

# Water-energy-ecosystem nexus in small run-of-river hydropower: Optimal design and policy

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## ABSTRACT

Small run-of-river hydropower may significantly contribute towards meeting global renewable energy targets. However, exploitation of river flows for energy production triggers environmental impacts and conflicts among stakeholders, thereby requiring optimal water resources allocation strategies. The variety of interests at stake demands instruments to quantitatively assess manifold effects of water management choices. In this work, analytic tools to guide design of run-of-river power plants when incommensurable objectives must be jointly maximized are presented. The approach is grounded on the concept of Paretian efficiency and applied to a hypothetical case study in Scotland, where energy production could compete with regionally relevant ecosystem services. We found that a multi-objective design complying with predefined environmental regulation entails significant economic losses without safeguarding ecological functions. Conversely, if the environmental flow is regarded as a decision variable subject to minimum lawful values, economically appealing and ecologically effective plant configurations emerge. Our findings suggest the existence of broadly valid alternative strategies for designing small run-of-river hydropower while preserving ecological functions, associated to small or large plant capacities. Local hydrologic conditions and target ecosystem services determine the most effective strategy for specific case studies. The analysis indicates that larger power plants are sometimes the most effective way to preserve ecosystems services through economically viable projects. Therefore, renewable energy policy should avoid incentive schemes that penalize a priori larger installations. The approach offers an objective basis to identify effective hydropower design, management and policies when additional ecosystems services are considered, thus supporting a sustainable intensification of run-of-river energy production.

## 1. Introduction

Global policies aimed at the reduction of carbon dioxide in the atmosphere have boosted the growth of renewable energy production [1] and revived the interest of investors and society for hydropower [2]. This technology is characterized by high conversion efficiency, and has been widely employed during the twentieth century especially in conventional plants relying on large dams and reservoirs. Several decades of studies have contributed knowledge [3] and a growing awareness about the environmental impacts of this form of energy generation [4]. While the development of large (i.e., with installed capacity > 10 MW) hydropower projects continues in the global south [5], small (i.e., installed capacity < 10 MW) run-of-river hydropower is becoming increasingly important for off-grid uses [6] and in western countries [7],

where conventional plants are close to saturation and strongly opposed by local populations because of their large-scale effects [8]. Run-of-river technology does not involve large reservoirs and regulation, as streamflows are continuously diverted, processed through turbines and returned to rivers. For this reason its environmental impact is considered smaller (see [9] and references therein). However, this belief is often unsupported by scientific evidence [10]. Rather, this thinking stems from a limited knowledge of the water-energy-ecosystem nexus (*sensu* [11]) inherent in this technology and from the paucity of studies on the effects of small run-of-river installations on rivers [12].

In particular, long distances between the intake and outflow of run-of-river power plants (a common practice in sloping regions to increase hydraulic head and power potential) [13] determine flow reduction

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along extended river stretches, causing strains on aquatic ecosystems and local communities [14]. Moreover, economic subsidies granted to small hydropower by many countries worldwide have often originated cascade installations, with environmental disturbances replicated several times along river courses [10]. This can lead to significant large scale cumulative impacts [15] and threatens the ability of river networks to deliver important ecosystem services such as the provision of preferential corridors for the dispersion of plants, invertebrates and fishes [16]. Therefore, the recent development of run-of-river hydropower has caused harsh social conflicts involving public authorities, green organizations, energy companies and local population in many regions of the world [8]. Accordingly, it has also been highlighted as one of the emerging global issues for biological conservation [17].

The complexity of reconciling interests related to renewable energy production, environmental preservation and the variety of economic and social activities relying upon river ecosystems [18] demands tools to predict and analyze the multifaceted implications of different water allocation strategies [19]. Such quantitative tools could help guide water managers and policy developers in the difficult task of trading among varied economic and ecologic goals towards an equitable and sustainable exploitation of water and energy resources [12].

In the existing literature, multi-objective optimization has been already applied to tackle water resources issues [20]. Leveraging the intrinsic capability of reservoirs to modulate downstream flows [21], the latest research aims to identify downstream release strategies that optimize a variety of objectives in addition to energy production and economic profitability [22]. Among them, societal needs [23] and the conservation of hydrological signatures regarded as ecologically meaningful are prominent [24]. However, the majority of the available studies deal with dammed river systems. Analyses that focus on run-of-river hydropower are rare [9], with a few noteworthy exceptions concerned with the sizing of the plant capacity to jointly maximize profitability and minimize hydrologic disturbance [25], the choice of optimal water allocation rules and diversion practices [26] and the assessment of the effects of different flow regimes and methods to determine the environmental flow on hydropower production and hydrologic alteration [27]. In this context, the development of impact metrics identified from a mechanistic description of ecological processes, in place of the standard use of predefined sets of hydrological and habitat indices, would constitute a major step forward [19].

