3,4]. There are two main categories of hydropower plants; Large Hydropower Plants (LHP) and Small Hydropower Plants (SHPs) [6]. Regarding the installed capacity, an SHP has an installed capacity that usually varies from 0.1 to 10 MW, although this range may vary from country to country [7]. Regarding the operation mode, SHPs are classified into non-diversion with daily or weekly storage regulation, without storage (i.e., kinetic), diversion with hourly storage regulation, and without storage (i.e., in-weir schemes) [8]. The last three types of SHPs have been widely recognised as Run-of-River (RoR) hydropower plants. According to the hydraulic head, RoR hydropower plants are often classified into three sub-categories: ultra-low head (up to 3 m); low head (above 3 m); and medium/high head (above 40 m) [7]. Due to their lack of storage, RoR power plants usually share the base load of the daily energy production curve with nuclear plants and other renewable energy sources. The peak load is handled by hydropower plants with enough water storage, usually LHPs. Until the mid-20th century, LHPs used to have a favourable public acceptance and were considered as the cleanest among other renewable energy sources [7]. However, despite many social and economic benefits, non-run-of-river LHPs cause significant alteration of the Natural Flow Regime (NFR) by interrupting the connectivity of river flow [9] and intensely impairing the riverine ecosystem [10,11]. SHPs may thus represent a less invasive solution compared to LHPs. Therefore, considered as a more friendly solution, development of SHP has gained remarkable momentum, especially during the last decades, and is still drawing high interest on policymakers and investors [12]. Predominantly, Europe has a long tradition in the development of SHPs and already has installed more than 48% of the potential capacity [13,14]. Worldwide installed capacity of SHPs is estimated to be more than 78 GW, while the total estimated potential is around 217 GW [14]. So far, a little more than 36% of the total global SHPs potential energy production is being exploited. To some extent, SHPs are becoming progressively successful options and seem promising renewable energy sources to provide sustainable and inexpensive electricity, particularly for small localities in remote areas [4,15,16]. There has been notable progress of automated tools, mainly GIS-based tools, to identify the most suitable site for SHP development [17,18]. Also, there are developed a plethora of tools to optimise water allocation among several users and maximise the SHP's energy generation [9,19]. Nevertheless, still, electricity production and efficiency of SHP, particularly RoR hydropower plants, strongly depend on the intra-annual hydrological regime [20,21]. There are periods of the year with less water available. Furthermore, there are predictions that climate change will negatively affect the energy generation, particularly from RoR hydropower plants located in alpine regions [22]. Therefore, counting such situations, it is essential that in general, SHPs potential capacity should be carefully designed in order to maintain high efficiency [15]. In practice, very often, to cope with low flow periods, multiple turbines of a different size may be installed in the same hydropower plant. The utilisation of multiple turbines in economic terms is a good strategy to maintain high efficiency and profitability, but it may lead to profound water exploitation by altering the abiotic environment and threatened the riverine ecosystem [8,12,23]. Therefore, regardless of the predominant positive perception that exists about SHPs, there is also evidence of ecological impacts [23,24]. In addition to the temporary impacts, such as landscape destruction (i.e., tree uprooting, soil removal, space occupation and so on), there are indications of permanent impacts as well [15,23]. SHPs affect the stream connectivity by causing water depletion in the diverted river reach [23,24], and threatens the existence of several fish species, particularly non-migratory species, e.g., trout (*trutta)* [15]. Literature also shows that SHPs may affect macro-invertebrates diversity [25], morphology and sediment distribution along the river as well [26]. Extensive utilisation of SHPs may also affect water quality and physical-chemical related parameters (e.g., water temperature, pH, conductivity, turbidity, dissolved oxygen, water depth, and flow velocity) [27,28]. Although, in different regions and flow regimes, ecological impacts may not be similar and in the same magnitude, still it is essential considering mitigation measures to preserve the riverine ecosystem and support the sustainable development of SHPs. Among the mitigation measures, environmental flows (hereafter e-flows) are the most common and effective way to ensure ''good ecological status'' of the riverine ecosystem downstream the water intake [29]. There is already a vast number of E-Flows Methods (EFMs) applied in practice for addressing e-flows requirements [30]. EFMs are usually clustered in three categories; the first category represent holistic approaches which mainly includes: Building Blocks Method (BBM), Downstream Response to Imposed Flow Transformation (DRIFT), and Ecological Limits of Hydrologic Alteration (ELOHA) framework [30,31], second category includes habitat simulation [32], and the third category comprises conventional methods (i.e., hydrological based and hydraulic rating) [30]. In many occasions, data availability, resources, timing, geographical location, social and economic aspects determine the type of EFM to be applied for defining the e-flows. In the mid-20th century, when the concept of the e-flows started evolving, first EFMs aimed to ensure a minimum flow downstream the water diversion or dams based on poorly ecologically grounded rules. Still, e-flows determination in case of RoR hydropower plants has been given much less attention. Furthermore, as RoR hydropower plant, among others is subject to seasonal river flows and hydrological regime variability. Thus, the hydropower plant will operate therefore as an intermittent energy source. Therefore, e-flows are very often seen by hydropower stakeholders as a physicalconstraint in maximising energy production [23,33]. Although no generalised and systematic methodology exists so far, in case of SHPs and particularly for relatively small RoR hydropower plants up to 10 MW, hydrological based EFMs are the most common in practice [30]. Moreover, the percentage of minimum mean annual flow and indices of flow duration curve EFM are among the most common, even though not strongly ecologically grounded [34]. Inconsistent application of the EFMs may affect hydrological attributes that drive some of the essential ecological processes but also the energy generation from the hydropower plant [35,36]. There are few recent studies that involve trade-offs between socio-economic benefit and environmental flows requirements, such as considering several EFMs to define possible trade-offs in case of RoR hydropower plants [35,37], complex environmental flow requirement to improve habitat condition for particular target fish species [36,38,39], proportional and non-proportional rules to optimize energy production and e-flows releases [40,41], which can provide suitable ecological conditions without significantly affecting the energy production. Nevertheless, in many cases, regardless of the evidence of the ecological impacts from RoR hydropower plants [23], optimisation models prioritise mainly energy production, e-flows very often remains excluded or poorly considered [8]. However, there are some examples where e-flows are considered as a physical constraint or optimization objective in the model process [33]. It should be highlighted that in case of the cascade system, the optimization difficulty will be sharply increased with the growing number of hydropower plants and also physical constraints [42]. Therefore, considering the importance of riverine ecosystem preservation and supporting the sustainable development of renewable energy sources, is indispensable to provide an eco-friendly solution by incorporating interdisciplinary knowledge into planning and operation phases of RoR hydropower plants. In this regard, one of the most ecological based frameworks (i.e., ELOHA), which was built on the impression that several ecological processes are shaped by ecologically meaningful hydrological parameters (i.e., magnitude, duration, timing, frequency, and rate of change), recommends classification of the river segments within biogeographic and climatic region based on the flow regime type according to the hydrological parameters similarities among them [31]. Thus, flow-ecology relationships can then be used to predict potential ecological consequences due to the flow regime alteration. Therefore, taking into consideration both riverine ecosystem protection and economic benefits derived from energy production, potential trade-offs might be proposed. In this study we particularly examine the trade-offs between energy production e-flows release, and e-flows regime alteration at 20 RoR hydropower plants, considering four flow regimes types, in five basins in the Iberian Peninsula; by applying different e-flows restriction imposed from eight hydrologically-based EFMs. To our knowledge, there has been little attention on how the e-flows determination affects both energy production and river ecosystem at RoR hydropower plants considering different e-flows methods and flow regimes types. This gap is partially addressed in this paper by analysing the indirect impacts of different energy generation scenarios on e-flows releases and vice versa. Therefore, such interdisciplinary studies bring more insights to understand the impacts of seasonality and e-flows in the energy-water nexus. The innovative nature of this study lies in the integration of different components in order to have a clear view about tools that promote sustainable development of RoR hydropower plants. The outcome is quantified in terms of energy generation, e-flows releases, and flow alteration. Finally, this study provides some novel approaches, findings, conclusions and presents a practical methodology that might help decision-makers and water managers, ensuring sustainable development and operation of RoR hydropower plants.

The main objectives of this study were: (i) to evaluate the implications of eight hydrologically-based EFMs on hydropower production and e-flows releases regarding each river flow regime type, (ii) flow alteration characterisation due to water diversion, (iii) in particular, we were also interested in investigating if e-flows restriction imposed by a combination of two different EFM could reduce flow alteration without significantly affecting the hydropower production, and last (iv) examine whether potential trade-offs and ecologically meaningful hydrological parameters differ among them depending on the applied EFM and river flow regime type. The paper is structured as follows: Section 2 presents information about the case studies and data acquisition and describes the applied methodology; Section 3 presents the main results; discussion and interpretation of main results are presented

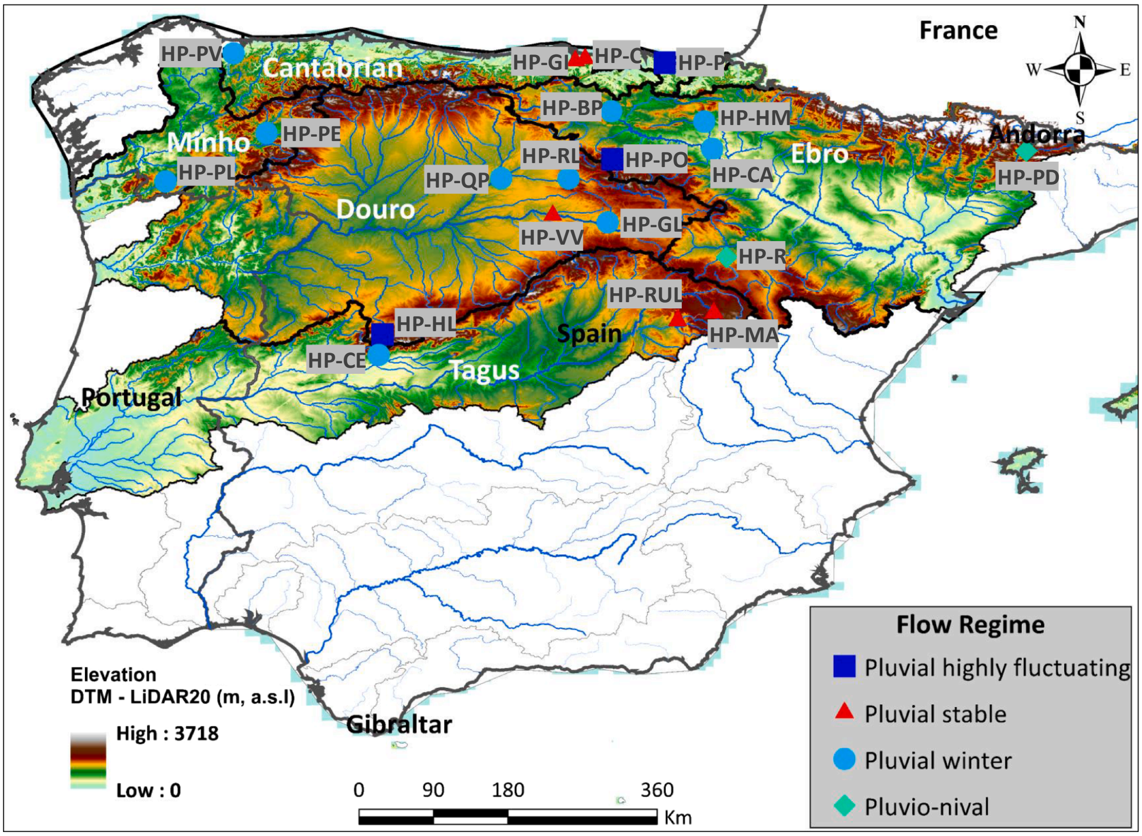

Fig. 1. Study area, location of the 20 RoR hydropower plants over five basins in the Iberian Peninsula, and flow regime along the river reach, regarding the indicated gauging stations, located near to the water intake of each hydropower plant. Standardised mean monthly natural streamflow for each flow regime type is presented in Fig. 3.

in Section 4. Finally, an outlook for future work and a range of conclusions concerning the most suitable flow regime type, implications imposed by EFMs on energy production, e-flows releases, and flow alteration are presented in Section 5.

2. Material and methods

2.1. River basins description

The quantitative analysis of the e-flows scenarios imposed by eight EFMs and their implications on hydropower production, e-flows releases and flow alteration is applied to 20 RoR hydropower plants located within five river basins in the Iberian Peninsula; respectively: Cantabrian, Minho, Ebro, Douro, and Tagus basin (Fig. 1).

