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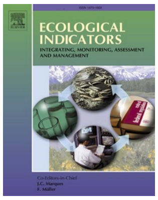

Review

Rethinking ecosystem service indicators for their application to intermittent rivers

A.V. Pastor[a,b,c,*], O. Tzoraki[d], D. Bruno[e], T. Kaletová[f], C. Mendoza-Lera[g,h], A. Alamanos[i], M. Brummer[j], T. Datry[k], A.M. De Girolamo[l], J. Jakubínský[m], I. Logar[n], L. Loures[o], M. Ilhéu[p], P. Koundouri[q], J.P Nunes[c,r], C. Quintas-Soriano[s], T. Sykes[t], A. Truchy[u], S. Tsani[v], D. Jorda-Capdevila[w]

[a] *ITAP, Univ Montpellier, INRAE, Montpellier SupAgro, Montpellier, France*
[b] *ELSA, Research Group for Environmental Life Cycle Sustainability Assessment, Montpellier France*
[c] *cE3c: Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciencias da Universidade de Lisboa, 1749-016 Lisbon, Portugal*
[d] *Marine Sciences Department, University of the Aegean, University hill, 81100 Mytilene, Greece*
[e] *Pyrenean Institute of Ecology (IPE-CSIC), Zaragoza, Spain*
[f] *Slovak University of Agriculture in Nitra, 94976 Nitra, Slovakia*
[g] *iES, University of Koblenz-Landau, Forststr. 7, 76829 – Landau, Germany*
[h] *Stroud Water Research Center, Avondale, PA, USA*
[i] *The Water Forum, Centre for Freshwater and Environmental Studies, Dundalk Institute of Technology, Marshes Upper, Dundalk Co. Louth, A91K584, Ireland*
[j] *University of Bayreuth, GCE Koordination Lehrstuhl für Biogeografie Universitätsstr, Bayreuth, Germany*
[k] *INRAE, UR-RiverLy, Centre de Lyon-Villeurbanne, Villeurbanne Cedex, France*
[l] *Water Research Institute, National Research Council, Bari, Italy*
[m] *Global Change Research Institute CAS, Brno, Czech Republic*
[n] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland*
[o] *VALORIZA, Research Center for Endogenous Resource Valorization, Polytechnic Institute of Portalegre, Portugal*
[p] *Department of Landscape, Environment and Planning, School of Science and Technology and MED-Mediterrenean Institute for Agriculture, Environment and Development, University of Évora, Portugal*
[q] *School of Economics and ReSEES Laboratory, Athens University of Economics and Business, Director Sustainable Development Unit ATHENA RC, Co-Chair UN SDSN Greece and Europe*
[r] *Soil Physics and Land Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, the Netherlands*
[s] *Departamento de Biología Vegetal y Ecología, Centro Andaluz para la Evaluación y Seguimiento de Cambio Global (CAESCG), Universidad de Almería, La Cañada de San Urbano 04120, Almería, Spain*
[t] *Biological Sciences, University of Southampton, UK*
[u] *Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden*
[v] *Department of Economics, University of Ioannina, Greece*
[w] *Area of Resources and Ecosystems, Catalan Institute for Water Research (ICRA), Girona, Spain*

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ABSTRACT

In these times of strong pressure on aquatic ecosystems and water resources due to climate change and water abstraction, intermittent rivers and ephemeral streams (IRES) (rivers that periodically cease to flow and/or dry) have become valuable assets. Indeed, not only do they supply water but they also offer services for humanity. Despite a growing recognition towards IRES, information for assessing their ecosystem services (ES) remains scarce. In a first step, an international interdisciplinary group of researchers developed a methodological framework to acknowledge ES provided by IRES using 109 indicators. A subset of selected ES indicators was then applied to two case studies: the Rio Seco in the Algarve (Portugal) and the Giofyros River in Crete (Greece). This paper discusses the applicability of these indicators, including the temporal and spatial variability of IRES flow regimes. Aspects of the framework, such as the methods and time required for data collection, the nature (demand or supply) and functionality of each indicator are discussed. The new framework accounts for flow

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Abbreviations: ES, Ecosystem services; IRES, Intermittent rivers and ephemeral streams; CS, Case study; COST, Cooperation in science and technology; EU, European Union; SMIRES, Science and management of intermittent rivers; EC, European Commission; EDS, Ecosystem disservices.

* Corresponding author.

E-mail address: amandine.pastor@inrae.fr (A.V. Pastor).

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intermittence in ES analyses and can help scientists and water managers to i) increase the ease and justification for IRES use in management approaches and ii) improve their conservation and restoration with a comprehensive set of appropriate indicators for IRES. In addition, the comprehensive nature of the proposed indicators ensures that they can be understood by a broad audience and easily applicable. Since they were designed through a public participation process, the setting has been prepared for holistic stakeholder analysis and education around IRES functions and associated ES. From a management point of view, it would be particularly relevant to perform an economic evaluation with this new framework to understand the value of each ES category and their trade-offs. For the scientific community, however, it is important to consider public preferences to design socially accepted policies. The proposed indicators can successfully bridge these elements, hereby establishing a solid basis for the assessment of ES provided by IRES.

1. Introduction

Rivers that do not flow permanently (thereafter referred to as IRES, Intermittent Rivers and Ephemeral Streams) are characterized by flow cessation and dry events at certain periods of the year and for one or more river reaches of the river network (Arthington et al., 2014; Costigan et al., 2017; Gallart et al., 2012). Three distinct hydrological phases can be defined within IRES: a) the flowing phase where water flow is maintained, either directly due to rainfall and snowfall and/or from baseflow contribution; b) the non-flowing phase when the interruption of flow creates connected or isolated pools; and c) the dry phase when surface water is absent but significant hydrological processes can occur in the hyporheic zone. Complementary classifications exist as in Gallart et al. (2017) with the description of eight aquatic states: quasi-perennial; alternate-fluent; fluent-stagnant; stagnant; alternate-stagnant; alternate; occasional; and episodic. Each of these eight states is characterised by its flow permanence, pool permanence and dry channel permanence. IRES represent the most widespread type of flowing water worldwide (Messager et al., 2021) and are expected to expand further as the climate becomes drier and the societal demand for water increases (Acuña et al., 2014; Datry et al., 2018; Messager et al., 2021).

According to the geology, lithology and climate, drying can either occur in specific river reaches (e.g., headwaters) or diffuse throughout the entire river network (Costigan et al., 2016; Crabot et al., 2020; De Girolamo et al., 2017). Although the frequency, timing and duration of the dry phase are recognized as important drivers in riverine ecosystems, the ecological effects of the hydrological phases are yet not fully understood (Leigh and Datry, 2017). Indeed, the hydrological transition between flowing and dry phases is crucial for influencing biota and physical–chemical processes, since flow intermittence interrupts the longitudinal connectivity and creates habitat isolation (Boulton, 2003; Larned et al., 2011). From a management perspective, IRES should be considered as an integral part of the global river network despite their current undervaluation by society (Armstrong et al., 2012; Armstrong and Stedman, 2020). They are characterized by complex biogeochemical processes (Arce et al., 2019) and unique aquatic (Bogan et al., 2017) and terrestrial (Sánchez-Montoya et al., 2020) species and habitats. Nevertheless, the legal status of IRES varies across the world. For example, in the European Union, the Water Framework Directive 2000/60/EC does not protect most IRES, because they are not formally considered as water bodies. This complicates the development and application of specific indicators for the ecological status of IRES to be properly assessed and can in turn lead to their mismanagement (Acuña et al., 2014; Crabot et al., 2020; Stubbington et al., 2018).

Recent studies have highlighted the ecological and economical values of IRES for society (Koundouri et al., 2017). Ecosystem services (ES) are defined as “the benefits and services people obtain from ecosystems” (MEA, 2005). Both ecosystem structure and processes of IRES are vital for the provision of ES, but differ from those of perennial rivers (Datry et al., 2018). Flow intermittence regimes are highly diverse, ranging from very ephemeral sites that flow only after major rainfall events to perennial sites that occasionally dry during severe droughts (Boulton et al., 2017; Datry et al., 2014). Each IRES is hydrologically and ecologically distinct, with key implications for water and sediment transport, biota, and biogeochemical cycles (Allen et al., 2020); yet, the assessment of their different phases (flowing, non-flowing and dry) and associated dynamics in space and time still remains challenging (Datry et al., 2018).

IRES furnish multiple ES: provisioning ES, such as the freshwater supply, regulating ES such as flood control and water regulation, supporting ES such as habitats for aquatic and terrestrial organisms, and cultural ES, such as aesthetic and recreational values (Datry et al., 2018; Jorda-Capdevila et al., 2020; Stubbington et al., 2020). The supply of ES is strongly related to the different hydrological phases. Firstly, certain ES provided by IRES are altered, reduced or lost when the flow ceases, while others are enhanced (Datry et al., 2018; Steward et al., 2012). For example, the riverbed operates as a carbon sink when dry, but it can act as a carbon source during rewetting events (Datry et al., 2018). Secondly, for the provision of given specific services, such as sediment extraction or fishing, the different hydrological phases are interdependent (Magand et al., 2020). Indeed, while the flowing phase enhances sediment transport and fish habitats, the non-flowing and dry phases facilitate river access and sand and gravel extraction (Boulton, 2014; Stubbington et al., 2020). Finally, certain ES, such as cultural services, can vary according to the different phases (Jorda-Capdevila et al., 2021). For instance, the types of recreational activities depend upon the hydrological phase, e.g. canyoning in the flowing phase, fishing in the flowing and pool phases, and hiking in the dry phase (Jorda-Capdevila et al., 2020; Kaletova et al., 2021).