This work proposes a set of instruments to model the nexus between energy, water and ecosystem interests and jointly consider and maximize contrasting objectives in the design and management of small run-of-river power plants. The approach is illustrated for a hypothetical case study in Scotland, where interests for renewable energy production and preservation of river network connectivity supporting migratory salmon often compete. The key novelties of the study are: (i) economic interests and actual ecological requirements are reconciled up front (i.e., during the design phase of small run-of-river installations), and environmental flows are considered as a decision variable of the problem. Besides purely engineering and economic targets considered in conventional optimization frameworks [28], the proposed method accounts for environmental protection goals to identify the optimal size and operation of power plants. This proactive approach that jointly involves design and policy allows for overcoming the limited possibilities of run-of-river technology to adjust downstream flow releases ex post; (ii) a relevant ecosystem service (in the considered case study, hydrological connectivity enabling salmon access to spawning headwaters) is used as an objective function in the optimization, as opposed to generic indicators of hydrological alteration and habitat availability which have hitherto been mostly used in the scientific and technical literature [29]. The metric adopted to assess this ecosystem service has been identified based on a mechanistic model of fish dynamics [30], as urged by recent reviews on the topic [19]; (iii) general strategies to guide design run-of-river plants are identified, and interactions between design and policy highlighted. Recommendations for the conception of

hydropower policies and environmental regulations that might support an equitable and sustainable exploitation of water and energy resources are also provided based on the results of the investigations. In this way, the paper responds to the call [9] to develop tools and analyses that, examining interactions between energy, economic and environmental aspects, could assess the suitability of current environmental laws and incentive schemes for renewable energy.

## 2. Methodology

Methods utilized in this study include the estimation of gross hydropower potential along river networks (Section 2.1) and multi-objectives analyses of economic and environmental performances of small hydropower plants (Section 2.2). These methods are described in the following subsections, which also detail the approaches used to quantify economic and ecological outcomes of different plant designs and hydropower policies.

### 2.1. Plant location

Locations of intake and outflow of run-of-river power plants are usually selected to maximize gross hydropower potential (GHP), which is proportional to the product of net hydraulic head (i.e., the net energy drop along the plant)  $H$  and mean streamflow at the plant intake (i.e., the amount of water processed by the plant per unit time). In catchments with spatially uniform runoff generation, the mean streamflow can be calculated as the product between contributing area ( $A$ ) and mean specific (i.e., per unit catchment area) discharge ( $\langle q_s \rangle$ ). GHP can thus be expressed as:

$$GHP = \rho g H A \langle q_s \rangle \quad (1)$$

where  $\rho$  is the water density and  $g$  is the standard gravity. The net hydraulic head (the term  $H$  in Eq. (1)) is calculated as the difference between the change in gravitational potential and the hydraulic energy losses in the plant:

$$H = \Delta z - kL \quad (2)$$

where  $\Delta z$  is the difference of elevation between intake and outflow, whereas the second term on the right-hand side of Eq. (2) expresses energy losses within penstocks, which linearly increase with their length  $L$  according to a friction coefficient ( $k = 0.005$ ) [31]. The penstock is usually built near the river due to logistic reasons (e.g., trucks access). Therefore, its length can be assumed equal to the distance between intake and outflow measured along the stream.

Additional restrictions to positioning of intake and outflow along the river, such as environmental protection areas, may exist and constrain the choice of the plant location. Once this is set and the related features of the installation (i.e., contributing area  $A$  and hydraulic head  $H$ ) determined, small run-of-river power plants are optimized according to different objectives.

### 2.2. Multi-objective optimization

Decisions among different options often affect a variety of competing objectives. In such cases, the mathematical framework of Paretian efficiency helps selecting efficient (i.e., Pareto-optimal) choices among all possible solutions [32]. Efficient solutions are those for which any improvement in an objective can only be made at the expense of other objectives. These Pareto-optimal solutions form the Pareto front, which provides a set of alternatives among which decision-makers should take the final choice [33].

A multi-objective optimization is mathematically addressed by defining a vector of objective functions,  $\mathbf{F}(\mathbf{x}) = [F_1(\mathbf{x}), \dots, F_m(\mathbf{x})]$ , where  $m > 1$  is the number of independent objectives,  $F_j$  ( $j = 1, \dots, m$ ) are objective functions components of the vector  $\mathbf{F}$ , and  $\mathbf{x}$  is a set of decision variables. Any possible combination of the decision variables

determines different values of the objective functions  $F_j$ , that represent the degree of fulfillment of every objective. Usually,  $F_j$  are formulated to be dimensionless numbers ranging between 0 (complete fulfillment of objective  $j$ ) and 1 (complete unfulfillment of objective  $j$ ). The main advantage of this formulation is that the multi-objective optimal solution can be identified by the set of decision variables,  $\mathbf{x}_{opt}$ , that minimizes the Euclidean norm of vector  $\mathbf{F}$  [34]. This is based on the assumption that all competing goals have the same level of importance, or that decision-makers cannot express specific a priori preferences in this regard.

This work proposes a framework to guide the multi-objective optimal design of a small (i.e., single turbine) run-of-river power plant which simultaneously maximizes its economic value and minimizes its impact on hydrological connectivity. The latter is suitably defined as a function of the water flow left in the reach between the intake and the outflow of the plant. Decision variables considered in the optimization problem are the maximum flow processed by the plant turbine (i.e., the plant capacity  $Q$ ) and the minimum environmental flow to be maintained downstream of the intake (hereafter Minimum Flow Discharge, MFD). In the following sections, the objective functions required to identify Pareto-optimal solutions are specified in terms of the decision variables.