Table 1
Main features of the river basins regarding basin area ($\boldsymbol{A}$), climate type, average precipitation ($\bar{\boldsymbol{P}}$),and water exploitation represented as a number of hydropower plants (HPP) in operation.

Basin name	A (km^2)	Climate type	$\bar{P}$ (mm)	Water exploitation (no. of HPP)		References
				RoR	LHP	
Cantabrian	19,002	Oceanic	1000	> 139	67	[43]
Ebro	85,939	Mediterranean-Continental	700	> 205	216	[44]
Minho	17,619	Oceanic	1050	> 7	15	[45]
Douro	95,880	Temperate, Mediterranean-Continental	700	> 70	58	[46]
Tagus	80,629	Mediterranean	650	> 26	41	[47]

The five river basins where the study cases are located differs among them in terms of geomorphology, size, climate, rainfall/runoff regime, water exploitation, and so on. In general, all these river basins are subjected to extensive water resources exploitation, notably for energy production, water supply, and irrigation. The natural flow regime, especially in the main rivers of these river basins, is profoundly altered, particularly by LHP. Nevertheless, interest in SHPs development is rapidly sprawling across the Iberian Peninsula and beyond [14]. Some of the main characteristics and water systems development of the river basins are presented in Table 1.

2.2. Hydropower plants description

The 20 RoR hydropower plants considered in this study differ from each other regarding the head, design discharge, installed capacity, and length of the diverted river reach (Table 2). The head-based classification of hydropower plants was done according to Abbasi and Abbasi [27]. Basic information (i.e., location, head, length of diverted river reach, and so on) about the selected hydropower plants were obtained from Spanish Geoportal [48]. The study cases were chosen considering the following criteria. First, all selected hydropower plants should have a gauging station in the main river, which may be located instantly upstream of the water intake. Second, the flow regime should not be altered by regulated reservoirs or regulated area upstream should be < 10% of the entire catchment [49]. Third, the gauging station should have consecutive records of the mean daily flow data, and as little as possible gaps to capture the natural flow regime. Fourth, the selected river reaches should represent typical flow regime types, i.e., pluvial highly fluctuating, pluvial stable, pluvial winter, and pluvio-nival [50,51]. Some of the technical characteristics of the hydropower plants are presented in Table 2.

Table 2
Technical features of the 20 RoR hydropower plants considered in this study: river name, hydropower plant name, water intake coordinates($\boldsymbol{Lat}$, $\boldsymbol{Lon}$), gross head ($\boldsymbol{H_g}$), design discharge($\boldsymbol{Q_d}$), minimum technical operating discharge ($\boldsymbol{Q_{tech}}$), turbine type ($\boldsymbol{T}$), diversion length ($\boldsymbol{L}$) and hydropower plant typology; run-of-river: ultra-low head ($\boldsymbol{RoR - UL}$), low head ($\boldsymbol{RoR - L}$), medium head ($\boldsymbol{RoR - M}$), high head ($\boldsymbol{RoR - H}$). Hydrological characteristics for each hydropower plant are shown in Table 3.

River name	Hydropower plant name**	Lat, Lon (°N, °E)	H_g (m(	Q_d ($m^3 s^{-1}$)	Q_{tech} ($m^3 s^{-1}$)	T*	L (km)	Typology
Asón	Coterillo (HP-C)	43.328, −3.441	5	18	0.4	K/K	0.5	RoR-L
Agüera	Guriezo Inferior (HP-GI)	43.296, −3.327	25	3.5	0.08	K/K	5.4	RoR-L
Eo	Pe de Viña (HP-PV)	43.396, −7.180	11	16.8	0.38	K/K	1.2	RoR-L
Artibai	Plazakola (HP-P)	43.297, −2.475	5	2.7	0.06	K/K	0.1	RoR-L
Ucero	Güera, La (HP-GL)	41.569, −3.087	5.2	4.7	0.11	K/K	0.3	RoR-L
Tormes	Higuerilla, La (HP-HL)	40.353, −5.533	4	18.7	0.42	K/K	0.4	RoR-L
Arlanza	Quintana del Puente (HP-QP)	42.073, −4.218	4.5	28.2	0.63	K/K	0.5	RoR-L
Arlanza	Rachela, La (HP-RL)	42.045, −3.545	3	12.6	0.28	K/K	0.7	RoR-L
Duero	Virgen de las Viñas (HP-VV)	41.653, −3.679	8.5	18.7	0.42	K/K	0.1	RoR-L
Omecillo	Barrio del Puente (HP-BP)	42.780, −3.046	5	3.4	0.08	K/K	0.4	RoR-L
Ega	Cárcar (HP-CA)	42.392, −1.966	5.7	12.8	0.29	K/K	1.2	RoR-L
Ega	Hijos de Martínez (HP-HM)	42.668, −2.023	2	13.4	0.30	K/K	0.2	RoR-UL
Segre	Parque Deportivo (HP-PD)	42.358, 1.472	7.8	15.4	0.35	K/K	1.1	RoR-L
Oja	Posadas (HP-PO)	42.237, −3.043	22	2.5	0.06	F/K	0.6	RoR-L
Piedra	Requijada (HP-R)	41.157, −1.789	72	1.3	0.03	F/K	2.2	RoR-M
Burbia	Pelgo, El (HP-PE)	42.557, −6.785	5	16.3	0.37	K/K	0.3	RoR-L
Lima	Ponte Liñares (HP-PL)	42.015, −7.887	40	9.8	0.22	F/K	1	RoR-M
Garganta	Castillejo, El (HP-CE)	40.160, −5.570	277	3.3	0.03	P/F	2.4	RoR-H
Tagus	Molino de Arriba (HP-MA)	40.580, −1.916	10.9	4.4	0.1	K/K	0.4	RoR-L
Guadiana	Ruidera, La (HP-RUL)	40.478, −2.377	10	6.2	0.14	K/K	0.3	RoR-L

* K: Kaplan, F: Francis, P: Pelton.
** For simplicity, instead of the full hydropower name, the acronym HP-abbreviation of the full name is used, hereafter (e.g., Coterillo: HP-C).

2.3. Methodological framework

The flowchart (Fig. 2) summarises the applied methodology to compute and characterise hydropower production, e-flows releases, and flow alteration considering several operation scenarios imposed by eight EFMs. The methodology used in this study includes four main steps, starting with comprehensive hydrologic data collection from gauges located near to the water intake structure of the hydropower plants. Hydrological data consist of at least 20 consecutive years of mean daily flow data [52]. The mean daily flow data were firstly used to characterise flow regime type related to each study case. In the second step, the computation of energy production from hydropower plants and e-flows releases considering technical and ecological constraints is presented. Technical constraints consist of minimum and maximum operating discharge, depending on the turbine type [53]. Ecological constraints include eight scenarios of e-flows releases imposed by eight hydrological-based EFMs. The third step involves characterisation of the energy production and e-flows release for each hydropower plant regarding the flow regime type. This step also involves characterisation of the water diversion degree in monthly time-scale and flow alteration analysis based on the ''*Indicator of Hydrologic of Alteration (IHA)*'' approach [52].

Finally, in the last step, a trade-off analysis presents the possible cases where energy production maximisation can go with less flow alteration.

2.4. Hydrological data and natural flow regime characterisation

Natural mean daily streamflow series were obtained at gauging stations near to the hydropower plants site from Hydrographic Studies Centre (http://ceh-flumen64.cedex.es). Observed flow series considered in this study span over 36 years (1978–2015) of mean daily flow data. The same time span was considered for all study cases. Detailed information about gauging station location, river names, catchments upstream of the gauging station and some statistics of mean daily streamflow series are presented in Table 3. The mean daily flow dataset includes only full years; missing observation in a few gauges have been linearly interpolated.

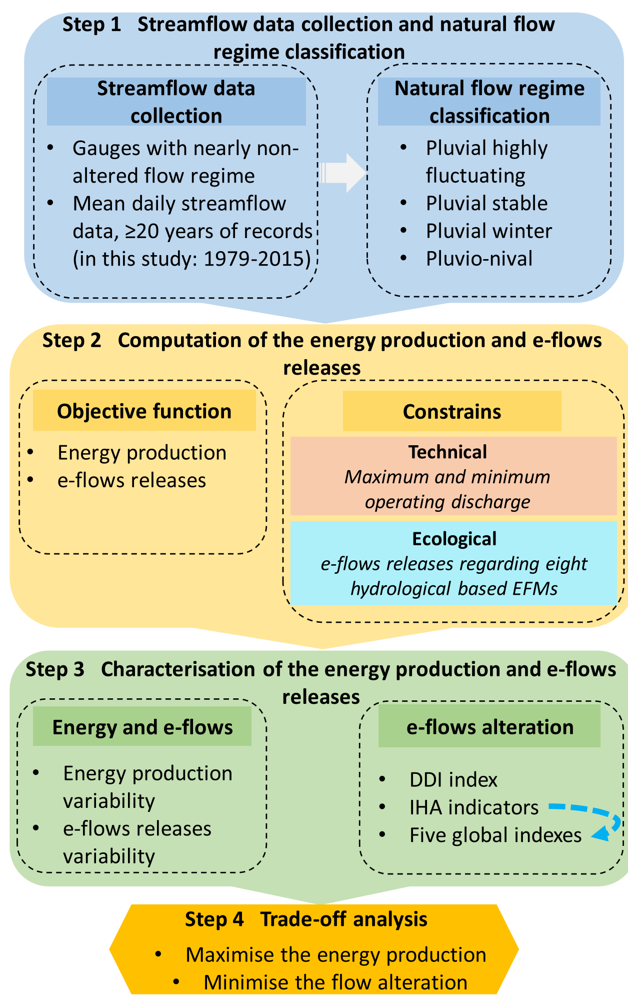

Fig. 2. Conceptual framework of the applied methodology.

Table 3
Main features for the 20 stream gauges considered in this study: gauges name, gauges location coordinates (***Lat***, ***Lon***), basin name, river name, flow regime type, gauge's basin area (***A***), minimum ($\boldsymbol{Q_{min}}$), mean ($\bar{Q}$), and maximum streamflow ($\boldsymbol{Q_{max}}$) related to each hydropower plant in Table 2.

Gauges name	Lat, Lon (°N,°W)	Basin name	River name	Flow regime*	A (km^2)	Q_{min} (m^3 s^{-1})	$\bar{Q}$ (m^3 s^{-1})	Q_{max} (m^3 s^{-1})
Coterillo	43.330, −3.436	Cantabrian	Asón	PS	485	0.5	21.4	793.5
Guriezo	43.354, −3.329	Cantabrian	Agüera	PS	112	0.01	3.9	216.8
San Tirso de Abres	43.412, −7,143	Cantabrian	Eo	PW	712	0.3	17	505.5
Berriatúa	43.310, −2.465	Cantabrian	Artibai	PHF	93	0.03	3.2	558.1
Osma	41.575, −3.083	Douro	Ucero	PW	900	0.001	4.1	193.6
El Barco de Ávila	40.360, −5.527	Douro	Tormes	PHF	768	0.004	23.1	391.4
Quintana del Puente	42.056, −4.240	Douro	Arlanza	PW	5256	0.04	24.2	570.9
Covarrubias	42.053, −3.508	Douro	Arlanza	PW	1200	0.02	11.6	701.9
Aranda de Duero	41.654, −3.680	Douro	Duero	PS	7356	0.9	16.4	305
Berguenda	42.783, −3.044	Ebro	Omecillo	PW	350	0.01	2.9	101.3
Andosilla	42.374, −1.948	Ebro	Ega	PW	1445	0.05	11	324.8
Estella	42.671, −2.0359	Ebro	Ega	PW	943	0.4	11	239.6
Seo de Urgel	42.352, 1.459	Ebro	Segre	PN	1233	0.3	11.8	213.4
Glera u Oja	42.262, −3.033	Ebro	Oja	PHF	74	0.001	1.9	68.5
Nuévalos	41.197, −1.792	Ebro	Piedra	PN	72	0.1	1.1	35
Toral de Los Vados	42.544, −6.787	Minho	Burbia	PW	492	0.04	13.5	267.6
Puente Linares	42.021, −7.883	Minho	Lima	PW	684	0.15	7.6	142.3
Losar de la Vera	40.110, −5.581	Tagus	Garganta	PW	71	0.004	3.3	438.6
Peralejos de las Truchas	40.594, −1.932	Tagus	Tagus	PS	410	0.2	4.1	159.9
Alcantud	40.507, −2.325	Tagus	Guadiana	PS	666	0.006	5.1	115.3

* PS: Pluvial stable, PW: Pluvial winter, PHF: Pluvial highly fluctuating, PN: Pluvio-nival.