Although recent ES assessments of IRES do exist (Jorda-Capdevila et al., 2020; Stubbington et al., 2020), the complex ecological and geochemical nature of IRES has, to this date, hindered the possibility for an accurate and thorough ES evaluation (Datry et al., 2018). Case-specific ES assessments in IRES are still scarce (Acuña et al., 2014; Kaletová et al., 2019), and, despite the recent growing literature on ES, there is still no clear guidance for properly identifying, assessing and valuing the ES provided by IRES. Morever, current indicators do not cover all the ES that IRES can provide (Magand et al., 2020). Consequently, the application of the ES paradigm to IRES has been largely overlooked (Boulton, 2014; Datry et al., 2018) and the development of a new framework specific to IRES has become crucial (Böck et al., 2018; Datry et al., 2018). In addition, the application of holistic and transdisciplinary methods including trade-offs among ES, disservices (EDS) and ecosystem functions are still lacking for IRES (Acuña et al., 2020; Datry et al., 2018). The concept of ecosystem disservices is employed to describe the ecological costs that humans experience from nature. Like ES, disservices result from ecological processes and interactions (Saunders, 2020). According to Shapiro and Báldi, (2014), ES disservices, such as the transmission of vector-borne diseases, are described as negative for humans. However, these negative impacts are often due to the mismanagement of naturel systems by humans, which lead to imbalances between services and disservices. For example, vector-borne diseases have recently been observed to increase due to the massive destruction of natural habitats (Priyadarsini et al., 2020).

The objective of this study was to i) develop a set of ES indicators specifically tailored to IRES, ii) apply this new framework to two contrasting case studies. In this view, a methodological framework is presented, involving a feedback loop composed of six recurring steps including: a literature review on IRES and their related ES, the development of ES indicators, the design of a survey to collect ES information, two case study applications on a subset of indicators and a discussion on indicator applicability. In addition to the development of ES indicators, a framework is presented with information on potential data sources, relevant hydrological phases to assess each ES, information on ES supply/demand and, the time required for data collection.

2. Methodological framework

Both the development of the methodological framework and the process of developing indicators (Fig. 1) involved multiple phases including: i) a pre-workshop period to select the leading experts and prepare the literature review on ES indicators; ii) a two-day interdisciplinary and gender-balanced workshop in Hungary (February 2018) in the context of the Science and Management of Intermittent and Ephemeral Streams (SMIRES) COST Action program with 13 researchers from ten different European countries (Datry et al., 2017a), see Appendix A1; iii) two online meetings dedicated to the design of the survey to be applied to the case studies; iv) implementation of a subset of indicators on two case studies (CS); v) interviews with stakeholders and data collection (onsite and offsite) in the respective case studies (Portugal and Greece); vi) several online and presential meetings to discuss the final framework and list of ES indicators (at least 3 meetings in 2020).

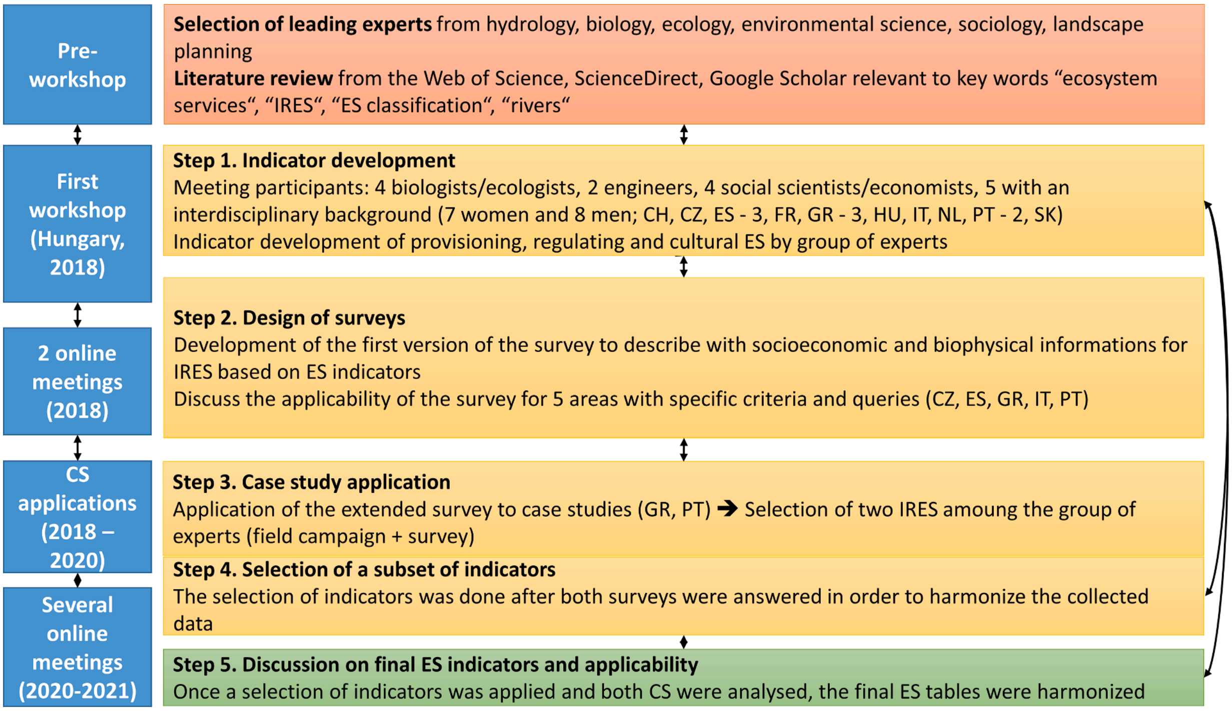
Most phases of this whole process followed a feedback loop (Fig. 1), and can be categorized according to the different objectives described below.

2.1. Literature review

The literature review focused on the classification systems of ES indicators used for perennial rivers, and their potential contribution to ES assessments of IRES (biophysical, social and economic). There are three types of existing ES classification: Millenium ecosystem assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, Russi et al., 2012) and Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin, 2013, 2018). The present framework was developed according to the CICES (v. 4) produced by the European Environment Agency (Haines-Young and Potschin, 2018) because it is the most recent classification, and was based on the two previous classifications (MEA and TEEB). It is also a more detailed classification that provides a clear distinction between ecosystem and society by describing the ecosystem structures, functions and services. In addition, indicators were also provided according to the MEA, TEEB, literature review and expert knowledge. It is noteworthy that in the latest CICES revision, Haines-Young and Potschin (2018) removed supporting ES from the final framework because they claim that supporting services should not be accounted as 'services' but rather as 'structures, processes and functions that give rise to services'. The removal of supporting services therefore does not imply that they are insignificant but rather that a choice was made to better describe the boundary between ecosystems and society, since humans benefit from the outputs of ecosystems (Haines-Young and Potschin, 2018). The presence of supporting services could create double-counting, especially when adding up the economic values of the different classes of ES (Patterson and Cole, 2013). However, fundamental supporting services, such as nutrient cycling, were maintained in the final list of regulating ES. On the 14th February 2018, 36 articles were reviewed in the different search engines (SCOPUS, Web of Science and Google scholar) with the following specific query: "intermittent rivers" OR "IRES" OR "ephemeral rivers" OR "dry rivers" OR "temporary rivers" OR "rivers" AND "ecosystem services" and we searched for technical reports on ecosystem services and indicators of temporary rivers, and rivers in general. Thus, by adding the technical reports to the scientific articles, in total, 78 documents were reviewed (Appendix A2).

2.2. Indicator selection

Based on the interdisciplinary expertise of the group, a list of ES indicators was discussed and adapted to IRES according to their particularities, e.g., dry phase, higher anthropogenic disturbances, and mismanagement. Section 3 provides the full set of indicators and their



Selection of leading experts from hydrology, biology, ecology, environmental science, sociology, landscape planning
Literature review from the Web of Science, ScienceDirect, Google Scholar relevant to key words "ecosystem services", "IRES", "ES classification", "rivers"

Step 1. Indicator development
Meeting participants: 4 biologists/ecologists, 2 engineers, 4 social scientists/economists, 5 with an interdisciplinary background (7 women and 8 men; CH, CZ, ES - 3, FR, GR - 3, HU, IT, NL, PT - 2, SK)
Indicator development of provisioning, regulating and cultural ES by group of experts

Step 2. Design of surveys
Development of the first version of the survey to describe with socioeconomic and biophysical informations for IRES based on ES indicators
Discuss the applicability of the survey for 5 areas with specific criteria and queries (CZ, ES, GR, IT, PT)

Step 3. Case study application
Application of the extended survey to case studies (GR, PT) ➔ Selection of two IRES amoung the group of experts (field campaign + survey)

Step 4. Selection of a subset of indicators
The selection of indicators was done after both surveys were answered in order to harmonize the collected data

Step 5. Discussion on final ES indicators and applicability
Once a selection of indicators was applied and both CS were analysed, the final ES tables were harmonized

Fig. 1. Methodological workflow for the selection of indicators for assessing ecosystem services of intermittent rivers.

applicability to IRES. The indicators had to be comprehensible (i.e. understandable by a multidisciplinary scientific audience), generalizable (applicable worldwide) and implementable (easy to use by IRES managers). The scientists were distributed across three groups corresponding to provisioning ES, regulating ES and cultural ES according to their expertise. Each indicator was then characterized using different criteria. Firstly, the indicator was specified to represent supply (S) or demand (D), based on the definition given by Burkhard et al., (2012), where supply stands for 'the capacity of a particular area to provide specific ES within a given period'; demand stands for 'the ES currently consumed or used in a particular area'. Secondly, the data collection method was defined, including the literature source, survey/interviews, *in situ* observations, remote-sensing, regional statistics, online qualitative information and modelling. Thirdly, the hydrological phase to which the indicator applies was identified, (i.e. flowing, pool and drying phases). Finally, each indicator was classified according to the time spent in obtaining the data – *low* (takes less than a day, e.g., information from open-source statistics), *medium* (takes between one day and one week, e.g., field observation) and *high* (takes more than one week, e.g., public survey, modelling).

2.3. Design of surveys

After the first round of indicator development, the experts got together twice in order to design the surveys to be applied to IRES. For this, the foundation of the survey was based on the first round of selected indicators such as provisioning ecosystem services comprising socioeconomic information, regulating services mainly based on biophysical and geomorphological information and cultural services which were based on local socioeconomic information and local tourism agencies (Appendix A5-A6). The second round was related to increasing the comprehensiveness of chosen indicators (Fig. 1).