### 2.2.1. Economic profitability

Revenues from hydropower plants are related to their energy production, which in turn depends on the amount of flows processed by turbines, hereafter named workable flows and indicated as  $q_w$ . As shown by [35], workable flows  $q_w$  can be expressed as a function of variable streamflows  $q$  available at the plant intake, minimum flow discharge released downstream (MFD), and a set of technical features of the installation, namely the plant capacity  $Q$  and the cutoff flow (i.e., the minimum workable flow)  $Q_C$ . Since  $Q_C$  is a fraction of  $Q$  ( $Q_C = \alpha_C Q$ , with  $\alpha_C \in [0.1, 0.2]$  [36]), flows that can be exploited for hydropower production only depend on the naturally varying streamflow  $q$  at the intake and on the variables  $Q$  and MFD. More specifically,  $q_w$  can be calculated taking into account two different types of constraints: (i) the maximum and minimum flows that the plant can process; (ii) the minimum environmental flow that must be guaranteed downstream regardless of the amount of water withdrawn for energy production. These constraints originate three possible configurations of plant functioning: (i) inflows are not sufficient to allow for the diversion of any streamflow from the river; (ii) inflows are sufficient to activate the plant, but this does not work at the maximum capacity; (iii) flows are sufficient to saturate the capacity of the plant, which produces energy at its maximum possible rate. Mathematically, this is expressed by the following relationships [25]:

$$q_w = \begin{cases} 0 & \text{if } q < \alpha_C Q + MFD \\ q - MFD & \text{if } \alpha_C Q + MFD \leq q < Q + MFD \\ Q & \text{if } q \geq Q + MFD \end{cases} \quad (3)$$

Likewise, flows released downstream of the plant intake,  $q_{ds}$ , are calculated as the amount of water at the intake that is not processed by the plant as [37]:

$$q_{ds} = q - q_w = \begin{cases} q & \text{if } q < \alpha_C Q + MFD \\ MFD & \text{if } \alpha_C Q + MFD \leq q < Q + MFD \\ q - Q & \text{if } q \geq Q + MFD \end{cases} \quad (4)$$

where all parameters and variables have the same meaning referred above.

It is worth noting that Eqs. (3) and (4) describe three diverse conditions occurring during the lifetime of a run-of-river plant. When the incoming flow is insufficient to simultaneously maintain the minimum flow downstream of the plant intake and activate the turbine, the plant is switched off and no water is diverted from the river (i.e., the incoming streamflow is released downstream, as indicated in the first

lines of the right-hand sides of Eqs. (3) and (4)). On the contrary, when the incoming flow exceeds the value of  $Q + MFD$ , the diverted discharge is equal to the plant capacity  $Q$ . In these circumstances, the potential of the installation is completely exploited and discharge in excess of  $Q$  is released downstream in addition to the MFD (as indicated by the last lines of the right-hand sides of Eqs. (3) and (4)). For intermediate values of the incoming flows ( $\alpha_C Q + MFD \leq q < Q + MFD$ ), the discharge released downstream of the plant intake is equal to MFD and the processed flow is  $q - MFD$  (as represented in the second lines of the right-hand sides of Eqs. (3) and (4)).

The energy  $E$  produced by a hydropower plant during a time period  $\Delta T$  can be expressed as the integral in time of the power generated during any single day within  $\Delta T$  as [35]:

$$E(Q, MFD) = \rho g \eta_p \int_0^{\Delta T} H \eta \left( \frac{q_w(t)}{Q} \right) q_w(t) dt \quad (5)$$

where  $\rho$  is the water density,  $g$  is the standard gravity,  $\eta_p$  is the efficiency of the plant,  $\eta$  is the turbine's efficiency (here described as a piecewise linear function of the ratio between workable flow  $q_w$  and plant capacity  $Q$  [35]), and  $H$  is the net hydraulic head, which is here assumed to be constant (see [35] for a detailed discussion on the effects of this simplification). The notation emphasizes the dependence of  $E$  on the plant capacity  $Q$  and the minimum flow discharge MFD.

The economic profitability of run-of-river power plants is here evaluated by means of the Net Present Value (NPV) [38], which represents the sum of cash inflows and outflows discounted back to their present values. Revenues from energy selling ( $R_N$ , where  $N$  is the lifetime of the plant) are calculated as the product between produced energy ( $E$ ) and a fixed price (called feed-in tariff,  $e_p$ ) guaranteed to promote renewable energies in many countries worldwide [8]. Construction costs, which are typically the most relevant cost item in run-of-river technology, are here expressed as a power-law function of the plant capacity,  $C(Q) = aQ^b$ , with  $a$  and  $b$  empirical parameters [39]. Costs for ordinary maintenance of the plant, which are usually small, have been neglected in this work. The net present value of a run-of-river power plant can thus be expressed as a function of  $Q$  and MFD as the difference between the revenues from energy selling during the entire lifetime of the plant (which are computed discounting the value of future revenues) and the initial construction costs:

$$NPV(Q, MFD) = R_N(Q, MFD) - C(Q) = \sum_{i=1}^N \frac{1}{(1+r)^i} e_p E_i(Q, MFD) - aQ^b \quad (6)$$

where  $E_i(Q, MFD)$  represents energy production during the  $i$ th year and is a function of  $Q$  and MFD through Eqs. (3) and (5),  $r$  is a constant discount rate and  $N$  is the number of years for which the feed-in tariff is guaranteed. All the parameters in Eq. (6) besides the plant capacity ( $Q$ ) and the Minimum Flow Discharge (MFD) are independent of the optimization.  $Q$  and MFD instead constitute the decision variables of the considered multi-objective problem.

### 2.2.2. Hydrological connectivity

Run-of-river hydropower plants might induce loss of hydrological connectivity and the fragmentation of river networks, as flow reductions occur in the river reaches between their intake and outflow. In mountain regions, the typical length of impacted reaches is about 2 km [37] for each power plant operating along a given river. Therefore, cascading hydropower plants potentially have pronounced large scale cumulative impacts on river connectivity [25].