Natural flow regime was categorised following the methodology proposed by Bejarano, Marchamalo [50]. Considering interannual monthly fluctuation, four flow regime types prevailed among the 20 study cases (Fig. 3). Pluvial highly fluctuating flow regime type, (Fig. 3a), is characterised by several rises, falls, and multipeak along the year. This flow regime type is characterised by shorter duration of maximum flows compared to other flow regime types. Maximum flow values occurred mainly in early winter and spring seasons. Pluvial stable regime (Fig. 3b) is characterised by a prolonged period of maximum flow between winter and spring season and a scarce number of mean monthly flow reversals. Pluvial winter regime (Fig. 3c) presents a bimodal hydrograph with first maximum flow occurring in the winter and second peak in the early spring season. This flow regime type shows a decreased gradient of maximum flow duration compared to pluvial stable flow regime. Pluvio-nival flow regime (Fig. 3d) shows low flow values during the autumn and winter season. High flows, influenced mainly by the snowmelt, occur during a short period of late spring and early summer season.

Flow regime type, duration of low/high flow events, frequency, and timing shape several ecological processes [31] but also affect hydropower production [36].

2.5. E-flows methods

Eight EFMs applied in this study represent the most commonly used methods worldwide for e-flows determination in case of RoR hydropower plants [30]. The selected EFMs involve different categories among hydrologically-based EFMs and are briefly described in Table 4. Most of the EFMs were applied in their original form. EFM7, which is a new approach, resulted as a combination of two other EFMs. EFM8 also was modified to improve transferability and to see how this modification influenced the e-flows releases and hydropower production among different flow regimes types [37].

2.6. Water diversion characterisation

Downstream Diversion Index (DDI) proposed by Kuriqi, Pinheiro [56] was applied to characterise the degree of water diversion due to the hydropower production Eq. (1):

$$DDI\,(Q) = \frac{\bar{Q}_{nfr} - \bar{Q}_{afr}}{\bar{Q}_{nfr}}\{q_d,\, Q_{mfr},\, Q_{dj},\, Q_{tech}\} \tag{1}$$

where $\bar{Q}_{nfr}$ (m^3 s^{-1}): mean daily natural flow regime before diversion and $\bar{Q}_{afr}$ (m^3 s^{-1}): mean daily altered flow regime left in the river after diversion. In case of the RoR hydropower plant, $\bar{Q}_{afr}$ is the e-flows released after water diversion and the surplus flow spilled over intake structure. DDI vary as a function of q_d (m^3 s^{-1}): mean daily inflow to the turbine in day d, Q_{mfr} (m^3 s^{-1}): minimum flow regime regarding each EFM, Q_{dj} (m^3 s^{-1}): design discharge of the hydropower plant for the j^{th} turbine, and Q_{tech} (m^3 s^{-1}): minimum technical operation flow which depends on the turbine type [53]. In this study, the DDI was applied at a monthly time step. The DDI ranges between 0 and 1. The 0 value of DDI implies no water diversion while the value of 1 implies total water diversion in the river section where water intake takes place. To clarify the interpretation of results, DDI is scaled as follows: low (0–0.25), mild (0.25–0.5), moderate (0.5–0.75) and high diversion (0.75–1).

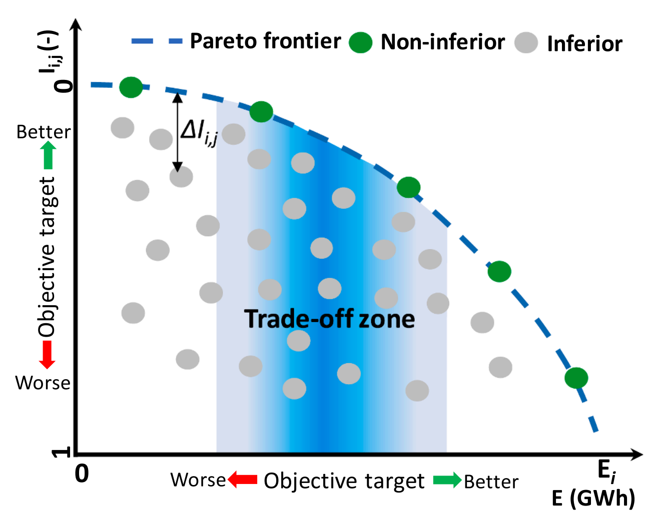

Fig. 3. Standardised mean monthly natural streamflow for each flow regime type and study case. Spatial distribution of each flow regime among 20 study cases over five basins in the Iberian Peninsula is shown in Fig. 1.

Table 4
Description of the hydrologically-based environmental flow methods applied in this study.

Method	Acronyms	Description	Reference
75% Exceedance	Q_{75} (EFM1)	*Annual minimum flow*. These exceedance percentiles of flow duration curve (FDC), represent the mean magnitude of flows that exceeded respectively 75% and 95% of the time (i.e., 274 and 347 days of the year), considering long series of interannual mean daily flow data. For a representative FDC, at least 10 consecutive years of mean daily flow data is required	[54,55]
95% Exceedance	Q_{95} (EFM2)		
One-third of the Average Summer Flow	1/3ASF (EFM3)	*Annual minimum flow*. According to this method, e-flow releases corresponds to one-third of the average/mean summer flow, which includes three months, respectively; July, August, and September for a water year that begins in October and ends in September	[30,53]
10% of Mean Annual Flow	10%MAF (EFM4)	*Annual minimum flow*. Mean annual flow, also known as MQ. According to this method, e-flows releases should be at least 10% or 25% of MAF, depending on the ecological conditions intended to be achieved or maintained in the river reach. At least five years of consecutive mean daily flow data are required to apply this method. However, for more representative results, a more extended series of interannual mean daily flow data is needed	[30,34]
25% of Mean Annual Flow	25%MAF (EFM5)		
Annual Mean Minimum Flow	MMQ (EFM6)	*Annual minimum flow*. The e-flows releases, according to this method, correspond at least to the minimum yearly mean flow observed in the river considering a long series of interannual mean daily flow data	[30]
10% of Mean Daily Flow + Annual Mean Minimum Flow	10%Q-Daily + MMQ (EFM7)	*Daily minimum flow* and *Annual minimum flow*. Represent a combination of two EFM. Daily mean flow + annual minimum mean flow. The purpose of this combination is to ensure water availability in the river during medium and low flow periods. According to this method, e-flows releases correspond to 10% of daily mean flow + annual mean minimum flow observed in the river considering long series of interannual mean daily flow data. This combination is valid when available flow in the river reach is higher than the total amount of flow provided from this combination. Otherwise, the e-flows will be equal to the available flow in the river reach. This situation may happen during very low flow periods. The e-flows releases provided from this EFM follow the natural hydrograph pattern by providing so-called dynamic e-flows	[30,41]
30% of Mean Daily Flow	30%Q-Daily (EFM8)	*Daily minimum flow*. The e-flows release, according to this method, corresponds to 30% of mean daily flow considering a long series of interannual mean daily flow data. This EFM, similarly to previous EFM (i.e., 10%Q-Daily + MMQ), allows for dynamic e-flows releases	[40,41]

2.7. Hydropower generation and e-flows computation

Energy production from hydropower plants was computed in a daily time step, considering the ecological restriction imposed by eight EFMs and technical limitations due to the technical features of the turbine. To cope with flow variability, two turbines for each hydropower plant were assumed (Table 2). It was considered that two turbines work coupled in parallel whenever there is enough water available, while during low flows period only one turbine is working. Therefore, the turbines have been chosen with different design discharges. The potential hydropower production is proportional to the product of discharge and hydraulic head. The installed capacity of the hydropower plant, P, in megawatt (MW) is calculated using Eq. (2):

$$P(t) = \frac{1}{10^6}\gamma H_{net} Q_{dj}\eta_{T_j} \tag{2}$$

where $\frac{1}{10^6}$: multiplication factor to convert the units of P from watt (W) to megawatt (MW), η_{T_j} (%): j^{th} turbine efficiency, which depends on turbine type [53], vary as a function of turbine inflow and design discharge, respectively; η_{T_j} is computed based on empirical expression proposed by Voros, Kiranoudis [57], γ ($\approx$9810 N m^{-3}): the unit weight of water, andH_{net} (m): net head. In this study, for simplicity of the computation, $H_{net}$was assumed constant and equal to the gross head (H_g), neglecting hydraulic losses. The amount of daily energy, E, in gigawatt-hours (GWh) that a j^{th} turbine produces over a given period, Δt (days) is computed using Eq. (3):

$$E(t) = \frac{\tau_h}{10^9}\gamma H_{net}\eta_G \sum_{t=1}^{t+\Delta t=d_y} q_d(t)[\eta_{T_j}\{q_d(t), Q_{dj}\}] \tag{3}$$

where $\frac{1}{10^9}$: multiplication factor to convert the units of E from watt-hours (Wh) to gigawatt-hours (GWh), τ_h (h): number of operating hours per day (24 h), and q_d (m^3 s^{-1}): mean daily turbine inflow, η_G(%): generator efficiency, assumed to be 90%, and d_y: number of days in a year (365). As mentioned above, the hydropower production is constrained by minimum technical operating discharge (Q_{tech}), e-flows, and design discharge (Q_{dj}). In this study, Q_{dj} was obtained from hydropower description, while $Q_{tech}$is determined by the manufacturer in order to prevent turbine damage, and it depends on turbine type [53]. Consequently, there is no energy production if the natural flow discharge is lower than the minimum e-flows resulting from a given EFM. Thus, considering the minimum flow (Q_{mfr}), released downstream of the water intake, the turbine inflow is calculated as follows, Eq. (4):

$$q_d(t) = [Q_{hydro}(t) - Q_{mfr}(t)]\text{where}Q_{tech} \le Q_{hydro} \le Q_{dj} \tag{4}$$

The e-flows releases (Q_{env}) imposed by EFMs and hydropower production was computed according to following decision rules, (Eqs. (5)–(8)):

$$If Q_{nfr}(t) \le Q_{mfr}(t),\ then Q_{env}(t) = Q_{nfr}(t) \tag{5}$$

$$If Q_{hydro}(t) > Q_{dj},\ then Q_{env}(t)=[Q_{hydro}(t) - Q_{dj}] + Q_{mfr}(t) \tag{6}$$

$$If Q_{hydro}(t) < Q_{tech},\ \text{then} Q_{env}(t) = [Q_{hydro}(t) + Q_{mfr}(t)] = Q_{nfr}(t) \tag{7}$$

$$If Q_{tech} \le Q_{hydro}(t) \le Q_{dj},\ then Q_{env}(t) = Q_{mfr}(t) \tag{8}$$

where Q_{nfr} (m^3 s^{-1}): natural flow regime before water diversion, Q_{mfr}(m^3 s^{-1}): minimum flow regime regarding each EFM, Q_{hydro}(m^3 s^{-1}): available flow for energy production, Q_{env}: represent the e-flows, which in the case of decision rule (5), should be at least, $Q_{env} = Q_{mfr}$ or $Q_{env} = Q_{nfr}$.

2.8. E-flows alteration characterisation

Lack of the quantitative ecological data not only at selected study cases but in general has led this study to focus exclusively on flow alteration characterisation rather than assessing real impact resulting from water diversion. To do this, we applied the well-recognised *"Indicator of Hydrologic of Alteration (IHA)"* approach [52]. IHA approach consists of 33 hydrological indicators and 34 e-flow components, combined in five groups. Each group represents an ecologically meaningful parameter; respectively: magnitude, duration, timing, frequency, and rate of change. For simplicity of analysis we derived one alteration index for each group as proposed by Kuriqi, Pinheiro [56], namely: Mean Monthly flow alteration Index ($\mathbf{I_{MM}}$), Magnitude and Duration of Extreme flow alteration Index ($\mathbf{I_{MDE}}$), Timing of Extreme flow alteration Index ($\mathbf{I_{TE}}$), Frequency and Duration alteration Index ($\mathbf{I_{FD}}$), Rate and Frequency alteration Index ($\mathbf{I_{RF}}$). All five indices are computed as follows, Eq. (9):

$$I_{i,j}(HI_{i,j}) = \left(\sum_{i=1}^{n} \left| \frac{HI_{i,j}nfr - HI_{i,j}afr}{HI_{i,j}nfr} \right| \right)\left(\frac{1}{\#HI_{i,j}}\right) \tag{9}$$

where $I_{i,j}$: alteration index regarding to hydrological indicators i for each group j, $HI_{i,j}nfr$: hydrological indicator related to the natural flow regime, $HI_{i,j}afr$: hydrological indicator related to the altered flow regime, and $\#HI_{i,j}$: the number of hydrological indicators for each group. The five indices are scaled from 0 to 1 and classified into four categories: low (0–0.25), mild (0.25–0.5), moderate (0.5–0.75) and high alteration (0.75–1).