2.4. Case study application

After the indicator development phase and the design of the survey, their applicability was tested in specific case studies (Appendix A). For this purpose, a survey was developed to obtain information as detailed as possible based on the first round of selected ES indicators. The subset of indicators was selected according to the expert knowledge and literature review during the first meeting in Hungary.

The interviews and the survey were conducted in two specific IRES: the Rio Seco (Algarve, Portugal), and the Giofyros River (Crete, Greece). These two case studies were selected because they both concerned Mediterranean intermittent rivers with similar levels of pressure for waterressources due to summer irrigation and tourism. Local and European research funds were used for performing the survey through different interviews. The first survey was conducted for Rio Seco in September and October 2018 and the second survey was performed in spring 2020 for the Giofyros River.

2.5. Selection of a subset of indicators

After completing the interviews, a subset of indicators was selected, allowing for the data collected in each CS to be synchronised with the updated table of ES indicators. Besides being comprehensible, robust and implementable, the criteria for the selection of the final subsets were that the required information should be collected during the respective surveys. In addition, this information should not demand additional time during the field monitoring and/or modelling phases, because of resource and time constraints.

2.6. Discussion on applicability

Each CS application was followed by a discussion on the adaptation, applicability, suitability and usefulness of each indicator for ES assessment. The potential application of the final ES indicator table was also discussed, and finally, the potential improvement in monitoring and management of IRES was addressed. Section 5 summarises the discussion.

3. List of indicators for the assessment of intermittent river ecosystem services

Based on the indicator selection methodology described in Section 2, a total of 109 indicators were selected. These were grouped into 23 ecosystem services (ES), of which 40 provisioning ES indicators were clustered into nine ES groups (Table 1), 64 regulating indicators were clustered into nine ES groups (Table 2) and 25 cultural indicators were clustered into five ES groups (Table 3). The developed indicators or proxies include information on biophysical and socio-economic data. An exhaustive list of potential indicators that are suitable for quantitative and/or qualitative assessments of ES for IRES is presented here. This list comprises information based on measurements, modelling, expert assessment, statistics, public surveys and participatory methods (Grizzetti et al., 2016; Haines-Young and Potschin, 2018; Maes et al., 2016a, b). For each indicator, the characteristics of the supply/demand, type of method, hydrological phase, application time and references are provided.

3.1. Indicators of provisioning ecosystem services

The 40 provisioning ES indicators encompass nine provisioning ES groups such as food, water and other non-food materials (Table 1). In general, and in comparison with other ES types, large amounts of data are available from official statistics (or remote sensing, among others) requiring a notable amount of time (several weeks to months) for data collection from long-time series (usually with an annual time-step). Most data can be collected from surveys, from online regional databases and/or spatial sources (e.g. map of land use). However, in comparison with regional and/or statistical databases, although spatial data (e.g. remote sensing) provide refined spatial and temporal information, their obtention and processing may be very time-consuming. Statistical information is often aggregated at larger spatial and temporal scales (e.g., annual time step), particularly on the demand side of ES. This can become an issue when characterizing certain indicators such as irrigation intensity during the different hydrological phases. Most of the data underlying these indicators can be provided by local authorities, modelling and/or *in situ* observations (e.g. water extracted for agriculture and human consumption, inland salt production, etc.), while other data, such as firewood produced by riparian forests or the number of floodplain inhabitants, can also be obtained from regional institutions and literature. In the EU, for example, it is particularly relevant to consider the public data collected by the Water Framework Directive 2000/60/EC and associated river basin plans.

Data related to both surface- and groundwater supplies are usually readily available from local authorities, including water agencies, environmental regulators, water withdrawal permit records, etc. (Alley, 2017). Several socioeconomic proxies such as gross domestic products (GDP) per sector or price of hydropower electricity, can be used for evaluating the potential ES demand. A larger number of indicators related to the freshwater provision (whether for consumption, agricultural, industrial or energy) can only be useful during the flowing phase. Indeed, water availability is seasonal and there is a greater risk of reduced water quality, especially during receding pools (Datry et al., 2018). Although large rivers are increasingly drying up in the Mediterranean area, this is currently a typical phenomenon for smaller watercourses. However, large water abstractions and use for energy purposes (e.g., location of hydropower plants) are uncommon or not applicable in these streams.

Nine out of 40 selected indicators, such as the quantity of fish harvested or the presence of aquatic plants, can only be used during the

Table 1
Selected indicators that represent provisioning ecosystem services in IRES. Abbreviations used are S (Supply); D (Demand); 1 (Survey, interviews to local authorities, associations, NGOs, experts, universities etc.); 2 (In situ observations, samplings, measurements etc.); 3 (Spatial information such as remote sensing); 4 (Literature, Regional statistics, Databases); 5 (Online information coming from social networks or other); 6 (Modelling); F (Flowing); P (Pools); Dr (Drying); I (Independent); L (Low); M (Medium); H (High).

Ecosystem service	Indicator	Supply/ Demand	Method	Hydrological phase	Application time	References
Fiber & fuel: production of logs, fuelwood, peat, and fodder	Weight of fiber & fuel extracted in the floodplain (t/ha/year)	D	1, 4	F-P-D	M/H	Ferrari, 2014; De Groot et al., 2010; Grizzetti et al., 2016; Egoh et al., 2012; Van Jaarsveld et al., 2005; Vihervaara et al., 2010
	Number of collectors/consumers/ beneficiaries (number/basin ha or IRES km)	D	1, 5	I	M/H	
	Volume of inorganic matter extracted (m^3/IRES km/year)	D	1, 5	D	L	Vermaat et al., 2013
	Inland salt production (t/ha/year)	D	1	I	L	Vidal-Abarca et al., 2014
	Firewood produced by riparian forests (t or m^3/ha/year)	S, D	3, 4	I	L/M	Maes et al., 2016
	Surface of exploited wet forests (e.g., poplars) and reeds (ha)	D	3, 4	F-P-D	L/M	
Food provisioning: grains	Area used for crop production for food and feed (ha)	D	4	I	L/M	Maes et al., 2014; La Notte et al., 2017
	Grain species produced for food and feed (number/ha)	D	4	F-P-D	L/M	
	Yield of food and feed crop species (kg/ ha/year)	D	4	I	L/M	
Food provisioning: berries, mushrooms etc. for gathering	Production of wild plants in riparian and floodplain (kg/ha/year)	S	1, 4, 6	I	M	Maes et al., 2014; Layke et al., 2012
	Density (individual/ha) and/or coverage (%) of different edible wild plants in riparian/floodplain	S	1, 4, 6	F-P-D	M	
	Distribution and richness of edible riparian plants estimated through modelling (species/ha)	S	1	I	M	
	Sales of edible wild riparian plants and associated nourishment (€/ha/year)	D	1	I	M	
Biochemical. extraction of medicines and other material from biota	Diversity and quantity of plant elements extracted in the fluvial area (number of plant elements/ha)	D	1	P-D	H	Layke et al., 2012; Russi et al., 2012; MEA, 2005; Grizzetti et al., 2016
	Coverage (%) and diversity (species richness/ha) of aquatic and riparian plant species with medical applications	S	1	F-P-D	M	
Food provisioning: fish	Quantity of fish harvested for consumption (kg/ha/year)	D	1, 4	F-P	M/H	Egoh et al., 2012; Layke et al., 2012; Russi et al., 2013; Grizzetti et al., 2016; Maes et al., 2016
	Abundance of fish species (number of individuals/ha)	S	1	F-P	M	
	Fishing licenses (number/ha/year)	D	1, 4	I	M	Maes et al., 2016
	Aquaculture farms (number/ha)	D	1, 3, 4	F	L/M	Maes et al., 2016; Vidal-Abarca et al., 2014
Food provisioning: wild game	Population size of species of interest (individuals/ha)	S	1, 3, 4	F-P-D	M/H	Maes et al., 2014, 2016
	Kills (kills/ha/year)	D	4	I	M/H	
	Hunting licenses (number/ha/year)	D	1, 4	I	L	Maes et al., 2016
Genetic material. Resistance to pathogens, ornamental species	Provision/extraction of genetic material from flora and fauna for use in non-productive (biomass)	S, D	1	F-P-D	H	
Fresh water: surface water for drinking purposes	Water abstracted for drinking purposes (m^3)	D	1	F	L	De Groot, Wilson, Boumans, 2002
	Water exploitation index (%)	D	6	F-P-D	M/H	Grizzetti et al., 2016; Maes et al., 2014
	Permanent and non-permanent population within floodplain (inhabitants/ha)	D	4	F-P-D	L	Jenerette et al., 2006; Vanham et al., 2019
Fresh water: surface water for non-drinking purposes	Water extracted for agricultural use (m^3/basin ha/year)	D	1	F-P-D	M	Supit et al., 2010
	Total irrigated land, if possible, per crop (ha) or (% per basin)	D	1	F-P-D	M	Jorda-Capdevila et al., 2020
	Irrigation intensity (m^3/ha/crop)	D	1	F-P-D	M	Vidal-Abarca & Suárez-Alonso, 2013
	Farmers/ha	D	1	I	M	
	Gross Domestic Product of agriculture (€/ha/year)	D	1	I	M	Vidal-Abarca & Suárez-Alonso, 2013
	Water abstracted for industrial use (m^3/basin ha)	D	1	F-P-D	M	Vidal-Abarca et al., 2014
	Industrial plants (number/ha/sector)	D	1	I	M/H	
	Labor force of industry (full-time equivalent FTE)	S	1	I	M/H	
	Gross Domestic Product of industry (€/ha/sector)	D	1, 4	I	M/H	
		D	1	F-P-D	M/H	Vidal-Abarca & Suárez-Alonso, 2013

(*continued on next page*)

Table 1 (*continued*)

Ecosystem service	Indicator	Supply/ Demand	Method	Hydrological phase	Application time	References
	Water abstracted for energy production (m^3/ ha)					
	Hydropower plants (number/IRES length)	S	1	F	M/H	
	Installed capacity of hydropower plant generators (MW)	D	1	F	M/H	Vidal-Abarca & Suárez-Alonso, 2013
	Annual power generation (GWh/year)	D	1	F	M/H	Vidal-Abarca et al., 2014
	Price of electricity obtained from hydropower (€/kWh)	D	1, 4	F-P-D	M/H	
	Groundwater bodies (m^3/basin ha)	S	1, 5	F-P-D	Low	Maes et al., 2016

flowing and pool phases, while two out of 40 indicators (surface of exploited wet forest, diversity and quantity of plants extracted in the fluvial area) can only be applied during the dry phase. The remaining indicators apply to the three phases (e.g., the density of riparian plants) or are unrelated to the hydrological phase (e.g., number of farmers). However, some indicators can vary according to the type of agriculture system. For example, while irrigation might be significant for intensive agricultural systems, it can be low for extensive farming systems.