The hydrological connectivity between intake and outflow of a run-of-river plant is here quantitatively evaluated according to the framework proposed by [30] and can be linked to ecological impacts. Specifically, an average passage probability for fish migrating along a river is introduced and calculated based on a fish passage function  $f(q)$ , which varies between 0 (i.e., no passage) and 1 (i.e., unlimited

passage).  $f$  depends on  $q$  as the discharge available in the stream controls the actual suitability of a given reach to act as an ecological corridor for fish movement:

$$f(q) = \begin{cases} 0 & \text{if } q \leq Q^* \\ 1 - \exp\left(-\frac{q-Q^*}{\sigma}\right) & \text{if } q > Q^*. \end{cases} \quad (7)$$

In Eq. (7),  $Q^*$  represents the minimum flow threshold allowing migration and  $\sigma$  indicates how steeply  $f(q)$  shifts from optimal to no passage conditions (i.e., the vulnerability of fish to partial flow reductions). A combination of  $Q^*$  and  $\sigma$  can be defined for any species during a specific life stage. In simple terms, Eq. (7) states that if  $q$  decreases below  $Q^*$  the connectivity is lost and fish migration is not possible ( $f = 0$ ), while for  $q > Q^*$  the passage probability exponentially increases with  $q$  towards 1, indicating that hydrologic conditions are more favorable to fish migration as the discharge increases.

In this study, a long-term hydrological connectivity,  $HC$ , is calculated as the integral over the entire range of flows of the product between the fish passage function (Eq. (7)) and the probability distribution of streamflows downstream of the plant intake,  $p_{ds}(q_{ds})$ :

$$HC(Q, MFD) = \int_0^{\infty} f(q_{ds}) p_{ds,Q,MFD}(q_{ds}) dq_{ds} \quad (8)$$

$HC$  represents the average ability of a given reach to permit or prevent fish migration when the temporal variability of streamflows is properly accounted for. The hydrological connectivity downstream of the plant intake is thus function of the residual amount of water in the river,  $q_{ds}$  (see Eq. (4)), which in turn depends on the varying incoming flows and the decision variables identified for this problem: the plant capacity ( $Q$ ) and the Minimum Flow Discharge (MFD).  $HC$  varies in the range  $[0, 1]$ , and it should be calculated with specific reference to ecologically relevant time periods.  $HC = 0$  means a complete lack of connectivity (when flows released downstream of the plant intake are always lower than  $Q^*$ ), whereas  $HC = 1$  implies that all flows are much larger than the minimum flow threshold and the connectivity is optimal throughout the study period. When the altered flow regime observed downstream of the plant intake is considered in place of the natural flow distribution, the hydrological connectivity is always lower than the natural connectivity because  $q_{ds} \leq q$ .

### 2.2.3. Objective functions

The maximization of the economic profitability of the plant and of the hydrological connectivity downstream of the intake (i.e., the minimization of the loss of connectivity induced by the plant) are the competing goals of the considered multi-objective problem. Objective functions corresponding to these goals must be defined to identify a plant design which guarantees an optimal allocation of water resources between economic (maximization of  $NPV(Q, MFD)$ ) and environmental needs (maximization of  $HC(Q, MFD)$ ).

In analogy with [25], the economic objective function is defined as:

$$F_1(Q, MFD) = \frac{NPV_{max} - NPV(Q, MFD)}{NPV_{max} - NPV_{min}} \quad (9)$$

where  $NPV_{max}$  and  $NPV_{min}$  are the maximum and minimum economic values of the run-of-river plant. Notice that a purely economic optimization of plant characteristics ( $Q_{NPV}, MFD_{NPV}$ ) determines  $F_1 = 0$  (i.e., the economic goal is completely fulfilled).

The objective function for the hydrological connectivity in the altered river reach is instead defined as:

$$F_2(Q, MFD) = \frac{HC_{max} - HC(Q, MFD)}{HC_{max} - HC_{min}} \quad (10)$$

where  $HC_{max}$  and  $HC_{min}$  are the maximum and minimum possible values of connectivity resulting from the choice of  $Q$  and MFD.  $HC_{max}$  is experienced when the natural streamflow distribution,  $p(q)$ , is used in Eq. (8) instead of  $p_{ds}(q_{ds})$  (which implies that the plant is always

switched off). When the natural connectivity is maintained downstream of the plant (i.e.,  $HC(Q, MFD) = HC_{max}$ )  $F_2 \simeq 0$ .

Mathematically, the main objective of plant design and management is to concurrently minimize the values of  $F_1$  and  $F_2$  (i.e., maximizing the economic benefit and preserving an optimal connectivity along the river).

A range of values for the plant capacity and the Minimum Flow Discharge must be defined a priori for computational reasons [25]. Therefore,  $Q$  has been varied between zero and a discharge with a cumulative exceedance probability of 0.01, whereas MFD ranges from the value prescribed by law ( $MFD_{law}$ ) to the value for which the fish passage function (Eq. (7)) reaches 0.99 (i.e., a value which poses no restriction to the passage of fish). Notice that further increments of the upper limit of MFD would not improve hydrological connectivity, as flows maintained downstream of the plant intake are already sufficient to fully sustain fish migration.

### 2.2.4. Workflow of the study

Fig. 1 provides an overview of the key steps of this study.