2.9. Trade-off analysis

Pareto-optimal frontier was used to explore possible trade-offs between hydropower and ecological objectives. Objective functions in this study consist of maximising energy production (Eq. (10)) and minimise the flow alteration (Eq. (11)).

$$Obj1 = max\left\{\frac{\tau_h}{10^9}\gamma H_{net}\eta_G \sum_{t=1}^{t+\Delta t=d_y} q_d(t)\eta_{T_j}\right\} \tag{10}$$

$$Obj2 = \min\left\{\left(\sum_{i=1}^{n} \left| \frac{HI_{i,j}nfr - HI_{i,j}afr}{HI_{i,j}nfr} \right| \right)\left(\frac{1}{\#HI_{i,j}}\right)\right\} \tag{11}$$

At the two extremes along the frontier curve (Fig. 4), there are either better ecological objectives (Y-axis) or better hydropower objectives (X-axis). Between these two extreme points, lie choices that balance ecological and energy objectives. Solutions positioned below the curve should be avoided because better choices exist concerning at least one of the objectives [58].

Mean annual energy production is plotted against each five alteration indices for each study case. Non-inferior and inferior points falling respectively on and under the Pareto curve represent the performance in terms of energy production and flow alteration regarding each EFM. Then, the distance ($\Delta I_{i,j}$) between each point (EFM) and the Pareto curve was measured. The distance of each EFM regarding five global indices for each study case is presented in Annex 1 (Table A1). The smaller the distance from the Pareto curve is, denote lower flow alteration; consequently, better ecological objectives [52]. Higher distance does not necessarily mean better hydropower objectives. All the points (i.e., FMs) that have a smaller distance relative to the Pareto curve and perform best in terms of energy production and hydrological alteration were identified as trade-off solution regarding each flow regime type.

2.10. Limitations of the methodology

The methodology described is based on a number of simplifications that determine its applicability and the interpretation of results. The analysis was limited to hydrological-based e-flows methods. These methods were chosen for their simplicity because the only required data is the time series of mean daily flows. There are other methods to estimate e-flows which are more directly based on ecological concepts. They were not used in this study due to lack of data for their application, but the methodology could be expended to include such methods if enough data was available. The hydropower plant operation was also simplified. The only decision variable is to turbine or not to turbine. This decision was based solely on available flow. If available flow exceeds the technical minimum of the smallest turbine in the plant, the plant is considered to be in operation. It was assumed that maintenance periods coincide with periods of low flow when the plant is not in operation. This assumption cannot always be reached in practice due to several reasons: there may be previously scheduled maintenance operations during high flows, or there may not be enough low-flow days any given year to carry out maintenance operations. The assumption of two turbines per plant may also not hold, since some plant may be equipped with only one turbine, two identical turbines or more than two. The two turbines are assumed to work in a coordinated way,

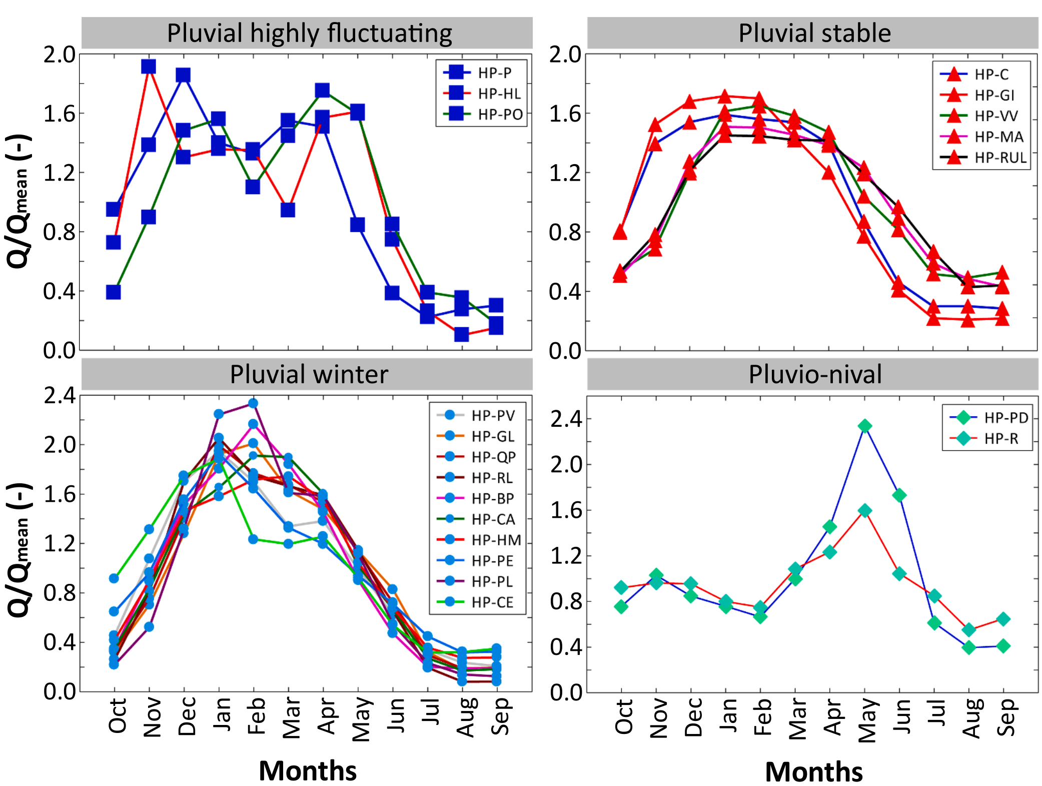

Fig. 4. Conceptual diagram of the Pareto frontier illustrates the concept that there are trade-offs between hydropower and ecological objectives (i.e., energy production vs alteration indices). The thick-dash curve stands for the Pareto-frontier, the non-inferior points on the frontier denote Pareto optimal choices considering both objective functions. The inferior points situated under the frontier stand for non-efficient Pareto choices.

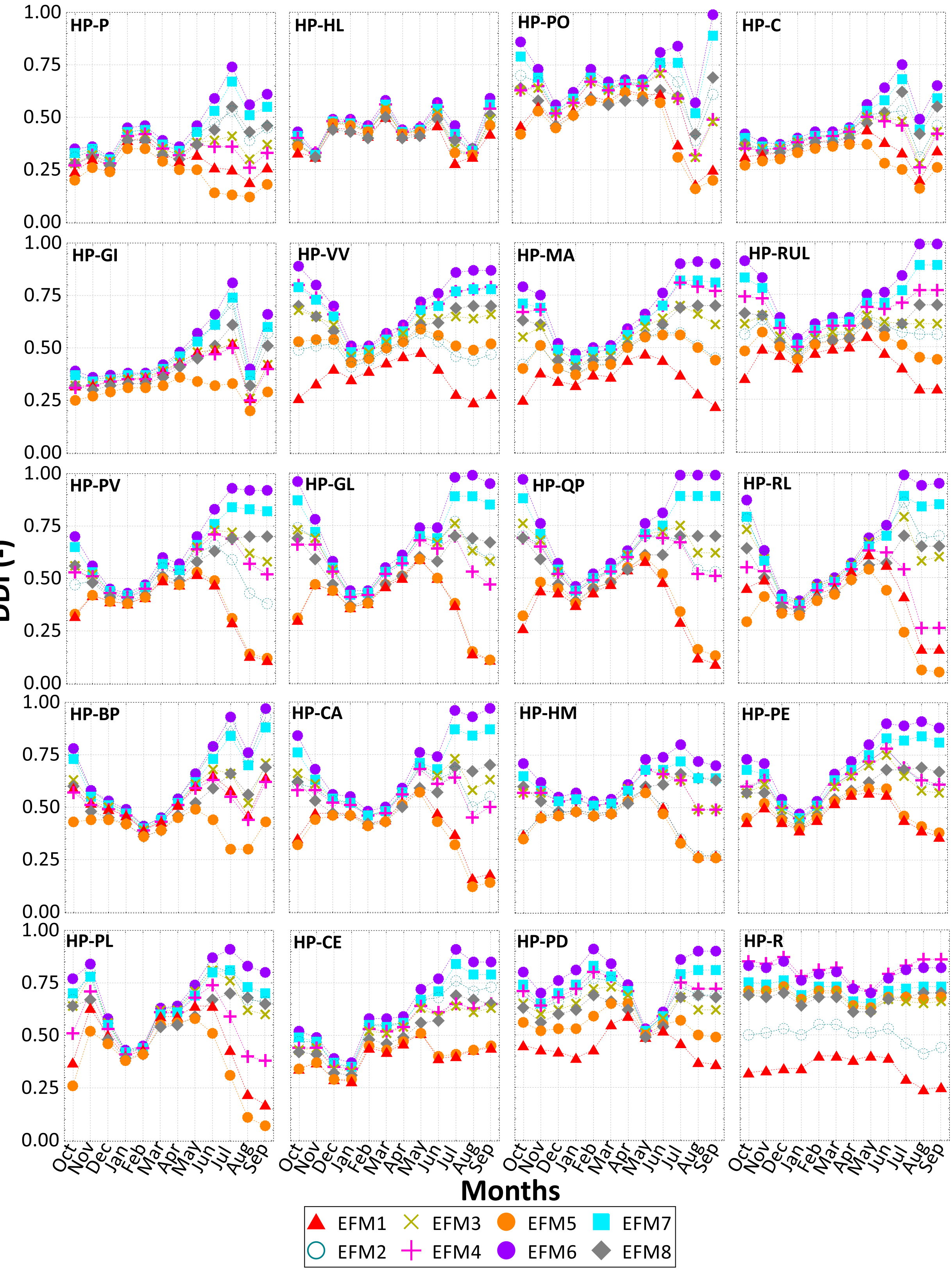

Fig. 5. Downstream diversion index related to eight EFMs and each flow regime: pluvial highly fluctuating (HP-P, HP-HL, HP-PO), pluvial stable (HP-C, HP-GI, HP-VV, HP-MA, HP-RUL), pluvial winter (HP-PV, HP-GL, HP-QP, HP-RL, HP-BP, HP-CA, HP-HM, HP-PE, HP-PL, HP-CE), and pluvio-nival (HP-PD, HP-R). The DDI = 0 denotes no water diversion, and DD = 1 implies the total diversion of the natural flow. DDI scaling: low (0–0.25), mild (0.25–0.5), moderate (0.5–0.75) and high diversion (0.75–1).

taking the whole available flow in the range between the technical minimum of the smallest turbine and the maximum capacity of both turbines. They are also assumed to work under the constant head, and the hydraulic losses were neglected. In practice, turbines may not be able to work with adequate efficiency for the whole range of possible discharges and are exposed to variable head and variable efficiency. Finally, it is assumed that the grid is ready to take the full production of the plant, regardless of fluctuations in energy demand or the production