Finally, most of the provisioning indicators identified for raw materials (production of wood logs, fuelwood, peat and fodder) and for ES food provisioning (grains, wild plants, fish and wild game) were associated with the demand for ES but occasionally also with the supply of ES (11 indicators), especially those related to wild plants and animals.

An important obstacle that hinders the application of certain provisioning ES indicators in IRES is the decoupling of ES spatial and temporal variation due to the available data source, the resolution and differing time series. For example, hunting/fishing licences are often only provided at a regional level. In many cases, when only annual statistical data are available (e.g., crop production area), translating to distinct hydrological phases can become an issue. Another example concerns GDP, which is generally only available over an annual scale for administrative regions based on political borders. Finally, the collection of required information, such as monitoring of the dry riverbed using time-lapse photography, can be intensively time and resource consuming (Stamataki, 2021).

3.2. *Indicators of regulating ecosystem services*

Regulating ES are considered to play a crucial role in the perpetuation of ecosystems and in the maintenance of fundamental biophysical processes such as climate regulation, water purification, etc. (Table 2). The selected regulating ES are represented by 64 indicators covering nine categories, ranging from nutrient cycling, natural hazards, erosion, water and climate regulations, water purification to pollination and diseases and pest control. Most of the proposed indicators are connected to river channel characteristics (e.g., cross-section pattern or variability), floodplain (e.g., presence of typical fluvial landforms in the floodplain), structures (e.g., presence of dams or other storage constructions), water and air quality parameters (e.g., air temperature change) and vegetation presence and status (e.g., vegetation management).

Data from a large amount of indicators, such as natural hazard indicators, can be obtained from local authorities (27 indicators) and from *in situ* measurements (43 indicators). A few indicators can be assessed through modelling (e.g., water self-purification) or remote sensing (e.g., riparian forest area). Data collection could demand little to moderate timescales (e.g., databases). However, missing information can increase the implementation time. More than half of the indicators, such as transport of nutrients and pollutants or aquatic insect visitation rates, only apply to the flowing and pool phases. One indicator (CO_2 fluxes from dry riverbeds) was identified as only applicable to the drying phase. Conversely, many indicators, such as the nutrient delivery ratio, should be analysed during each of the different hydrological phases. This ratio is highly dependant upon flows, while other indicators, such as the presence of dams, are unrelated to the hydrological phases.

The spectrum of regulating ES is strongly influenced by the hydromorphological state of the watercourse, which in turn also affects the overall ecological state of the riverine ecosystem. In the case of IRES, there are often specific morphological features. For example, pools can receive high amounts of organic matter, which can be rapidly mineralized and represent the dominant pool of dissolved inorganic nitrogen (Ribot et al., 2017). Information can also be obtained from *in situ* observations, detailed maps, aerial photography with remote sensing and discussions with local water authorities. However, relevant information related to the hydrological phases should be provided from long-term *in situ* measurements.

3.3. *Indicators of cultural ecosystem services*

Cultural ES and their indicators represent the smallest group of ES, including recreational, educational, aesthetic and spiritual ES, with 25 indicators grouped into five ES clusters. Cultural ES are usually less represented for all types of rivers and communities, as has been previously highlighted for riparian vegetation (Riis et al., 2020). They are mostly based on knowledge provided by local communities and authorities, non-governmental organizations, experts and literature (Table 3). Most data collection approaches can therefore take place on-site with face-to-face surveys, participatory workshops, (online) surveys and interviews, all of which are time-consuming. Given the different types of activities planned in each phase, survey results can be easily related to the hydrological phases. For example, the number and types of activities can be attributed to the flowing (e.g., canyoning), and pool and dry phases (e.g., walking, hiking, picnics, birdwatching, etc.). Similarly, photos from social media, the number of formal and informal education activities or the number of scientific studies can be easily associated with specific hydrological phases.

Most of the proposed cultural ES indicators reflect the demand for ES rather than the supply. Rather than identifying tools and methods to quantify the demand and supply of ES in the fields of education and local knowledge, most of the current literature investigates the locations and requirements to enhance public awareness of such aspects. Nevertheless, Datry et al. (2018) identified a set of concepts, knowledge, and methods, typically applied in ecology, that could be used to assess both the demand and the supply of ES in the realms of education and traditional knowledge of local communities.

4. Case study application

A subset of the above-mentioned indicators was applied to two contrasting IRES to identify their comprehensibility and applicability in practice. As a result, and based on the selected indicators (Table 1, 2 and 3), a survey was designed and carried out to obtain general administrative, statistical, and spatial data from local institutions and associations, including the local population (Appendix A). The studies were

Table 2
Selected indicators that represent regulating ecosystem services in IRES. Abbreviations used are S (Supply); D (Demand); 1 (Survey, Interviews to local authorities, associations, NGOs, experts, universities etc.); 2 (In situ observations, samplings, measurements etc.); 3 (Spatial information such as remote sensing); 4 (Literature, Regional statistics, Databases); 5 (Online information coming from social networks or other); 6 (Modelling); F (Flowing); P (Pools); Dr (Drying); I (Independent); L (Low); M (Medium); H (High).

Ecosystem service	Indicator	Supply/ Demand	Method	Hydrological phase	Application time	References
Nutrient cycling regulation	Nutrient Delivery Ratio	S	2	F-P-D	M/H	Sharp et al., 2014
	Presence of aquatic plants and biofilms	S	2	F-P	M	Srivastava et al., 2017; Levi et al., 2015
	Presence of geomorphological elements	S	2	F-P-D	M	Newcomer Johnson et al., 2016; van Looy et al., 2017
	Presence of riparian forest	S	2, 3	F-P-D	M	van Looy et al., 2017
	Connectivity with the floodplain	S	2, 3, 6	F-P-D	M/H	
	Transport of nutrients and pollutants	S	1, 4	F	M/H	Koundouri et al., 2017
	Drying-flowing oscillation	S	2, 4	F-P-D	H	Datry et al., 2018
	Ecological status according to the WFD	S	1, 4	F-P	L/M	Maes et al., 2016
	Physicochemical indicators (e.g., NO_3, PO_{43-}, total N, total P)	S	1, 4	F-P	L	
	Patchiness of morphological units	S	2	F-P-D	L	Gonzalez del Tanago et al., 2016
	Fluxes of POC and CO2	D	2	F-P-D	H	Goldsmith et al., 2008; Hilton et al., 2011
	Presence of dams or other storage constructions	S, D	2, 3, 1	I	L	Li et al., 2015; Mendonca et al., 2012
	Presence of woody debris	S	1, 2	F-P-D	L	Ekoungoulou et al., 2018
	Presence of L-gradient, broad valley bottoms	S	1, 3	I	L	Wohl et al., 2012
	Self-purification capacity	S	2, 4, 6	F-P-D	M/H	Stream Solute Workshop, 1990
Odour reduction, noise attenuation, visual screening		S	1	F-P-D	L	
Natural hazard regulation	Presence of a modern floodplain	S, D	1, 2	I	L	Vermaat et al., 2013; Maes et al., 2016
	Hillslope – river corridor connectivity	S	1, 2	I	L	Gonzalez del Tanago et al., 2016
	Crossing structures, other bed stabilization structures	D	2	I	L	Vermaat et al., 2013; Gonzalez del Tanago et al., 2016
	Bank protections	D	1, 2	I	L	Vermaat et al., 2013; Maes et al., 2016
	Artificial changes of the river course	D	1, 2	I	L	Vermaat et al., 2013; Bastian et al., 2012
	Sediment and wood removal	D	1	F-P-D	L/M	
	Vegetation management	D	1, 4	F-P-D	L/M	
	Number of floods	S	1, 2	I	L	Maes et al., 2011; Burkhard et al., 2012
	Morphological type of the reach	S	2	I	L	Gonzalez del Tanago et al., 2016
Erosion regulation	Longitudinal continuity in sediment and wood flux	S	2	I	L	Nicholas et al., 2006; Noe & Hupp, 2005
	Processes of bank retreat; presence of a potentially erodible corridor	S	1, 2	I	L	Gonzalez del Tanago et al., 2016
	Bed configuration – valley slope (° or %)	S	1, 2	I	L	
	Planform pattern (e. g. multi-thread, single-thread, transitional…)	S	1, 2	F-P-D	L	
	Presence of typical fluvial land forms in the flood plain (e. g. meanders, oxbow lake)	S	1, 2	F-P-D	L	Vermaat et al., 2013
	Variability of the cross-section	S	1, 2	F-P-D	L	
	Structure of the channel bed (e.g., armouring, clogging, natural heterogeneity)	S	2	F-P-D	L	Gonzalez del Tanago et al., 2016
	Presence of in-channel large wood (presence/absence matrix)	S, D	2	F-P-D	L	
	Alteration of sediment discharge	D	2, 4	I	L/M	
	Bank protections (presence/absence matrix; alternatively km of protections)	D	2	I	L	Vermaat et al., 2013
	Wood removal (t/km or t/ha)	D	1, 4	F-P-D	L/M	Vermaat et al., 2013
	Vegetation cover (%)	S	1, 2	F-P-D	L	Kandziora et al., 2013
	Loss of soil particles (t/ha/year)	D	1, 2	I	L/M	
Water regulation	Upstream alteration of flow (number of structures upstream)	D	1, 4	I	L	Aylward et al., 2005
	Alteration of flow in the reach	D	1, 4	F-P	L/M	
	Groundwater recharge rate (mm/ha/year)	D	2	I	M/H	Kandziora et al., 2013
	Groundwater level (m per surface)	S	2	F-P-D	L/M	Maes et al., 2016
Pollination and seed dispersal	Area of crops that need pollination (ha)	D	2	I	H	Santos et al., 2018, Raitif et al., 2019
	Number of mammals using the stream	S	2	F-P-D	H	Trolliet et al., 2014
	Visitation rate of aquatic insects	S	2, 4, 6	F-P	H	Raitif et al., 2019