Topographical and streamflow data (see Sections 3.2.1 and 3.2.2) are used to estimate the gross hydropower potential along the river network of the considered case study by means of Eq. (1). This analysis enables selecting the most favorable location for the construction of a small hydropower plant.

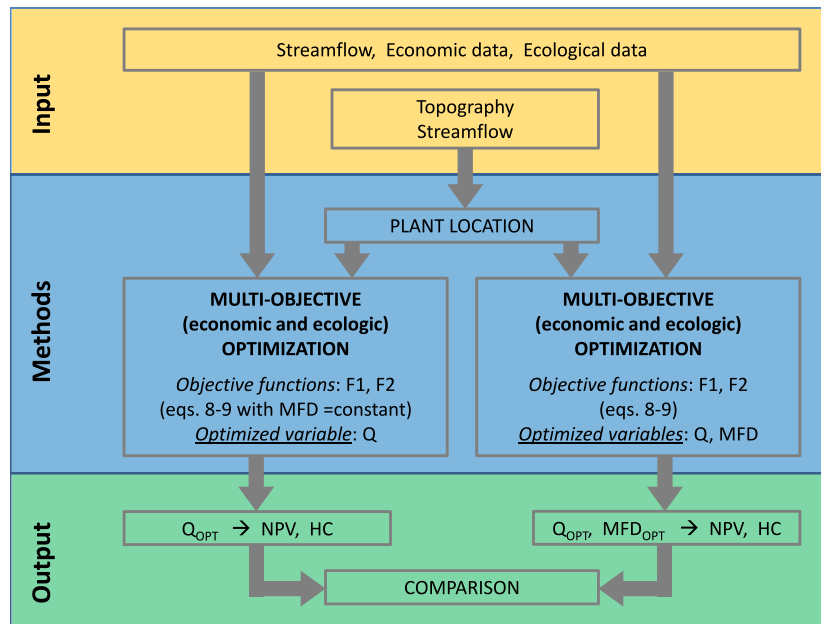
Streamflow, economic and ecological data are then provided as inputs to the methods described in Sections 2.2.1 and 2.2.2, thus allowing for a characterization of the economic profitability of the plant (Eq. (6)) and the hydrological connectivity resulting from its operation (Eq. (8)). These are key components of a multi-objective optimization of either  $Q$  or  $Q$  and MFD, which accounts for the objective functions  $F_1$  (Eq. (9)) and  $F_2$  (Eq. (10)). Parameters required for the evaluation of the economic and ecologic objective functions are summarized in Table 1.

The multi-objective optimization is first performed by setting MFD constant (i.e., the only optimized variable is  $Q$ ) and then by considering both  $Q$  and MFD as optimization variables. All ( $Q, MFD$ ) combinations with their corresponding economic and ecological performances have been explored by means of an algorithm implemented in Matlab, and dominant (Pareto-efficient) solutions identified. Multi-criteria optimal plant characteristics ( $Q_{OPT}, MFD_{OPT}$ ) are defined as those minimizing the norm of  $\mathbf{F} = [F_1, F_2]$  (i.e., its distance from the origin of the Pareto chart). Results of the multi-objectives optimizations (i.e., the optimal solutions  $Q_{OPT}$  and  $MFD_{OPT}$  and their resulting Net Present Value  $NPV$  and long-term hydrological connectivity  $HC$ ) are finally compared and discussed.

## 3. Case study and data

### 3.1. Girnock Burn

The Girnock Burn is a small tributary (30.3 km<sup>2</sup> drainage area) of the River Dee, an unregulated river flowing from the Cairngorms to the North Sea at Aberdeen (north-east Scotland, UK). The Girnock is particularly important for the reproduction of Atlantic salmon, an economically and ecologically fundamental species for the region. Salmon population monitoring in the Girnock began in 1967 and much is known about the flow requirements of the species. Adult salmon travel considerable distances upriver from the North Sea to reach spawning sites in the Girnock Burn [44]. While hydrological connectivity in the main stem of the Dee River is ensured throughout the year, salmon migration can be affected by low flow conditions in small tributaries such as the Girnock [45]. In fact, a minimum water depth is required to avoid physical limitations to fish movement and ecological fragmentation of the river network. Furthermore, low flow conditions increase predation probability in small streams, thereby impairing the reproductive success of returning salmon.



**Fig. 1.** Workflow of the study. Data required for each analysis are displayed as inputs (yellow background) to the methods of investigation (blue background). A multi-objective (economic and ecologic) optimization is performed, alternatively considering as optimization variables only the plant capacity  $Q$  or both the plant capacity and the minimum flow discharge MFD. Expected outputs of the analyses are also displayed on a green background.

**Table 1**

Values of parameters used for the multi-objective optimization of a run-of-river power plant located in the Girnock Burn, Scotland, UK. Contributing area ( $A$ ) and hydraulic head ( $H$ ) have been calculated following the procedure detailed in Section 2.1. The hydraulic head also determines the type of turbine [36]. A single turbine has been considered as the proposed framework is suited to small hydropower plants. Plant and turbine efficiencies come from [35]. The mean discharge at the intake ( $\langle q \rangle$ ) has been estimated as in Section 3.2.2, whereas the Minimum Flow Discharge ( $MFD_{intake}$ ) is given by [40]. The energy price ( $e_p$ ) has been taken from [41]. The plant lifetime ( $N$ ) is set equal to the duration of the feed-in tariff, and the discount rate ( $r$ ) is derived from [42]. Cost parameters ( $a$ ,  $b$ ) have been estimated based on data from [43], by applying the method illustrated in Section 3.2.4 and Appendix B. The minimum flow allowing for fish immigration ( $Q^*$ ) and the vulnerability of fish to flow reductions ( $\sigma$ ) have been taken from [30].