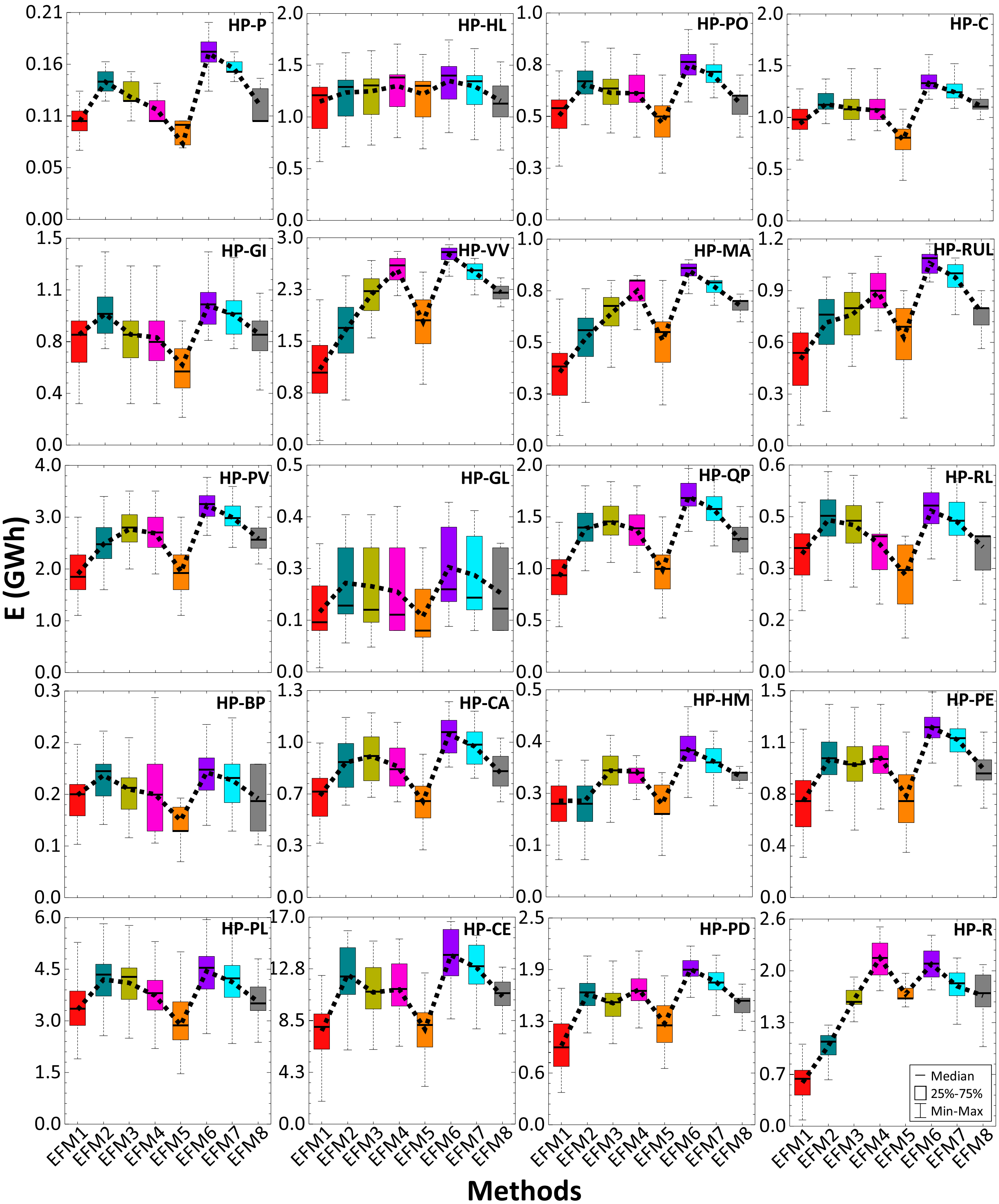

Fig. 6. Boxplots of interannual energy production related to eight EFM and each flow type regime: pluvial highly fluctuating (HP-P, HP-HL, HP-PO), pluvial stable (HP-C, HP-GI, HP-VV, HP-MA, HP-RUL), pluvial winter (HP-PV, HP-GL, HP-QP, HP-RL, HP-BP, HP-CA, HP-HM, HP-PE, HP-PL, HP-CE), and pluvio-nival (HP-PD, HP-R). The dotted line shows the mean values of interannual energy production.

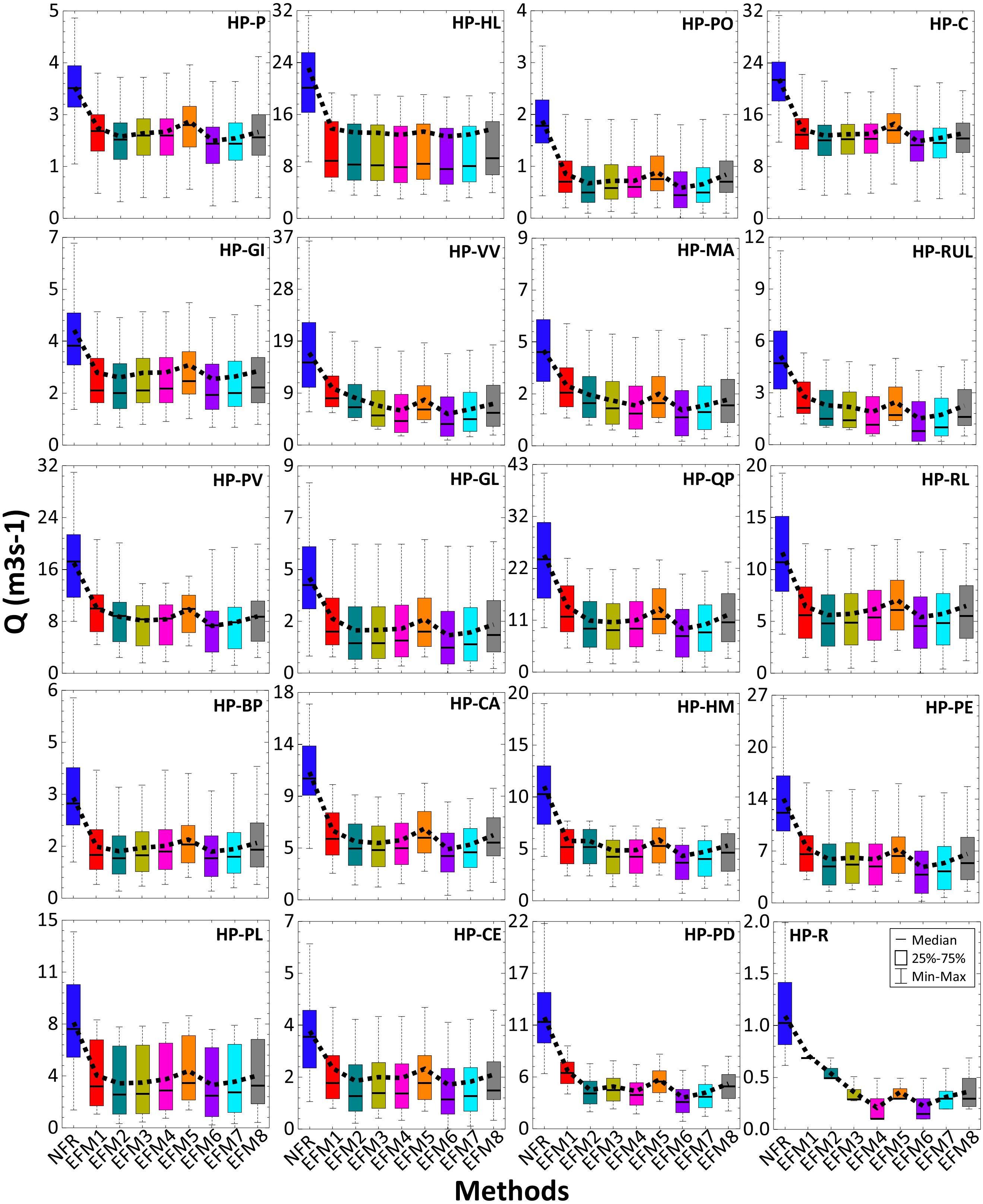

Fig. 7. Boxplots of interannual e-flows release regarding the eight EFM and each flow type regime: pluvial highly fluctuating (HP-P, HP-HL, HP-PO), pluvial stable (HP-C, HP-GI, HP-VV, HP-MA, HP-RUL), pluvial winter (HP-PV, HP-GL, HP-QP, HP-RL, HP-BP, HP-CA, HP-HM, HP-PE, HP-PL, HP-CE), and pluvio-nival (HP-PD, HP-R). The dotted line shows the mean values interannual e-flows releases.

of other renewable technologies. These simplifications may significant, but they have limited impact on the results, due to the limited degrees of freedom of RoR plants without storage.

3. Results

3.1. Water diversion

DDI was used to characterise water diversion due to hydropower production and therefore to distinguish the most flow-altered periods of the year. Fig. 5 shows monthly DDI imposed by eight EFMs regarding each flow regime type. Mean annual water diversion for each study case is presented in Annex 1 (Table A2). Pluvial highly fluctuating flow regime (Fig. 5: HP-P, HP-HL, HP-PO) is characterised by high DDI, particularly beginning at late spring (i.e., June) and during summer season (i.e., July, August, and September). Nevertheless, significant differences were observed among EMFs.

In general, EFM1 and EFM5 demonstrate lowest while EFM6 the highest DDI. Mild DDI and relatively small differences among EFMs in case of HP-HL, Fig. 5, is due to the abundant amount of water during the entire year although flow regime is highly fluctuating. Pluvial stable flow regime (Fig. 5: HP-C, HP-GI, HP-VV, HP-MA, HP-RUL), in general, indicates high DDI during autumn (i.e., October, November, and December) and summer season as well. However, following cases, respectively, HP-C and HP-GI (Fig. 5) demonstrate high DDI only during the summer season; this is due to specific geo-climatic conditions of the study cases but also related to the technical features of the hydropower plant.

In all cases regarding the pluvial stable flow regime, particularly EFM1 and EFM5, impose low to mild DDI while EFM6 mild to high DDI. Pluvial winter (Fig. 5: HP-PV, HP-GL, HP-QP, HP-RL, HP-BP, HP-CA, HP-HM, HP-PE, HP-PL, HP-CE), is characterised by mild to high DDI during autumn and summer season. In both seasons, EFM1 and EFM5, generally allow for quite low water diversion and therefore implying low to mild DDI. EFM6 allows for higher water diversion by resulting in mild to high DDI. Pluvio-nival flow regime (Fig. 5: HP-PD, HP-R), in general, is characterised by mild to high DDI almost during the entire year. This characteristic is mainly due to the strong dependence of flow discharge from snow malting which occurs mostly during spring (i.e., April, May, and June) and early summer season (i.e., July). Similarly, to other flow regime type, particularly EFM1 and in some cases EFM5 impose low to mild DDI while EFM6 mild to high DDI.

3.2. Energy production and e-flows variability

Interannual energy production (Fig. 6) and e-flows releases variability (Fig. 7) regarding each flow regime type indicate notable differences among eight EFMs. In the case of pluvial highly fluctuating flow regime (i.e., HP-P, HP-HL, HP-PO), EFM1 and EFM5 provide the lowest hydropower production but the highest e-flows at all study cases. On

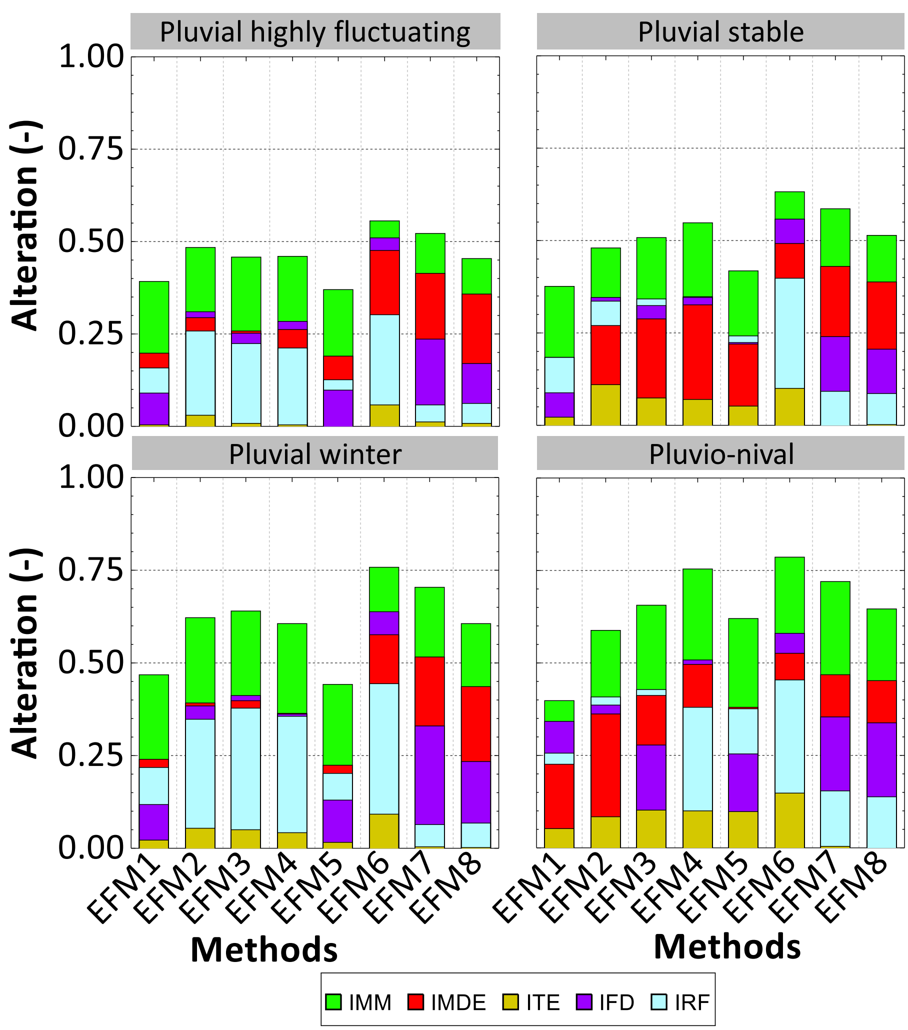

Fig. 8. Overlaid bars with the same origin show e-flows alteration presented as mean values of five global indices regarding the eight EFMs for 20 hydropower plants and each flow type regime. The five indices were classified into four categories, low (0–0.25), mild (0.25–0.5), moderate (0.5–0.75), and high alteration (0.75–1).

the contrary, EFM6 allows for the highest hydropower production while inflicting the most inferior e-flows releases among all EFMs. It is worth stating that the new proposed approach EFM7 is the second method that provides the highest hydropower production after EFM6, by allowing in the same time almost similar e-flows releases as EFM1 and EFM5, namely, around 7 and 6% less in mean values.