(*continued on next page*)

Table 2 (*continued*)

Ecosystem service	Indicator	Supply/ Demand	Method	Hydrological phase	Application time	References
	Pollination Sustainability Index for Riverine Landscapes	S	2, 4, 6	F-P-D	H	Santos et al., 2018
Disease and pest control	Abundance of mosquitoes	D	2	F-P-D	H	Carver et al., 2015
	Percentage of aquatic prey in the diets of terrestrial arthropod predators (%)	S	1	F-P	H	Raitif et al., 2019
	Presence of exotic and invasive riverine species	D	1, 4	F-P-D	H	McLaughlan et al., 2014; Muñoz-Mas, R., & García-Berthou, E. (2020)
	Presence of emblematic riverine species		1, 4	F-P-D	H	
Water purification and waste treatment	Structure of the channel bed	S	1, 2	F-P-D	L	Newcomer Johnson et al., 2016; van Looy et al., 2017
	Width of functional vegetation and linear extension of functional vegetation (m) and presence of emergent and floating aquatic macrophytes (number of species)	S, D	1, 2	F-P	M	Miretzky et al., 2004; Lu et al., 2008
	Nutrient excess	S	1, 2	F-P	M	
	Patchiness of morphological units	S	2, 3	F-P-D	L	
	Wastewater treatment plants - WWTPs (number)	D	1, 2, 4	I	L	
	Soil depth and litter cover (cm)	S	1, 2	F-P-D	M/H	Egoh et al., 2008
	Earthworms (number or mass/m2)	S	1, 2	F-P-D	H	Sandhu et al., 2008
	Bed configuration – valley slope (° or %)	S	1, 2	F-P-D	L	Chicaro, Müller & Fohrer, 2015; Grizzetti et al., 2016; Smith et al., 2013
Climate regulation	Width of functional vegetation and linear extension of functional vegetation (m) and presence of emergent and floating aquatic macrophytes (number of species)	S, D	1, 2	F-P	M	Nowak et al., 2014
	Presence of riparian forest (m or ha)	S	1, 3	I	M	Nowak et al., 2014
	CO_2 emissions from a dry bed (t/ha)	S, D	1	D	M/H	Keller et al., 2020
	Change of air temperature (river bank/corridor vs rest of the catchment) (°C)	S, D	1	F-P-D	M/H	Capon et al., 2013
	Change of air humidity (river bank/corridor vs rest of the catchment) (%)	S, D	1	F-P-D	L/M	Vidal-Abarca & Suárez-Alonso, 2013
	Carbon stored and sequestered on four different carbon pools	S	6	F-P	L	Sharp et al., 2014

conducted in two locations in Southern Europe, one in the Algarve (Portugal) and the other in Crete (Greece) (Fig. 2).

4.1. Implementation of ES evaluation to Rio Seco, Algarve, Portugal

The first case study is Rio Seco, located in the Algarve, southern Portugal (37°00′35.2″N 7°53′13.1″W). The area of the basin covers 300 km^2. The Algarve is characterized by a Mediterranean climate with three topographic zones (coastal, mountainous and intermediate). The average temperatures ranges from 15 to 29 deg. C and precipitation is low (<600 mm of mean annual rainfall). Tourism represents 60% of the GDP and 66% of total employment, while agriculture and industry represent 3% and 10% of GDP, respectively. The Rio Seco is one of the tributaries of Ria Formosa, the biggest coastal lagoon and wetland of Algarve also protected by the International Union for Conservation of Nature (IUCN) and the Ramsar Convention (Ramsar Convention, 1971). An environmental protection program is applied to the downstream coastal lagoon but does not directly concern the river itself. Land use is dominated by intensively irrigated agriculture (orchards, vineyards and greenhouses) in the lowlands and by semi-natural vegetation in the uplands (Fig. 2).

The upstream mountainous section of the riverbed is composed of schist, while the intermediate section is made of calcareous compounds allowing for strong water infiltration (where the groundwater aquifer is stored) and the downstream coastal section is mainly composed of sand. The river outlet is described as a multi-thread braid with a sandy riverbed. The hydromorphological status of the river is defined as ‘moderate’, while its ecological status is classified as ‘bad’ (according to the Water Framework Directive Standards). Rio Seco has a mean flow of about 1 m^3.s^{-1} showing a progressive reduction (from 1986 to 2010) that can be explained by decreasing precipitation and increasing water withdrawals along the river over the past 30 years (Appendix A5-7).

4.2. Implementation of ES evaluation to Giofyros river, Crete, Greece

The second case study is located in Crete, Greece. The Giofyros river (Fig. 2, Appendices 4, 6 and 8) is a Mediterranean catchment area (186.5 km^2) located in the central part of Crete with its outlet at the Amoudara beach (35°20′13.8″N 25°06′37.2″E) of Heraklion city. It is characterized as a temporary stream, class RM-5, according to the 2013/480/EU Decision (SSW, 2015). Average temperatures vary from 15 to 29 °C. Precipitation mainly occurs between October and April and is about 841 mm (average values for the 1960–2011 period). The total river flow represents about 32% of total precipitation with an average flow of 0.91 m^3 s^{-1} (1977–1997).

The lower part of the Giofyros catchment forms a valley characterized by high-quality agricultural soils and by urban areas, while upstream (maximum elevation 1764 m) the slopes are steeper, essentially hosting agricultural and grazing activities. The soil is mostly alluvial and composed of a geologic formation of marl, limestone, flysh and alluvial deposits. Irrigated vineyards (24%), olive trees (34%) and farmlands are the main agricultural activities, which are present both within the stream floodplain and on the river banks. In general, the urban part of the riparian zone is dominated by arbitrary constructions and small industries that constitute environmental degradation hotspots. However, the most significant environmental damage arises from hydromorphological alterations, such as channel re-profiling, resectioning, embankments, and general deterioration, due to the expansion of high-yield irrigated agriculture.

4.3. Comparison of the case studies based on ES assessment

For the Rio Seco survey, four out of seven experts responded to the investigation (from local water agencies to the local cultural association of Rio Seco). For the Giofyros survey, a response from nine out of 15 experts was obtained (from various offices, NGOs, institutes and associations such as the Office of Environment and spatial planning of the

Table 3
Selected indicators that represent cultural ecosystem services in IRES. Abbreviations used are S (Supply); D (Demand); 1 (Survey, Interviews to local authorities, associations, NGOs, experts, universities etc.); 2 (In situ observations, samplings, measurements etc.); 3 (Spatial information such as remote sensing); 4 (Literature, Regional statistics, Databases); 5 (Online information coming from social networks or other); 6 (Modelling); F (Flowing); P (Pools); Dr (Drying); I (Independent); L (Low); M (Medium); H (High).

Ecosystem service	Indicator	Supply/ Demand	Method	Hydrological phase	Application time	References
Recreation	Number & type of activities (e.g., walking, hiking, picnics, birdwatching)	S, D	1	F-P-D	H	
	Number of cultural organizations (number/ha)	D	1	I	H	
	Number of visitors for recreational purposes	D	1	F-P-D	H	Vidal-Abarca et al., 2014
	Maps of trails (km)	D	1, 3	F-P-D	M/H	Carolli et al., 2017
	Fishing licenses (number/km IRES)	D	1	I	M/H	Villamanga et al., 2014
	Spread of person-days of recreation - Visitation rate based on geotagged photos	S	1, 5	F-P-D	L	Sharp et al., 2014
Aesthetic & Local Ecological Knowledge	Index of Natura 2000 sites/UNESCO	S	1, 3, 4	I	M/H	Carolli et al., 2017
	Scenic/panoramic trails (km)	D	1, 3, 4	F-P-D	M	Brummer et al., 2017
	Social media photos (number of photos)	D	5	F-P-D	M/H	Tieskens et al., 2018
	Number of “viewer days” per year	S, D	5	F-P-D	M/H	Quintas-Soriano et al., 2020
Educational & Research	Number of formal and informal education activities	S, D	1	F-P-D	M/H	Carolli et al., 2017
	Number of scientific studies	S, D	1, 4	F-P-D	M	Vidal-Abarca et al., 2014
Spiritual, Religious And Therapeutic Services	Number, extent and density of sacred/religious sites	S	1	I	M	Maes et al., 2016; Czúcz et al., 2018
	Number of flora and fauna of symbolic, mythic or totemic significance	S	1	F-P-D	M	Pandey et al., 2016; Czúcz et al., 2018
	Visitor statistics to places where springs and streams heal them or religious sites	D	1	F-P-D	H	Maes et al., 2016
	Number and origin of participants in pilgrimages, festivals or rituals associated with sacred and therapeutic places	D	1	F-P-D	H	Pandey et al., 2016; Hernández-Morcillo et al., 2013
	Number, length and extent of IRES in watersheds granted legal personhood	S	1, 4	I	H	O’Donnell, et al., 2018; Cano, 2018; Arthington et al., 2018
	Number, length and extent of IRES for which environmental flows (eflows) or “cultural flows” targets have been developed and adopted	S	1, 4	I	H	Anderson et al., 2019; Arthington et al., 2018; Magdaleno, 2018
	Number of ‘nature on prescription’ schemes that include IRES	D	1	F-P-D	H	Bell et al, 2018; La Puma, 2019; Cook et al., 2019; Naor et al., 2019
	Positive health outcomes	D	1	F-P-D	H	
	Number of ecotherapy prescriptions	D	1	I	H	
	Nature connectedness to, and derived from IRES	S, D	1	F-P-D	H	Richardson, 2019; Brymer et al., 2019; Pritchard et al, 2019; McMahan et al., 2015
	Improved wellbeing, happiness and Quality of life indicators and scales	S, D	1, 5	F-P-D	H	Clark et al., 2014; Bratman et al., 2019
General	Perceived social importance	S, D	1	I	M/H	Quintas-Soriano et al. 2016, 2018, 2019
	Perceived location (in a map) of supply and demand of ecosystem services	S, D	1, 3	F-P-D	M/H	García-Nieto et al. 2016, 2019

Region of Crete, the WWF, the Union of Agricultural Associations of Crete and the Beekeeping Cooperative).