Parameter	Symbol	Value	Unit
<b>Hydrology and hydropower</b>			
Contributing area	$A$	23	km <sup>2</sup>
Hydraulic head	$H$	50	m
Type of turbine	Kaplan	–	–
Turbine efficiency	$\alpha_C$	0.10	–
	$\alpha_M$	0.33	–
	$\eta_0$	0.58	–
	$\eta_M$	0.89	–
Plant efficiency	$\eta_P$	0.95	–
Mean discharge at the intake	$\langle q \rangle$	0.43	m <sup>3</sup> /s
Minimum Flow Discharge	$MFD_{intake} = q_{95}$	0.04	m <sup>3</sup> /s
<b>Economy</b>			
Energy price	$e_p$	0.043	£/MJ
Plant lifetime	$N$	20	years
Discount rate	$r$	0.045	–
Cost parameters	$a$	0.91	ME/( $\frac{m^3}{s}$ ) <sup>b</sup>
	$b$	0.48	–
<b>Ecology</b>			
Minimum flow allowing for fish immigration	$Q^*$	0.17	m <sup>3</sup> /s
Vulnerability of fish to flow reductions	$\sigma$	0.01	m <sup>3</sup> /s

On the other side, the unexploited Gross Hydropower Potential (GHP) of rivers like the Girnock Burn (see Section 2.1 for details about its estimation) could raise the interest of investors searching for opportunities to contribute towards Scotland's target to supply all electricity from renewable sources by 2020.

For these reasons, the Girnock Burn represents a useful hypothetical case study to test multi-objectives optimization tools for understanding the potential tradeoffs between ecological and energetic goals. The methodology introduced in Section 2 has been applied to the fictional case of a run-of-river installation planned along part of the route followed by adult salmon returning from the sea to the headwaters of the Girnock for spawning. Effects of the choices of plant capacity ( $Q$ ) and minimum flow discharge (MFD) on economic profitability and hydrological connectivity are discussed in Section 4.

### 3.2. Data

#### 3.2.1. Topographical data

A digital terrain model (DTM) of the catchment is required to estimate the gross hydropower potential along the river network. At this purpose, the Ordnance Survey Land-Form Profile data set at 1:10,000 scale has been used. This data set is composed of 10 m × 10 m grid cells characterized by elevation values reported in meters. Standard operations to derive the river network of the catchment from the DTM have been performed by means of the software TauDEM [46].

#### 3.2.2. Streamflow data

Daily streamflow records of the Girnock Burn are available for the period 1972–2011 at the gauging station of Littlemill, located about 1 km upstream of the confluence with the Dee River. The mean annual discharge at Littlemill is 0.56 m<sup>3</sup>/s, which corresponds to 584 mm of annual runoff (the annual rainfall is 1100 mm) [45]. Streamflow variability is relevant, as indicated by the difference between discharges with a cumulative exceedance probability of 0.90 (i.e., exceeded 330 days per year;  $q_{90} = 0.07$  m<sup>3</sup>/s) and 0.10 (i.e., exceeded only 30 days per year;  $q_{10} = 1.19$  m<sup>3</sup>/s). Flows larger than  $q_{10}$  are observed mostly between late autumn and early spring, whereas low flow conditions (i.e.,  $q < q_{90}$ ) usually occur in summer [47]. In terms of specific streamflows, the hydrologic regime observed at the gauging station of Littlemill is assumed as uniform along the whole river network of the Girnock Burn. Therefore, the incoming flows at the intake of a hypothetical hydropower plant can be quantified based on the specific (per unit catchment area) discharges observed at Littlemill scaled by the contributing area at the plant intake.

The residual flow prescribed by the Scottish Environment Protection Agency has a cumulative exceedance probability of 0.95 (i.e.,  $MFD_{law} = q_{95}$ ) [40], and it is equal in this case to  $0.04 \text{ m}^3/\text{s}$ .

### 3.2.3. Ecological data

Two fish traps located a few hundred meters downstream of the discharge gauging station at Littlemill provide records of the number of juvenile salmon emigrating out of the catchment, and of the number of adult female salmon returning from the ocean to the Girnock to spawn. The traps, which are managed by the Marine Scotland Science Freshwater Laboratory, have continuously monitored emigration [48] and immigration [49] fluxes since 1967.

This dataset has been used [30] to estimate parameters  $Q^*$  and  $\sigma$  of the fish passage function (Eq. (7)) that best describe annual returns of female salmon in the Girnock Burn. The estimated parameters values (Table 1), which summarize the suitability of flows for upstream salmon migration from the River Dee, have been adopted in this work as a proxy for the accessibility of spawning sites in the Girnock Burn. Please refer to [30] for a more detailed description of the dataset and the method used to infer values of  $Q^*$  and  $\sigma$  from the records.