EFM7 compared to EFM6 imposes 5% less hydropower production and allows for 3.1% more e-flows releases. EFM8 also, indicate quite close values with EFM7, with an average difference, respectively 14% less hydropower production and 7% more e-flows than EFM7. EFM8 imposes 18% less hydropower production and 9.6% more e-flows than EFM6. A similar trend was also observed in the case of pluvial stable flow regime (HP-C, HP-GI, HP-VV, HP-MA, HP-RUL). EFM1 and EFM5 impose the lowest hydropower production by allowing, therefore, the highest e-flows releases. EFM6 provides the highest hydropower production and the smallest e-flows releases. Whereas after EFM6, EFM7 provides the highest hydropower production. Looking at the mean values, EFM7 provides respectively 43% and 34% more hydropower production than EFM1 and EFM5.

While, concerning the e-flows, EFM7 allows, respectively, 22 and 18% fewer e-flows compared to EFM1 and EFM5. Differences in mean values between EFM7 and EFM6 are respectively, 8.5% less hydropower production and 7% more e-flows provided by EFM7. EFM8 also shows good performance; it gives 13% less hydropower production but 10% more e-flows than EFM7. Differences between EFM8 and EFM6 were respectively, 20% less hydropower production and 16% more e-flows imposed by EFM8. Concerning the pluvial winter flow regime (HP-PV, HP-GL, HP-QP, HP-RL, HP-BP, HP-CA, HP-HM, HP-PE, HP-PL, HP-CE), all EMFs demonstrate a similar trend with two previous flow regime type.

Namely, EFM1 and EFM5 provide the lowest hydropower production and enable the highest e-flows releases among other EFMs at all study cases. EFM6 allows for highest hydropower production and imposes the lowest e-flows. EFM7 shows quite similar values with EFM6, by providing 6.7% less hydropower production enabling 8% more e-flows than EFM6. Also, results show that after EFM1 and EFM5, EFM8 allows the highest e-flows releases with respectively only 7% and 9% less than EFM1 and EFM5. However, the differences in hydropower production are notable; EFM8 facilitate respectively 24% and 26% more energy production than EFM1 and EFM5.

Differences between EFM7 and EFM8 regarding hydropower production and e-flows releases are respectively, 17% less energy production and 14% more e-flows imposed by EFM8. While, compared to EFM6, EFM8 imposes 23% less hydropower production and allows for 21% more e-flows releases. Pluvio-nival flow regime indicates that at one study case (HP-PD), EFM1 and EFM5 impose the lowest hydropower production, while at the other one (HP-R) the lowest hydropower production was imposed by EFM1 and EFM2. Similarly, to the previous flow regime type, EFM6 allows for the highest hydropower production.

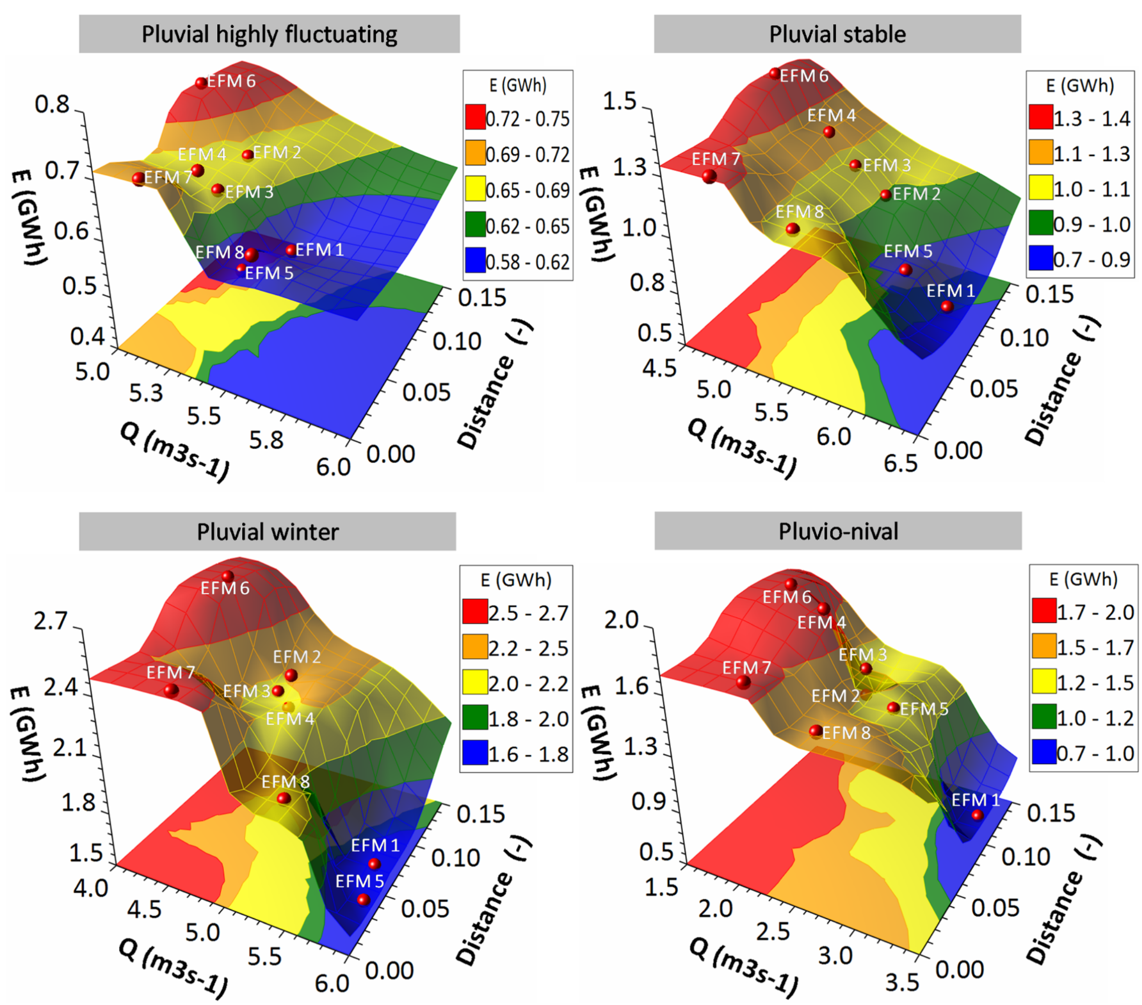

Fig. 9. Mean energy production and e-flows releases related to eight EFMs and the distance (suitability) of each EFM regarding the Pareto frontier principle for each flow type regime. The higher is the distance from the Pareto frontier, the less preferable is the EFM, both in terms of energy production and e-flows releases and vice-versa.

Again, EFM7 and EFM8 indicate good performance both in terms of hydropower production and e-flows releases. Namely, overall, EFM7 allows for 11% less hydropower production compared to EFM6, but it provides 16.2% more e-flows, EFM8 imposes 21% less hydropower production than EFM6 but it unable 32.3% more e-flows releases. Differences in mean values between EFM8 and EFM7, both in terms of hydropower production and e-flows are respectively, 11% less hydropower production and 20% e-flows imposed by EFM8.

3.3. E-flows regime alteration

Fig. 8 shows the e-flows regime alteration degree, represented by five indices, for each flow regime type, and regarding eight EFMs. Detailed information about e-flows regime alteration regarding each study case is given in Annex 1 (Fig. A1). Some of the EFMs cause substantial flow alteration regarding specific indices and flow regime type. In the case of pluvial highly fluctuating flow regime (Fig. 8a), except EFM6 and EFM7, which cause low to moderate alteration, the other EFMs imposes low to mild alteration. At this flow regime type, $\mathbf{I_{MM}}$ indicates the highest while $\mathbf{I_{TE}}$ the lowest alteration among all EFMs. Regarding pluvial stable flow regime (Fig. 8b), there are four EFMs; respectively EFM4, EFM6, EFM7, and EFM8 which cause low to moderate alteration, the rest of EFMs show low to mild alteration. Similarly, to the previous flow regime, $\mathbf{I_{MM}}$ indicates the highest and $\mathbf{I_{TE}}$ the lowest alteration among all EFMs.

In the case of pluvial winter flow regime (Fig. 8c), in contrast with two previous flow regimes, except EFM1 and EFM5 which imposes low to mild alteration, the other EFMs imposes low to moderate alteration. Again, $\mathbf{I_{MM}}$ shows the highest and $\mathbf{I_{TE}}$ the lowest alteration among eight EFMs. Whereas concerning the pluvio-nival flow regime (Fig. 8d), EFM1 shows low to mild alteration, EFM6 indicates low to high alteration while the rest of the EFMs imposes low to moderate alteration. In the case of pluvio-nival flow regime, $\mathbf{I_{MM}}$ indicates the highest while $\mathbf{I_{TE}}$ the lowest alteration compared to other indices and among all EFMs. Results show that regardless of the flow regime type, EFM7 and EFM8 imposes little alteration, particularly regarding $\mathbf{I_{TE}}$ and $\mathbf{I_{RF}}$, while EMF6 cause the highest alteration regarding five indices and among four flow regimes types.

3.4. Suitability of EFMs regarding the energy production and e-flows releases

Fig. 9 shows the performance of eight EFMs concerning the hydropower production, e-flows releases, and flow alteration indicated as the distance from the Pareto frontier curve. Regarding the pluvial highly fluctuating flow regime (Fig. 9a), EFM6 although it provides the highest energy production, shows the furthest distance among all EFMs. While EFM5, EFM7, and EFM8 indicate the smallest distance. Nevertheless, among the last three EFMs and the rest of other EFMs, EFM7 provides the highest energy production; with only 4.8% less than EFM6 and reasonable e-flows releases; with 5% more than EFM6, and therefore making it the most suitable EFM. In the case of pluvial stable flow regime (Fig. 9b), again EFM6, although it provides the highest energy production, has greater distance among the other EFMs. EFM7 has the smallest distance compared to the other EFMs; it gives 7.7% less energy production than EFM6 but 8.2% more e-flows releases. After EFM7, EFM8 has the smallest distance, it provides 10% more e-flows, nevertheless 14% less energy production than EFM7.

In the case of pluvial winter flow regime (Fig. 9c), results show that EFM5, EFM7, EFM8 have the smallest distance. However, it should be noted that EFM1 and EFM5 with a difference > -40% compared to the other EFMs provide the lowest energy production, and therefore making these two EFMs less preferable regardless of the flow regime type. EFM6 provides the highest energy production, but it has a greater distance compared to the other EFMs. EFM7 has the smallest distance among the other EFMs, in terms of energy production it provides 6.8% less energy production and 7% more e-flows than EFM6, while EFM8 offers 17% less energy production and 14% e-flows than EFM7.

Finally, regarding the pluvio-nival flow regime (Fig. 9d), similarly to the previous flow regime, EFM6 provides the highest energy production nonetheless has greater distance among the other EFMs. While EFM7 and EFM8 have smaller distance compared to the other EFMs. EFM7 provides 10% less energy but 6% more e-flows than EFM6. While EFM8 gives 10% less energy and around 20% more e-flows than EFM7. Overall, is worth to highlight that regardless of the flow regime type, hydropower plant typology (i.e., size, head), and other particularities related to each study case; EMF6, EFM7, and EFM8 shows a similar trend. Namely, EFM6 provides the highest energy production and shows greater distance; EFM7 and EFM8 allow for a little less energy production than EFM6 but have relatively small distance from the Pareto curve. Also, EFM7 and EFM8 provides reasonable e-flows and therefore cause less hydrological alteration. While the other EFMs seems to be entirely depended to flow regime type and hydropower plants features as well.