Both rivers have similar hydrological phases, although the Giofyros river has longer autumn and spring flowing seasons than the Rio Seco (Table 4). The assessment of the delivery of provisioning, regulating and cultural ES discussed in Section 3 for both case studies was based on the relative likelihood or potential of occurrence. Ecosystem services were semi-quantitatively evaluated along contrasting hydrological transitions (flowing, fragmentation, drying) for their potential intensity: “strong’, “moderate”, “low”, “weak/not relevant”. This evaluation was then used to develop an ES quantification matrix (Table 5).

The ten provisioning services described in Table 5 show similar rankings for both rivers, especially for services related to ecology and water availability. For instance, groundwater withdrawal is high during the dry season in both cases due to intensive agricultural and tourism activities. Wild plant production and harvesting are high during the dry season in the Giofyros river, while in Rio Seco, the traditional use of these plants has progressively disappeared (following the rural exodus to main cities and abroad). The “wild plant production” indicator was strongly related to the hydrological phase especially for the Giofyros river. Indeed, during the flowing and pool phases, the riparian area provides edible wild plants, whereas the collection of wild aromatic plants, such as wild oregano (*Origanum vulgare*), camomile (*Matricaria chamomilla*), caper (*Capparis spinosa*), and wild endemic teas (*Sideritis syriaca, Origanum majorana*) takes place during the dry periods (Hanlidou et al., 2004). Intermittent rivers are often associated with complex and dynamic riparian communities, characterised by woody plants and perennial herbs that have adaptive mechanisms for strong flow variations (e.g., *Tamarix* spp.). These communities also have a high temporal turnover of annual herbs in comparison with the hydrological phases of most Mediterranean rivers (Bruno et al., 2014).

The amount of fish harvested is particularly high during the flowing phase in the Giofyros river, while it is constant all year long for Rio Seco, due to the presence of aquaculture production at the outlet of the river in the Ria Formosa lagoon; however, no fish catches were reported during the pool and dry phases of both rivers. Fishes, such as eels (*Anguilla* spp.), mullets (*Mugilidae* spp.) and freshwater crab (*Potamon potamios*), observed in the headwaters of the river Giofyros were not intensively harvested for human consumption. Hydrological phases and especially floods are key factors driving eel migration (Teichert et al., 2020). Although fish are not industrially harvested, recreational fishermen can be observed in urban areas and at the outlet of the Giofyros river. The complex mosaic of connected and disconnected pools all along both IRES promotes high levels of aquatic and terrestrial biodiversity. A number of endemic fish species can tolerate the extreme environmental conditions that are often associated with wide hydrological variations

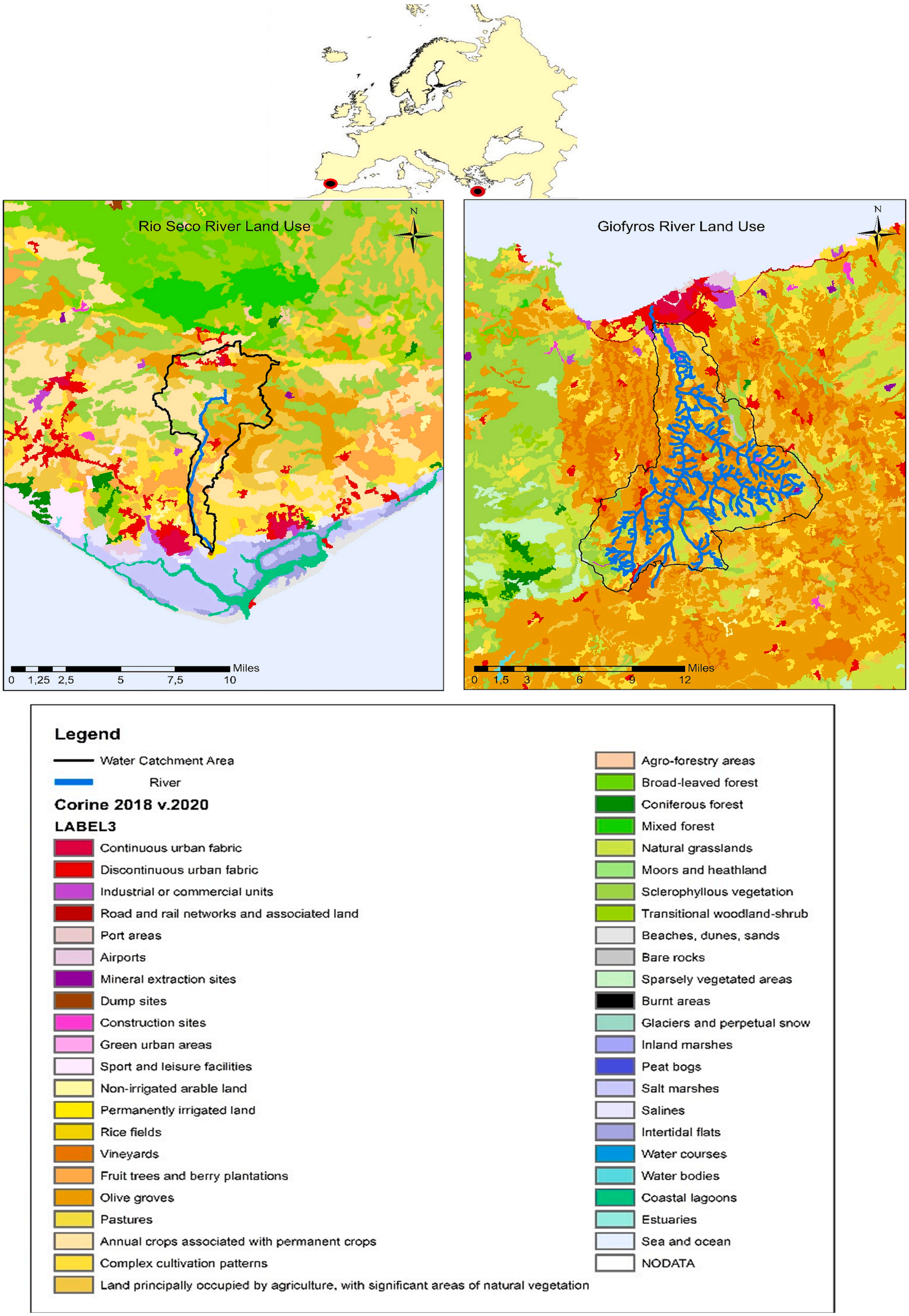


Fig. 2. Location and land use of the catchment areas of the two case studies (Corine Land Cover 2010).

(Chakona et al., 2019) and intensive harvesting (Menteli et al., 2019).

Concerning the seven evaluated regulating ES, the presence of native and invasive species was observed in both cases,. In Rio Seco, native plants, such as *Bromelia* spp., *Mentha aquatica* or *Typha angustifolia,* were identified, but so were a few exotic species (*Eichhornia crassipes, Arundo donax, Datura stramonium, Agave americana* and *Acacia saligna*) due to flow regime and river alterations during the past decades. In the case of the Giofyros River, the main riparian vegetation consists of wetland

Table 4
Hydrological phases in both rivers

	Flowing water		Pools		Dry phases	
	Rio Seco	Giofyros	Rio Seco	Giofyros	Rio Seco	Giofyros
Winter	X	X	X			
Spring				X	X	X
Summer					X	X
Autumn		X	X	X	X	

species, such as reeds (*Phragmites australis*), myrtles (Myrtaceae), oleander (*Nerium oleander*), plane trees (*Platanus* spp.) and white willows (*Salix alba*), located in the upper river reaches. The riverine vegetation (mostly herbaceous species) was more abundant during the flowing and pool phases in both studied cases. However, the analysis of different satellite images (Appendix A7) during this survey, revealed that riparian vegetation had been partly replaced by greenhouse constructions in various locations of the Rio Seco. According to local experts, this resulted in less infiltration and greater water abstraction for horticultural production. In addition, a few active wells situated upstream of the reach may also have contributed to the observed flow reduction of Rio Seco (Appendix A5-7). Water quality improved after the renovation of wastewater treatment plans (WWTP) in 2007 (SNIHR database: https://snirh.apambiente.pt/). However, groundwater quality was evaluated as 'bad' by the local authorities, probably due to diffuse pollution. Therefore, and besides the EU Nitrate Directive 91/676/EEC, measures such as restrictions on fertilization in the vicinity of streams have been implemented to reduce nitrate contamination from diffuse agricultural sources. Local experts also reported that the Rio Seco was suffering from a lower water retention capacity than a few decades ago. In fact, the Rio Seco has been continuously anthropized, from the construction of water wells upstream of the watershed, to the increasing construction of urban areas and greenhouses on the river margins. As a consequence, the flow velocity has increased subsequent to channelization operations in 2015, thus reducing soil–water infiltration and purification and increasing flood events (e.g., the most recent flood occurred in 2015). Experts also mentioned that recent public incentives are being implemented to create new natural margins downstream of the river in order to enhance water infiltration. In the case of Giofyros, the urbanization of the northern part of the basin is progressively increasing, resulting in weak regulating services and periodical hazardous floods. A major flood in 1994 inundated the valley along its entire length and the overall damage cost was estimated to exceed 10 billion euros (Koutroulis and Tsanis, 2010).