### 3.2.4. Economic data

Economic data, such as construction costs (C) and energy selling prices ( $e_p$ ), are required to assess the profitability of run-of-river hydropower plants. Feed-in tariffs paid for energy generated by small hydropower plants exist in most European countries (including the UK) to promote renewable energy production. This work refers to the UK tariff for small hydropower production as reported by [41]. An energy selling price of  $0.043 \text{ £/MJ}$  is guaranteed for 20 years to installations with a nominal power between 100 and 500 kW. The duration of the incentive also determines the length of the streamflow record used here for the analysis. Different sets of 20 consecutive years selected from the available record (1972–2011) have been tested, with no remarkable differences in the results. Therefore, streamflow data from 1992 to 2011 have been considered representative of the flow regime of the Girnock Burn and used to perform the calculation discussed in the manuscript.

A detailed database of characteristics and costs of run-of-river hydropower plants in the UK [43] has been used to estimate the cost function in Eq. (6). Seventy small run-of-river plants from contexts similar to the Girnock Burn (i.e., built in hilly regions and with hydraulic head higher than 30 m) have been selected and their construction costs (corrected by using a constant inflation rate) plotted against the corresponding plant capacities. Parameters  $a$  and  $b$  have been empirically estimated by fitting the function:

$$C = aQ^b \quad (11)$$

to this subset (see Appendix B). The obtained values are reported in Table 1.

## 4. Results

### 4.1. Plant location and characteristics

The gross hydropower potential GHP of each possible combination of plant intake and outflow along the river network of the Girnock Burn has been evaluated by means of Eq. (1) and a digital elevation model of the catchment with 10 m resolution. The maximum gross hydropower potential achievable varies considerably as the intake moves downstream (Fig. 2). The optimal location of the outflow for each intake varies as well (all possible lengths between intake and outflow have been considered) and is therefore not shown in the figure. The highest values of GHP are obtained when the plant intake is located in the middle course of the Girnock Burn, where an optimal trade-off between contributing area and hydraulic head between intake and outflow exists. In fact, steep headwaters channels offer the highest hydraulic head

but provide small workable flows as a result of insufficient contributing area. Conversely, large flows with limited exploitable  $\Delta z$  along the river course are available near the confluence with the River Dee, where the topography is relatively flat.

An additional restriction exists for choosing the positions of intake and outflow along the river. The Girnock Burn hosts along its main stem several well known and monitored salmon spawning areas (displayed in gray in Fig. 2) [45]. Spawning sites, which represent the final target of adult salmon migration, should not be altered by water abstraction to avoid irreversible impacts on the life-cycle of this species. For this reason, all combinations of intake-outflow locations containing some spawning sites have been discarded.

The selected intake and outflow locations, which leave spawning sites largely unaffected and maximize the GHP, are marked with pink triangles in Fig. 2. Under this configuration the contributing catchment at the plant intake has an area of  $23 \text{ km}^2$ , the hydraulic head between intake (placed at an elevation of 298 m a.s.l.) and outflow (at 248 m a.s.l.) is 50 m, and the length of the impacted river reach is 2.5 km. This information completes the set of parameters (Table 1) used in the multi-objective optimization of the run-of-river power plant.

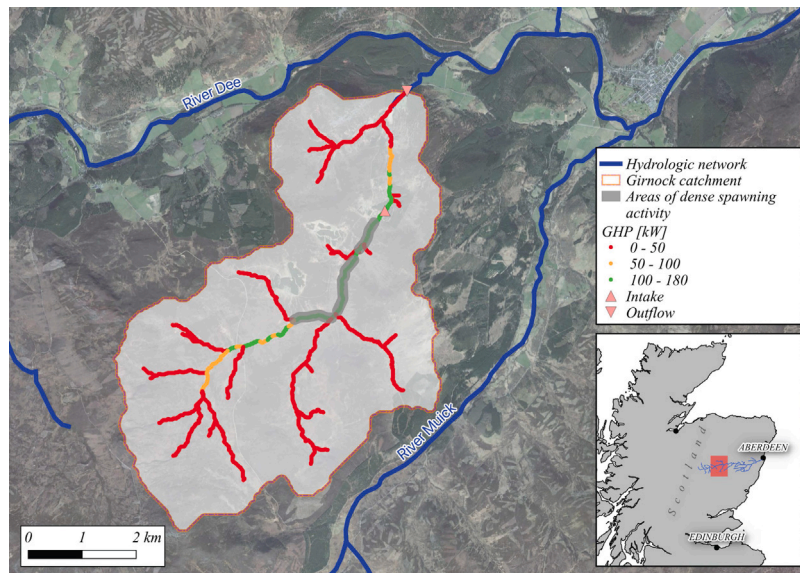
### 4.2. Multi-objective optimization of the plant capacity only

This section discusses results obtained when the minimum flow discharge is set as prescribed by environmental regulations ( $MFD_{law} = q_{95} = 0.04 \text{ m}^3/\text{s}$ ) [40] and the plant capacity  $Q$  is the only decision variable of a multi-objective optimization of the run-of-river power plant (i.e., MFD is set constant in Eqs. (9) and (10) and  $Q$  is the only variable of the objective functions  $F_1$  and  $F_2$ ).