4. Discussion

4.1. Energy production and e-flows releases

An RoR hydropower plant, in general, represents a simple scheme regarding the structure itself and the operation mode as well. However, the decision on the optimal operating scenarios is a challenging task because of the involvement of other actors with contrasting interests. E-flows releases downstream of the water intake structure poses one of the main actors which on the one hand may negatively affect the hydropower production but on the other hand represent a crucial instrument for preserving riverine ecosystem [11,59]. Although e-flows constitute a vital instrument in riverine ecosystem conservation, there is no consistent and global approach to determine them [30]. There is a wide array of EFMs available in literature where most of them are hydrologically-based. Hydrologically-based EFMs, although they do not have a strong ecological foundation, still are the most commonly applied in practice because of their simplicity, especially in case of RoR hydropower plants [34,54,55].

Interdisciplinary studies like this study contribute to emphasise the importance of linkage among different components such as e-flows, hydropower production, and hydrological alteration. As mentioned above, the RoR hydropower plant production is very sensitive to flow variability, which somehow affects the sale prices of electric energy. Sale prices of energy generated from RoR hydropower plants, in general, are highly fluctuating in time, and they also depend strongly on the electricity demand [39]. However, in this study because of the difficulties in obtaining information about the sale prices, which are also quite fuzzy, the impact of EFMs on hydropower production regarding each flow regime type was estimated based solely on energy production. As also indicated by Bejarano, Sordo-Ward [37], there may be an overestimation of impact on hydropower production from those EFMs which allocate much e-flows when energy is cheaper or underestimation of those EFMs which provide fewer e-flows when the energy price is much higher. Also, the maintenance period was not considered in the analysis. Therefore, the volume of e-flows releases in the diverted river reach may be slightly higher than the one computed in this study. Thus, a detailed analysis considering these circumstances and also to asses real economic impact; an economic analysis, e.g., payback period, net present value or internal rate of return on investment, could be done in future work to overcome aforementioned issues [56].

The analyses of energy production and e-flows releases from the hydropower plants showed that there are notable differences among EFMs related to each flow regimes type, particularly concerning the hydropower production. Namely, results show that EFMs based on minimum annual values either allow for higher hydropower production (e.g., EFM6) by restricting significantly e-flows releases or restricting hydropower production significantly (e.g., EFM1 and EFM5) with no notable differences regarding the e-flows releases. A similar result was observed at three flow regime types, except pluvio-nival flow regime. It is worth noting that two dynamic approaches, respectively EFM7 and EFM8, do not significantly affect hydropower production while providing reasonable e-flows releases. A similar trend was observed in all study cases, regardless of the flow regime type. Indeed, EFM7 and EFM8 impose almost no restriction regarding energy production, considering all study cases and flow regime types (see Table A3). Our findings, particularly those concerning the results obtained from dynamic approaches, are in line with those reported by other authors [35,40,56].

4.2. E-flows alteration

Flow regime constitutes an essential aspect of shaping and well-functioning of the aquatic systems [31]. Geoclimatic factors such as temperature, precipitation, topography, geomorphology have a direct influence on the river network and therefore playing a deterministic role in flow regime type [11]. However, as reported in the literature [11], natural flow regime may be altered by anthropogenic factors such as dams and even small hydropower plants like study cases analysed in this study [23,24]. Since hydrological-based EFMs do not consider specific requirements of target fish species, riparian vegetation or other aquatic system needs; the impact of water diversion was characterised based on well recognised flow-ecology approach [31,52]. Five alteration indices used in this study to compute e-flows alteration in the diverted river reach showed that there are considerable differences among alteration indices regarding each EFM and flow regime type. As demonstrated by $\mathbf{I_{MM}}$, monthly magnitudes [52], were most altered hydrological parameters, although it is quite variable along the year.

The degree of alteration seems to vary from EFM to EFM and among flow regime type. In general, the pluvial highly fluctuating flow regime appears to be less altered. This happens because the natural flow regime very frequently reaches such a low level that lead to the cutting off the hydropower production, which implies no water diversion and as a result, now flow alteration [50].

Except for EFM6, the other EFMs falls in the same category of alteration (i.e., low to mild). Therefore, in terms of flow alteration, most of the EFMs seems to provide quite similar e-flows releases. Pluvial stable flow regime with only some small differences among EFMs shows quite a similar pattern with pluvial highly fluctuating flow regime. Pluvial winter and particularly pluvio-nival flow regimes seem to be more sensitive to the water diversion. In the case of pluvial winter flow regime, only EFM1 and EFM5 fall into the low to the mild category of alteration while the rest of EFMs impose low to moderate alteration. Whereas, the pluvio-nival seems to be even more sensitive to the water diversion than pluvial winter flow regime. Indeed, only EFM1 causes low to mild alteration while the rest impose low to moderate and low to high alteration imposed by EFM6.

It is worth mention that following hydrological parameters; timing, duration, and rates of changes represented respectively by $\mathbf{I_{TE}}$ and $\mathbf{I_{FR}}$, which have an essential role in well-functioning of several ecological processes [52,56], were preserved continuously close to the natural flow regime at all study cases and among four flow regime types only by dynamic approaches (i.e., EFM7 and EFM8). In this regard, the finding of this study suggests applying dynamic approaches as an adequate method for determining e-flows at RoR hydropower plants regardless of the flow regime type. Nevertheless, these two approaches should be adopted based on the biota type and ecological objectives to be achieved.

4.3. Potential solutions to reduce e-flows alteration and maximise energy production

In practice, there are several solutions that might improve hydropower production and at the same time reducing the ecological impacts in the diverted river reach. Particularly in case of low head RoR hydropower plants, high-efficiency turbines may be an alternative solution to enhance hydropower production and therefore enabling higher e-flows, especially during critical biota related periods [4]. Adjustment of the turbine's blades or operation scheduling optimisation has shown that may significantly improve fish habit [38]. Also, multi-objective optimisation approaches are very often applied in practice to enhance hydropower production and minimise the potential ecological impacts induces by hydropower plants, especially during the operation phase [39].

So-called Pareto-optimal represents a practical approach to propose possible trade-offs between two or more objective functions [58]. Based on trade-offs derived from the Pareto-curve, the goal is to propose such solution that causes less possible alteration of the natural flow regime which consequently results in less ecological impact [52], while simultaneously maximising the hydropower production. In this study, we found that on the one hand, there are methods, e.g., EFM6 that provide the highest energy production but with some comparatively high potential ecological cost. Indeed, as shown in Fig. 5, EFM6 allows the highest water diversion and lowest e-flows releases (Fig. 7) by resulting in the highest degree of flow alteration (Fig. 8). On the other hand, some other methods, e.g., EFM1 and EFM5, restrict the hydropower production significantly at all flow regime types river reaches. While some other EFMs (i.e., EFM2, EFM3, and EFM4) show inconsistent results among all study cases and flow regime types. However, we found that two dynamic EFMs (i.e., EFM7 and EFM8) provide quite consistent results among all study cases and flow regimes types. In the case of these two EFMs, the highest hydropower production was obtained at the reasonable ecological cost at all flow regime types. Our findings are consistent with those obtained by other authors [35,37,40,56]. Similarities found at some EFMs with regard to four flow regime types and also differences among them, suggest that it is possible to define e-flows in regional scale and to set common management and ecological goals for several rivers at the same time as long as they have similar hydrological features [31,37,52].

Majority of RoR hydropower plants which are already in operation are predominantly located at highland rivers, which are mainly fed by snowmelt; namely pluvio-nival flow regimes [58]. Highland rivers are attractive for hydropower development mainly because of the favourable hydraulic head, which implies higher hydropower production. However, the findings of this study showed that hydropower plants located particularly at pluvio-nival flow regime river reaches resulted in higher flow alteration along the year, and energy production was highly unstable. Furthermore, other authors [21], found that climate change may further exacerbate the hydropower production located in such river reaches. Therefore, based on our findings, we suggest considering firstly pluvial river reaches; particularly pluvial stable river reaches for potential RoR hydropower plants development.

Also, it is essential emphasising that depending on the specific ecological objective to be achieved for a river reach under consideration; attention should be directed on the specific hydrological parameters rather than only on global indices. For instance, if the objective was on ensuring suitable habitat condition for both aquatic and terrestrial organisms, lateral river connectivity, and promoting riparian vegetation enhancement to improve streambank stability, water managers should guarantee minimal alteration of the mean monthly magnitudes, timing and duration of extreme flow events during specific periods of the year [31,52]. Alternatively, if the interest was on protecting the organisms, in particular, protecting fishes from stranding, soil oxygenation of the riparian zone and ensuring adequate distribution of the food web, frequency, duration and rate of changes of extreme flow events should be maintained close to the natural flow regime [52]. Also, since the energy demand is exponentially increasing, energy-generation mix; combining the hydropower with other renewable resources could be an effective mitigation measure to reduce anthropogenic stresses in the riverine ecosystem [60]. Findings of this study and suggestion made above might be helpful to water managers to guide them in ensuring sustainable development and operation of RoR hydropower plants.

5. Conclusions

This study shows that RoR hydropower production is massively dependent on the e-flows release imposed by hydrologically-based EFMs and flow regime type characterising the river reaches under consideration. Nevertheless, to guarantee sustainable development and operation of these type of hydropower schemes is essential considering hydropower production maximisation, and riverine ecosystem conservation equally. From the comprehensive analysis conducted in this study following the main conclusion may be drawn.

- The pluvial river reaches, particularly pluvial stable river reaches, guarantee stable hydropower production and were less sensitive to water diversion.
- The pluvial highly fluctuating river reaches, although were less altered, do not necessarily provide stable hydropower production.
- Pluvial-nival river reaches showed to be sensitive to water diversion and indicated unstable hydropower production.
- Environmental flows methods based on minimum annual values showed to be not suitable for providing a reasonable agreement between hydropower production and e-flows releases. In this regard, these methods either allows for relatively high hydropower production by profoundly altering the natural flow regime (e.g., EFM6) or restricting significantly (i.e., 15–45%) hydropower production (e.g., EFM1 and EFM5).
- Dynamic or so-called complex EFMs indicated to be the most suitable EFMs both in terms of hydropower production and e-flows regime alteration. Respectively two dynamic EFMs (i.e., EFM7 and EFM8) applied in this study, exclusive of EFM6, showed to provide roughly 10–35% more energy production than the other EFMs.
- Some of the EFMs, respectively, EFM2, EFM3, and EFM4, indicated inconsistent results among all study cases and flow regimes types.

Although this study proved that some of the hydrologically-based EFMs could guarantee a reasonable balance between hydropower production and e-flows releases, however, because of the flow regime alteration upstream and especially downstream of the water intake, RoR hydropower plants may still threaten several aspects of riverine ecosystem. Therefore, there is an imperative need for interdisciplinary research to find a sustainable solution by guaranteeing the riverine ecosystem conservation and feasible hydropower production. The hydropower production and e-flows constitute a complex interaction, and this complexity may be investigated by more comprehensive analyses such as through economic analysis, considering critical periods of the year, namely when demand for both e-flows releases and energy production is high. Further, climate change is predicted to exacerbate hydropower production on those of RoR type. Thus, taking in consideration several climate change scenarios with the focus on the most pessimist, one may foster the development of more novel, sustainable, and long-term solution. Finally, methodology and solution-oriented findings obtained in this study are intended to help water managers and hydropower designer to provide optimal solution regarding water allocation issues, particularly in the case of RoR hydropower plants.