In Giofyros river, the functional riparian area varies between 1 and 5 m, depending on the adjacent human activities. In river reaches where water has low momentum or forms ponds, the aquatic macrophyte community is dominated by *Potamogeton pectinatus*. Flow reduction as drying intensifies affects the functional diversity of riparian vegetation, decreases mesic plants (mainly shrubs and tall herbs) and increases the occurrence and coverage of xeric shrubs and reeds (Diehl et al., 2020). However, the temporary absence of flow enables the removal of opportunistic vegetation during dry conditions, especially reeds. Reeds have expanded over the past decades thoughout the riparian area due to high nutrient fluxes from agricultural soil runoff and untreated wastewater, as well as the fragmentation of native riparian forests.

However, further monitoring during this period would be required to correctly assess the presence and composition of macroinvertebrate communities in the pool phases. Indeed, in particular for the Giofyros River, the synergistic effects of water stress, land degradation and pollution (mainly agricultural soil erosion and wastewater) on the macroinvertebrate community resulted in a moderate river ecological status (Kalogianni et al., 2017). In both cases, the spring season coincides with the beginning of the drying phase. Consequently, the potential issues these two intermittent streams can face during spring and summer are the presence of mosquitoes, the development of local eutrophication blooms and odours due to stagnant water and to a larger extent, CO_2 emissions from the drying pools. The latter represent

Table 5
Evaluation of the ES indicators for the two study cases. A rating for each indicator was applied according to a consensus of local experts: Null (white), Low (yellow), Medium (green), High (blue). S means 'supply' and D means 'demand'.

			Giofyros river			Rio Seco		
	Hydrological phases	Supply/ Demand	Flow	Pool	Dry	Flow	Pool	Dry
Provisionning	Production of wild plants in riparian and floodplain (kg/ha/year)	S	🟨	🟨	🟦	🟨	🟨	⬜
	Distribution and richness of edible riparian plants (species/ha)	S	🟩	🟦	🟩	🟨	🟨	⬜
	Diversity and quantity of plant elements extracted in the fluvial area (number of plant elements/ha)	D	🟨	🟦	🟦	⬜	⬜	⬜
	Quantity of fish harvested for consumption (kg/ha/year)	D	🟨	🟦	🟨	🟨	🟦	🟨
	Abundance of fish species (number of individuals/ha)	S	🟩	🟨	⬜	🟦	⬜	⬜
	Water exploitation index	S, D	🟨	🟩	🟦	🟨	🟩	🟦
	Groundwater abstraction for non-drinking purposes (m^3).	D	🟨	🟩	🟦	🟨	🟩	🟦
	Visitation rate of aquatic insects	S	🟦	🟩	⬜	🟦	🟩	⬜
	Average yearly number of kills from wild game (individuals/ha)	D	🟦	⬜	⬜	🟦	🟩	🟨
Regulating	Percentage of endemic species relative to the total number of species	S	🟦	🟦	🟨	🟦	🟦	🟨
	Width of functional vegetation and linear extension of functional vegetation and presence of emergent aquatic macrophytes (nb of species)	S	🟦	🟩	🟨	🟦	🟩	🟨
	Vegetation management	D	🟦	🟦	🟩	🟦	🟦	🟩
	Change of air temperature (river bank/corridor vs rest of the catchment) (°C)	S	🟦	🟨	⬜	🟦	🟨	⬜
	Presence of a modern floodplain	S, D	⬜	⬜	⬜	🟦	🟩	🟩
	Artificial changes of the river course	D	🟦					
	Number of floods	S	🟦	🟩	🟩	🟦	🟩	🟩
	Abundance of mosquitos	S	⬜	🟦	⬜	⬜	🟦	⬜
Cultural	Number & type of activities (e.g., walking, hiking, picnics, birdwatching, passive, active)	D	🟨	🟩	🟩	🟨	🟩	🟩
	Number of formal and informal education activities	D	🟩	🟨	⬜	🟩	🟨	🟩

*Combination of two indicators from Table 2 relative to endemic and exotic species.

potential ecosystem disservices, especially during the drying and pool phases.

Finally, concerning the cultural ES in both case studies, the number of recreational activities and visitors increased during the pool and dry periods (e.g. hiking). The Giofyros River supports numerous and various types of recreational activities, especially during spring and summer (e.g. walking, hiking, picnicking, birdwatching). In Rio Seco, a continuous flux of tourists visits the Ria Formosa lagoon (by boat or on hikes in the nature reserve) with a larger number of hikers during the dry season. On one hand, the majority of educational and scientific activities in the Giofyros River takes place around the flowing season in order to assess the magnitude of the water flow, flood events, aquatic biomass and biodiversity, among other topics. On another hand, educational activities in Rio Seco such as river clean-up events, are more intense during the dry phase. In particular the *Ciència Viva* action organized by the University of Algarve (Fig. 3), takes place as an educational activity on environmental protection.

5. Discussion

The present work proposes a new framework to characterize and assess the ES of IRES. Recent studies have emerged in the field of ES characterization of IRES (Jorda-Capdevila et al., 2020; Kaletová et al., 2019; Stubbington et al., 2020), but to the best of the authors' knowledge, this is the first attempt in developing, guiding and applying a set of ES indicators that represent the whole range of ES (provisioning, regulating and cultural services) across the three hydrological phases. After screening exhaustive lists of indicators and literature, 109 potential indicators were selected. They comprise 40 provisioning, 64 regulating, and 25 cultural services. These findings are consistent with other studies, not only for IRES (Ruiz et al., 2021), but also for other terrestrial ecosystems (Feld et al., 2009). Finally, a representative easy-to-apply subset (19 ES indicators) was applied to the two case studies in Greece and Portugal with limited time and resources.

5.1. *Process of indicator selection*

In the present work, 40 provisioning ES were selected and analysed according to the hydrological phases, and nine of them were tested in the two case studies. The results indicated that for most of the selected indicators, the data required to characterize the ES can be accessed from *in situ* observations and official databases, which are generally public and open sources. However, for some indicators, a certain degree of uncertainty had to be associated with their evaluation. For instance, the lack of streamflow gauging stations and illegal water abstraction from surface and groundwater may affect water provisioning for agriculture and human consumption. The case studies highlighted the key role that hydrological phases play in the applicability of the indicators. Indeed, several indicators, such as some provisioning ES (e.g. fish harvesting), can only be used during the flowing phase whereas other indicators, such as wild food provisioning (berries, mushrooms, etc), can be applied to different hydrological phases.

Based on present knowledge, the provision of regulating ES, such as pollinisation, seed dispersal and disease and pest control, cannot be easily evaluated across the different hydrological phases. Out of the collected ES indicators, 64 were selected for the regulating category. However, the collection of most these indicators is time-consuming, especially when obtained from long-term *in situ* observations and measurements, and occasionally from literature and database research. Compared to provisioning and cultural services that are more easily quantified and/or qualified, regulating services require rigorous data collection and/or modelling. Some regulating ES are still under investigation, such as nitrogen and carbon decomposition, as well as characterisation of terrestrial and/or aquatic biota during drying and rewetting phases (Romaní et al., 2017). Moreover, flow regimes in IRES confer a unique 'biogeochemical heartbeat' with high temporal and spatial variations in nutrient and organic matter dynamics (i.e. biogeochemical processes) (von Schiller et al., 2017). During the dry phase, IRES remain active and can present significant levels of CO_2 emissions that are highly dependent upon soil humidity and available organic matter (Keller et al., 2020). Another key moment in IRES biogeochemistry is the flow resumption, which can mobilize large amounts of nutrients (Shumilova et al., 2019), result in high metabolic rates (Von Schiller et al., 2019) and generate peaks in CO_2 emissions (Datry et al., 2018a). Within this recurrent cycle of drying and rewetting, a dynamic exchange takes place between the groundwater and the

Fig. 3. Photo of the Action of cleaning the Rio Seco on September 26th 2018 (during Scientific Training Short Mission from Cost Action SMIRES by Pastor AV).

surface water zone, influencing the storage, filtration, biogeochemical cycling and biological production mediated by the hyporheic zone (Boulton, 2007).

Concerning cultural ES, Skoulikidis et al., (2017) highlighted that "IRES are particularly vulnerable because they lack adequate legislative and policy protection, as well as appropriate management practices". Consequently, the introduction of environmental legislation at national and local levels to improve IRES conservation is expected to enhance local knowledge and thus increase the demand for educational services. Acuña et al., (2013) concluded that educational services might also shape the attitude of local stakeholders who are directly involved in IRES management. Some studies have addressed the potential demand for education services provided by IRES from quantitative and qualitative perspectives. For example, Leigh et al., (2019) "investigated the strength and extent of negative and positive attitudes by surveying undergraduate students from Australia, UK, and USA about ES, moral consideration, and protection of perennial and temporary streams". The eco-touristic development of IRES basins (highland tourism, canyoning and rafting during the flowing phase, botanic and wildlife tourism, trekking and climbing) has also been found to generate a complementary income for local economies and societies (Kaya and Akis, 2012).

The lack of IRES-specific indicators for spiritual, religious, and therapeutic services reflects the paucity of wider cultural ES indicators (Koundouri et al., 2017). Several authors (Abhimanyu et al., 2016; Clark et al., 2014; Maes et al., 2016a,b), have developed indicators for spiritual or religious ES, which could apply to IRES. Pioneers of new indicators for spiritual, religious, and therapeutic services for IRES might explore the move towards nature-based health care delivery, or 'nature on prescription' (Cook et al., 2019; La Puma, 2019; Naor and Mayseless, 2020). For example, this can be assessed as the number of programs, number of prescriptions and positive outcomes. In addition, the 'blue health' benefits of 'blue spaces' that are increasingly being investigated (Summers and Vivian, 2018; Vert et al., 2019) can also be considered. Furthermore, the "one health" approach acknowlegdes that human health is strongly linked to ecosystem health, implying that health ultimately depends upon ES such as the availability of freshwater, food, fuel or pollination, thus suggesting a whole new educational scheme (Lerner and Berg, 2015). There may also be lessons to be learned with respect to cultural ES indicators. Indeed, there are cases where environmental flow (eflows) targets for rivers have been partly driven by spiritual and religious objectives rather than by ecologically-based minimum flow targets (O'Keeffe et al., 2012; Opperman et al., 2018). These are noteworthy opportunities for developing indicators of therapeutic and spiritual and religious cultural ES benefits. An interdisciplinary approach is essential, including participatory approaches (Hernández-Morcillo et al., 2013; Ruiz et al., 2021) involving spiritual and indigenous groups (Darvill and Lindo, 2015; Fagerholm et al., 2012), health care providers (Jennings et al., 2019) and agencies that facilitate and encourage hands-on interactions about river conservation (Rogerson et al., 2017).