Data availability

Flow data obtained from Hydrographic Studies Centre: http://ceh-flumen64.cedex.es/anuarioaforos/afo/estaf-mapa_gr_cuenca.asp.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] Bakis R, Demirbas A. Sustainable development of small hydropower plants (SHPs). Energy Sources 2004;26:1105–18. https://doi.org/10.1080/00908310390265932.
[2] Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? Appl Energy 2019;233–234:1027–50. https://doi.org/10.1016/j.apenergy.2018.08.109.
[3] IHA. Hydropower status report. 5 ed. London, United Kingdom: International Hydropower Association (IHA); 2018. p. 1–53. https://www.hydropower.org/publications/2018-hydropower-status-report.
[4] Balkhair KS, Rahman KU. Sustainable and economical small-scale and low-head hydropower generation: a promising alternative potential solution for energy generation at local and regional scale. Appl Energy 2017;188:378–91. https://doi.org/10.1016/j.apenergy.2016.12.012.
[5] Feng Z-k, Niu W-j, Wang W-c, Zhou J-z, Cheng C-t. A mixed integer linear programming model for unit commitment of thermal plants with peak shaving operation aspect in regional power grid lack of flexible hydropower energy. Energy 2019;175:618–29. https://doi.org/10.1016/j.energy.2019.03.117.
[6] Xu J, Ni T, Zheng B. Hydropower development trends from a technological paradigm perspective. Energy Convers Manage 2015;90:195–206. https://doi.org/10.1016/j.enconman.2014.11.016.
[7] Premalatha M, Tabassum A, Abbasi T, Abbasi SA. A critical view on the eco-friendliness of small hydroelectric installations. Sci Total Environ 2014;481:638–43. https://doi.org/10.1016/j.scitotenv.2013.11.047.
[8] Couto TBA, Olden JD. Global proliferation of small hydropower plants - science and policy. Front Ecol Environ 2018;16:91–100. https://doi.org/10.1002/fee.1746.
[9] Zhou Y, Chang L-C, Uen T-S, Guo S, Xu C-Y, Chang F-J. Prospect for small-hydropower installation settled upon optimal water allocation: an action to stimulate synergies of water-food-energy nexus. Appl Energy 2019;238:668–82. https://doi.org/10.1016/j.apenergy.2019.01.069.
[10] Auerbach DA, Deisenroth DB, McShane RR, McCluney KE, LeRoy Poff N. Beyond the concrete: accounting for ecosystem services from free-flowing rivers. Ecosyst Serv 2014;10:1–5. https://doi.org/10.1016/j.ecoser.2014.07.005.
[11] Poff NL, Zimmerman JKH. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw Biol 2010;55:194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.x.
[12] Kelly-Richards S, Silber-Coats N, Crootof A, Tecklin D, Bauer C. Governing the transition to renewable energy: a review of impacts and policy issues in the small hydropower boom. Energy Policy. 2017;101:251–64. https://doi.org/10.1016/j.enpol.2016.11.035.
[13] Manzano-Agugliaro F, Taher M, Zapata-Sierra A, Juaidi A, Montoya FG. An overview of research and energy evolution for small hydropower in Europe. Renew Sustain Energy Rev 2017;75:476–89. https://doi.org/10.1016/j.rser.2016.11.013.
[14] UNIDO, ICSHP. World small hydropower development report 2016. 2 ed. Vienna, Austria: United Nations Industrial Development Organization (UNIDO) and the International Center on Small Hydro Power (ICSHP); 2016. p. 1–44, http://www.smallhydroworld.org/menu-pages/reports/2016/.
[15] Ciric RM. Review of techno-economic and environmental aspects of building small hydro electric plants – a case study in Serbia. Renew Energy 2019;140:715–21. https://doi.org/10.1016/j.renene.2019.03.091.
[16] Pang M, Zhang L, Bahaj AS, Xu K, Hao Y, Wang C. Small hydropower development in Tibet: insight from a survey in Nagqu Prefecture. Renew Sustain Energy Rev 2018;81:3032–40. https://doi.org/10.1016/j.rser.2017.06.115.
[17] Korkovelos A, Mentis D, Siyal S, Arderne C, Rogner H, Bazilian M, et al. A geospatial assessment of small-scale hydropower potential in sub-Saharan Africa. Energies 2018;11. https://doi.org/10.3390/en11113100.
[18] Moiz A, Kawasaki A, Koike T, Shrestha M. A systematic decision support tool for robust hydropower site selection in poorly gauged basins. Appl Energy 2018;224:309–21. https://doi.org/10.1016/j.apenergy.2018.04.070.
[19] Kougias I, Szabó S, Monforti-Ferrario F, Huld T, Bódis K. A methodology for optimization of the complementarity between small-hydropower plants and solar PV systems. Renew Energy 2016;87:1023–30. https://doi.org/10.1016/j.renene.2015.09.073.

[20] Lavrič H, Rihar A, Fišer R. Simulation of electrical energy production in Archimedes screw-based ultra-low head small hydropower plant considering environment protection conditions and technical limitations. Energy 2018;164:87–98. https://doi.org/10.1016/j.energy.2018.08.144.
[21] Gaudard L, Avanzi F, De Michele C. Seasonal aspects of the energy-water nexus: the case of a run-of-the-river hydropower plant. Appl Energy 2018;210:604–12. https://doi.org/10.1016/j.apenergy.2017.02.003.
[22] Patro ER, De Michele C, Avanzi F. Future perspectives of run-of-the-river hydropower and the impact of glaciers' shrinkage: the case of Italian Alps. Appl Energy 2018;231:699–713. https://doi.org/10.1016/j.apenergy.2018.09.063.
[23] Anderson D, Moggridge H, Warren P, Shucksmith J. The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers. Water Environ J 2015;29:268–76. https://doi.org/10.1111/wej.12101.
[24] Santos JM, Ferreira MT, Pinheiro AN, Bochechas JH. Effects of small hydropower plants on fish assemblages in medium-sized streams in central and northern Portugal. Aquat Conserv Mar Freshwater Ecosyst 2006;16:373–88. https://doi.org/10.1002/aqc.735.
[25] Quadroni S, Crosa G, Gentili G, Espa P. Response of stream benthic macro-invertebrates to current water management in Alpine catchments massively developed for hydropower. Sci Total Environ 2017;609:484–96. https://doi.org/10.1016/j.scitotenv.2017.07.099.
[26] Csiki SJC, Rhoads BL. Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. Geomorphology 2014;206:215–29. https://doi.org/10.1016/j.geomorph.2013.10.009.
[27] Abbasi T, Abbasi SA. Small hydro and the environmental implications of its extensive utilization. Renew Sustain Energy Rev 2011;15:2134–43. https://doi.org/10.1016/j.rser.2010.11.050.
[28] Hayes DS, Brandle JM, Seliger C, Zeiringer B, Ferreira T, Schmutz S. Advancing towards functional environmental flows for temperate floodplain rivers. Sci Total Environ 2018;633:1089–104. https://doi.org/10.1016/j.scitotenv.2018.03.221.
[29] Ecological EC. Flows in the implementation of the water framework directive. Luxembourg: EC (European Commission); 2015. p. 1–108. https://doi.org/10.2779/775712.
[30] Tharme RE. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res Appl 2003;19:397–441. https://doi.org/10.1002/rra.736.
[31] Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, et al. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw Biol 2010;55:147–70. https://doi.org/10.1111/j.1365-2427.2009.02204.x.
[32] Rivaes R, Boavida I, Santos JM, Pinheiro AN, Ferreira T. Importance of considering riparian vegetation requirements for the long-term efficiency of environmental flows in aquatic microhabitats. Hydrol Earth Syst Sci 2017;21:5763–80. https://doi.org/10.5194/hess-21-5763-2017.
[33] Feng Z-k, Niu W-j, Cheng C-t. Optimization of hydropower reservoirs operation balancing generation benefit and ecological requirement with parallel multi-objective genetic algorithm. Energy 2018;153:706–18. https://doi.org/10.1016/j.energy.2018.04.075.
[34] Linnansaari T, Monk WA, Baird DJ, Curry RA. Review of approaches and methods to assess Environmental Flows across Canada and internationally. DFO Can Sci Advis Sec Res 2012/039.. p. vii + 75.
[35] Kuriqi A, Pinheiro A, Sordo-Ward A, Garrote L. Trade-off between environmental flow policy and run-of-river hydropower generation in Mediterranean climate. Eur Water 2017;60:123–30http://www.ewra.net/ew/pdf/EW_2017_60_17.pdf.
[36] Kuriqi A, Rivaes R, Sordo-Ward A, Pinheiro AN. & Garrote L. Comparison and validation of hydrological e-flow methods through hydrodynamic modelling. EGU general assembly conference. Vienna, Austria. 2017. p. 13634. doi:2017EGUGA..1913634K.
[37] Bejarano MD, Sordo-Ward A, Gabriel-Martin I, Garrote L. Tradeoff between economic and environmental costs and benefits of hydropower production at run-of-river-diversion schemes under different environmental flows scenarios. J Hydrol 2019;572:790–804. https://doi.org/10.1016/j.jhydrol.2019.03.048.
[38] Pragana I, Boavida I, Cortes R, Pinheiro A. Hydropower plant operation scenarios to improve brown trout habitat. River Res Appl 2017;33:364–76. https://doi.org/10.1002/rra.3102.
[39] Pérez-Díaz JI, Wilhelmi JR. Assessment of the economic impact of environmental constraints on short-term hydropower plant operation. Energy Policy 2010;38:7960–70. https://doi.org/10.1016/j.enpol.2010.09.020.
[40] Razurel P, Gorla L, Crouzy B, Perona P. Non-proportional repartition rules optimize environmental flows and energy production. Water Resour Manage 2015;30:207–23. https://doi.org/10.1007/s11269-015-1156-y.
[41] Gorla L, Perona P. On quantifying ecologically sustainable flow releases in a diverted river reach. J Hydrol 2013;489:98–107. https://doi.org/10.1016/j.jhydrol.2013.02.043.
[42] Feng Z-k, Niu W-j, Cheng C-t. Optimizing electrical power production of hydropower system by uniform progressive optimality algorithm based on two-stage search mechanism and uniform design. J Cleaner Prod 2018;190:432–42. https://doi.org/10.1016/j.jclepro.2018.04.134.
[43] Cantábrico CHd. Planificación hidrológica. Spain: Ministerio para la Transición Ecológica; 2015. https://www.chcantabrico.es.
[44] Ebro CHd. Planificación hidrológica. Spain: Ministerio para la Transición Ecológica; 2015. http://www.chebro.es.
[45] Miño-Sil CHd. Planificación hidrológica. Spain: Ministerio para la Transición Ecológica; 2016. https://www.chminosil.es.
[46] Duero CHd. Planificación hidrológica. Spain: Ministerio para la Transición Ecológica; 2015. http://www.chduero.es.
[47] Tajo CHd. Planificación hidrológica. Spain: Ministerio de Medio Ambiente y Medio Rural y Marino; 2015. http://www.chtajo.es.
[48] geográfica Sdi. Geoportal MAPAMA. Spain: Ministerio para la Transición Ecológica; 1991. https://sig.mapama.gob.es.
[49] MARM. Guía metodológica para el desarrollo del Sistema Nacional de Cartografía de Zonas Inundables. Madrid, Spain: Secretaría General Técnica del Ministerio de Medio Ambiente y Medio Rural y Marino; 2011. p. 349.
[50] Bejarano MD, Marchamalo M, Jalón DGD, Tánago MGD. Flow regime patterns and their controlling factors in the Ebro basin (Spain). J Hydrol 2010;385:323–35. https://doi.org/10.1016/j.jhydrol.2010.03.001.
[51] Alba Solans M, LeRoy Poff N. Classification of natural flow regimes in the Ebro basin (Spain) by using a wide range of hydrologic parameters. River Res Appl 2013;29:1147–63. https://doi.org/10.1002/rra.2598.
[52] Richter BD, Baumgartner JV, Powell J, Braun DP. A method for assessing hydrologic alteration within ecosystems. Conserv Biol 1996;10:1163–74. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.
[53] ESHA. Guide on How to Develop a Small Hydropower Plant. 2 ed. Brussels, Belgium: European Small Hydropower Association (ESHA); 2004. p. 1–296. https://electrical-engineering-portal.com.
[54] Karakoyun Y, Yumurtaci Z, Dönmez AH. Environmental flow assessment for energy generation sustainability employing different hydraulic evaluation methods: Çambaşi hydropower plant case study in Turkey. Clean Technol Environ Policy 2015;18:583–91. https://doi.org/10.1007/s10098-015-1023-9.
[55] Acreman M. Linking science and decision-making: features and experience from environmental river flow setting. Environ Modell Softw 2005;20:99–109. https://doi.org/10.1016/j.envsoft.2003.08.019.
[56] Kuriqi A, Pinheiro AN, Sordo-Ward A, Garrote L. Influence of hydrologically based environmental flow methods on flow alteration and energy production in a run-of-river hydropower plant. J Cleaner Prod 2019;232:1028–42. https://doi.org/10.1016/j.jclepro.2019.05.358.
[57] Voros NG, Kiranoudis CT, Maroulis ZB. Short-cut design of small hydroelectric plants. Renew Energy 2000;19:545–63. https://doi.org/10.1016/S0960-1481(99)00083-X.
[58] Jager HI, Efroymson RA, Opperman JJ, Kelly MR. Spatial design principles for sustainable hydropower development in river basins. Renew Sustain Energy Rev 2015;45:808–16. https://doi.org/10.1016/j.rser.2015.01.067.
[59] Operacz A, Wałęga A, Cupak A, Tomaszewska B. The comparison of environmental flow assessment - the barrier for investment in Poland or river protection? J Cleaner Prod 2018;193:575–92. https://doi.org/10.1016/j.jclepro.2018.05.098.
[60] Wang S, Fath B, Chen B. Energy–water nexus under energy mix scenarios using input–output and ecological network analyses. Appl Energy 2019;233–234:827–39. https://doi.org/10.1016/j.apenergy.2018.10.056.