5.2. Case study outcomes and usefulness of indicators for management

In this study, while a full set of ES indicators for IRES were collected and selected, a subset of ES indicators (19 indicators) were tested on two case studies. By using only 14% of the indicators, recommendations and conclusions could be drawn to improve the management of these IRES. For example, the provisioning services were found to have a higher rate of services classified as 'demand' than as 'supply'. Moreover, the majority of service deliveries were qualified as 'low', especially during the drying and pool phases. Regulating ES had a majority of services classified as 'supply' and represented the category with the highest provision of services in all phases (classified as 'high'). Two cultural services were evaluated and rated as 'demand' and were observed during all the hydrological phases of the IRES (e.g., hiking during the dry phase and/or fishing during the flowing phase).

A key challenge in ES management is to determine how to manage and optimize the supply of multiple ES across diverse and dynamic landscapes (Raudsepp-Hearne et al., 2010). The enhancement of provisioning ES, such as food, often led to trade-offs with regulating and cultural ES, such as water purification and maintaining aesthetic landscapes for tourism. Management indicators are crucial, not only to measure, monitor and understand landscape and ecosystem transformations, but also to identify and evaluate ecosystem performance and services, to enable the implementation or revision of specific designs of measures that may directly impact landscape evolution and enable a balanced provision of ES (Nunes et al., 2014; Yeganeh and Kiyani, 2019).

There is a widespread issue in characterizing IRES, due to their distinct hydrological phases and to the poor data availability and monitoring of IRES. *i.e.*, most IRES are not ackowledged as official waterbodies by the WFD (Stubbington et al., 2018), and this has hindered their biomonitoring, assessment and the collection of data with sufficient temporal and spatial coverage. Therefore, the collection of data on IRES in order to properly assess their ES across the different hydrological phases is time-consuming and hinders a systematic evaluation. An obvious common obstacle for most ES indicators is the estimation of a quantitative value for each hydrological phase. Furthermore, one of the most important difficulties is the application of most of the indicators during the dry phases. It would be interesting to study the temporal variation of each indicator of this framework in order to quantitatively determine how these indicators vary during the different hydrological phases (Datry et al., 2018). In addition, it would be essential to consider the changes occurring in the different sections of the river and to assess how spatial drying patterns cascade down to the ES dynamics.

Until recently, IRES ecosystems have been particularly threatened and affected by human activities. Strong resource extraction and pollution have contributed to the degradation of many ES (i.e. regulation, water purification, etc). However, over the past decade, awareness and consideration of IRES and related ES has increased (Acuña et al., 2014; Allen et al., 2020; Messager et al., 2021). For example, in their research on the complexity of the social value of IRES, Jorda-Capdevila et al. (2021) highlighted that more comprehensive studies were needed to incorporate the variety of hydrological phases and the interaction between them to estimate the provision of services. Indeed, the recognition of the typologies, delineations, discontinuities, boundaries and mappings of IRES and related ecosystem services is fundamental for any protection and restoration strategy, both ecologically and economically. In the future, with additional time and resources, the implementation of the 109 indicators on these two IRES (or even other IRES) could be further expanded to have a more comprehensive assessment of ES.

5.3. Usefulness of indicators for management and economic valuation of ecosystem services

The 'low' interest towards IRES by stakeholders and citizens in general, coupled with insufficient research has hindered IRES management, protection and restoration (Acuña et al., 2014; Armstrong et al., 2012; Armstrong and Stedman, 2020; Steward et al., 2012). Yet, IRES represent a considerable portion of global rivers (Messager et al., 2021) and are widely recognized as particularly threatened by climate change (Döll and Schmied, 2012; Sauquet et al., 2021; Schneider et al., 2013). Although the number of gauging stations installed in IRES is lower than in perennial rivers (Snelder et al., 2013), most flow trends indicate an increase in the duration of the drying phase, particularly in southern Europe (Datry et al., 2017b; De Girolamo et al., 2017; Tramblay et al., 2020). A review of recent hazardous flood events in IRES reveals the emerging need for flood adaptation strategies to protect human life and assets (Diakakis et al., 2020; Speis et al., 2019). However, the poor documentation concerning IRES ecosystem services hinders the development of a solid management plan for their restoration and protection

(Datry et al., 2017a). One way to increase public consideration and interest in IRES would be to conduct a comprehensive economic valuation with the help of this new framework. For example, provisioning services are the easiest type of ES to be monetarily assessed since the goods are often marketed. Consequently, these ES are relatively well understood and recognised and have usually been maximized at the expense of river health and other types of services (e.g., regulating ES). Provisioning ES supply can be quantified in terms of mass, volume, abundance or density of goods (Stubbington et al., 2020). The temporal variation of ES needs to be considered in relation to seasonality and different hydrological phases. For instance, surface water or fish are mainly extracted during flowing periods. Accessibility also depends on temporal variability; indeed, when rivers are dry, some of the materials are easier to extract from the riverbed (aggregates, organic matter, fallen trees) and crossing fords (low water crossing points) is made simpler. Moreover, given that IRES are common in sparsely populated arid and semiarid areas, where the number of beneficiaries and hence the actual use of their ES is limited, non-use values are expected to be of great importance for these ecosystems (Koundouri et al., 2017). Thus, the combination of this new framework with the concept of the total economic value (TEV) developed by Koundouri et al. (2017), could represent an added value for the management, maintenance and restoration of IRES.

5.4. Further research on ecosystem services from intermittent rivers and ephemeral streams

This research moves a step forward towards the assessment and characterization of ES for IRES. However, improvements are still required to increase accessibility to data, to strengthen the monitoring programs (especially concerning the role of IRES in regulating ES) and to apply the new ES framework to more case studies. Through the assessment of 109 indicators, it should be easier to identify knowledge gaps and/or highlight important ES provisions and/or trade-offs. Furthermore, the characterization and definition of certain ES should be clarified concerning ‘service’ and ‘disservice’ , while cultural ES in particular still remain poorly defined and tested. For example, the presence of mosquitoes, which is here classified as an ES indicator, could also be interpreted as a EDS, as it could provide information on potential disease transmission via mosquitoes (Benali et al., 2014).

Even though Maes et al. (2016a,b) and IPBES (Brondizio et al., 2019) explicitly included negative impacts on humans in their definitions of ES, the vast majority of ES research focuses on the positive services, the benefits and “goods” (Scholes et al., 2018). Shackleton et al., (2016) argue that there is a need to consider ecosystem disservices and services equally in order to fully understand the overall effects of ecosystems on wellbeing, i.e., a net effect. However, very few studies have yet assessed the net value of ecosystem effects or even consider both ES and EDS elements in a single study (Hirons et al., 2016; Kadykalo et al., 2019; Larson et al., 2019; Von Döhren and Haase, 2015). Ecosystem disservices of rivers have not been defined or characterized by human perceptions (Schneider et al., 2013). Von Döhren & Haase, (2015) analysed 103 studies on ecosystem disservices and found that, although the notion of detrimental ecosystem effects is not new, systematic research on EDS is only just beginning. The authors have differentiated EDS into three categories: health, economy, and environment. In addition, several disservices could be determined using specific flow regime components of IRES. For example, flash floods can be perceived negatively due to (i) damage to farms, and infrastructures (i.e. roads, bridges), (ii) bank erosion, (iii) and transport of sediment and coarse material. Similarly, chemical and biological pollutants are considered as a health risk (i.e. in F-P phases). When only pools occur along the stream, water pollution is perceived as an EDS both for aesthetic reasons and for unpleasant odours. The dry phase may also be perceived as negative for humans who fear to come across wild animals, such as snakes.

6. Conclusions

The present study proposes a new set of indicators that represent a step forward towards the processing and characterization of IRES ecosystem service indicators. A list of 109 ES indicators was developed based on IRES particularities, (e.g., hydrological phases, anthropogenic disturbances, mismanagement). A description of the information underlying each indicator, is provided, such as the supply and/or demand of ES and the methods and time required for data collection. The indicators can be assessed through measurements, modelling, expert evaluations, statistics, public surveys and participatory methods, all of which refer to functions of IRES. Once assembled, the integrated range of information captures the seasonal features of IRES. During the evaluation of the Giofyros and Rio Seco case studies, a major contribution of these indicators involved communication and stakeholder participation. The comprehensive nature of the proposed indicators ensures that they are understandable by an eclectic audience. Within this new framework, certain indicators can be directly applicable (e.g., those related to structural and functional vegetation features), while others still require a few adaptations or are difficult to apply due to lack of basic information (e.g., characterization of macroinvertebrates in pools). Some indicators can be used to assess more than one ES, e.g., vegetation management can be used as an indicator for both climate regulation and natural hazard regulation. Since they were designed through a public participation process, the ground is prepared for holistic stakeholder analysis and education covering their functions and ES. However, it remains crucial for the scientific community to be aware of the preferences of the public when designing valuation studies that seek for socially accepted policies. It appears that the proposed indicators can successfully bridge these elements, thus building a solid foundation for the theoretical and mathematical representation of IRES characterization, including hypothetical markets or experiments used for economic valuation. With this new framework, despite the limited information due to a lack of monitoring and recognition of IRES in the EU, a varied range of ES indicators has been semi-quantitatively assessed with interviews, open-access database/ and remote sensing, which could in turn promote a cost-effective and reliable evaluation of ES provision during the different hydrological phases (flowing, pool and dry).

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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