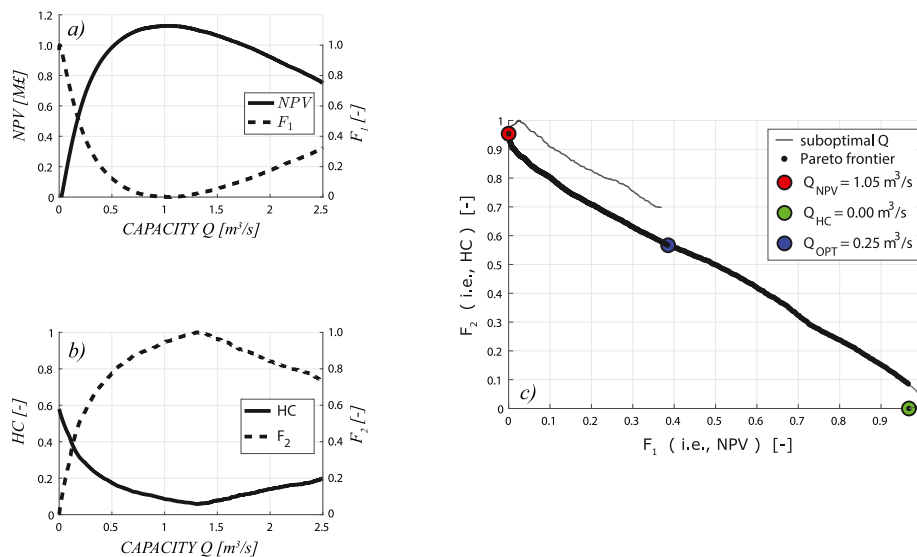
Solid lines in the left charts of Fig. 3 show variations of the net present value of the plant (NPV, Fig. 3a) and the long-term hydrological connectivity in the altered river reach (HC, Fig. 3b) with increasing plant capacity  $Q$ . The NPV reaches a maximum for  $Q_{NPV} = 1.05 \text{ m}^3/\text{s}$ , which provides an economic profitability of about  $1.10 \text{ M£}$  in 20 years. However, designing the plant to only maximize its economic value would result in a mean hydrological connectivity in the altered river reach of 0.08. In this case, the river reach between the intake and the outflow of the power plant would represent a barrier for salmon upstream migration, with an average of only 8% of adult females arrived at the confluence between the Dee and the Girnock that successfully reach their final target (i.e., the upstream spawning sites). This fraction would be larger than 50% under natural flow conditions ( $HC_{nat} = HC(Q=0) = 0.58$ , see Fig. 3b). The environmental flow prescribed by law is hence incapable of protecting the natural hydrological connectivity, 86% of which would be lost due to construction of a run-of-river plant complying with environmental regulations but optimized according to economic criteria only.

In the left plots of Fig. 3, dashed lines represent the objective functions corresponding to each goal, as defined by Eqs. (9) and (10).  $F_1$  and  $F_2$  are functions of the plant capacity only, as the minimum flow discharge is constant and equal to  $MFD_{law}$ . They have values equal to zero (one) when the corresponding goal is completely fulfilled (unfulfilled). In this case,  $F_1(Q_{NPV}) = 0$  and  $F_1(Q=0) = 1$ , the latter implying that the worst economic situation occurs when the plant is absent and no revenues are generated. Avoiding the construction of the plant also corresponds to the best condition for salmon upstream migration (i.e.,  $F_2(Q_{HC} = 0) = 0$ ), which is progressively hampered when the capacity increases. Notice however that  $F_2$  is a non-monotonic function of  $Q$ . This important feature, its origin and implications will be discussed later on in the manuscript.

Objective functions  $F_1(Q)$  and  $F_2(Q)$  represent contrasting goals only dependent on the plant capacity. They can thus be simultaneously optimized by identifying the Pareto frontier in a  $F_1$ - $F_2$  chart, as shown in Fig. 3c. Each point in the plot represents a tentative plant capacity for which economic and connectivity performances have been evaluated. Points embedded in the black solid line represent the Pareto frontier,



**Fig. 2.** Catchment area and river network of the Girnock Burn, Scotland, UK (the inset map shows its geographical location). Each point along the river network is color-coded according to the maximum Gross Hydropower Potential (GHP) achievable by installing the intake of a run-of-river hydropower plant in the same cross section. Important areas for salmon spawning activities that should be preserved by water abstraction are represented in gray. Triangular markers indicate the locations of the intake-outflow combination which maximizes the GHP.



**Fig. 3.** (a) Economic (NPV) and (b) environmental (HC) performances of a run-of-river plant in the Girnock Burn when the minimum flow discharge is set at the value prescribed by law (MFD =  $q_{95} = 0.04 \text{ m}^3/\text{s}$ ) and increasing values of the plant capacity  $Q$  are selected. The corresponding economic and ecologic objective functions,  $F_1(Q)$  and  $F_2(Q)$ , are also displayed as dashed lines. (c) Efficient (black dots forming a continuous line, i.e. the Pareto frontier) and non-efficient (gray line) plant capacities obtained for the considered case study. Notable capacities are highlighted with red (economic optimum), green (ecologic optimum) and blue (multi-objective optimum) markers.

i.e. the set of efficient capacities. The Pareto frontier contains  $Q_{NPV} = 1.05 \text{ m}^3/\text{s}$  (red dot in Fig. 3c) and  $Q_{HC} = 0 \text{ m}^3/\text{s}$  (green dot), plant capacities which respectively maximize the economic value of the plant and minimize the loss of connectivity in the altered river reach. Non-efficient capacities are those located along the gray line in the same plot. These are capacities larger than  $Q_{NPV}$ , for which both profitability and hydrological connectivity could improve with a different design choice (i.e., selecting a plant capacity on the Pareto frontier).

The nearest point to the origin of axis along the Pareto frontier is the multi-objective optimal plant capacity, in this case equal to  $Q_{OPT} = 0.25 \text{ m}^3/\text{s}$ . The corresponding performances are  $NPV(Q_{OPT}) = 0.68 \text{ M€}$  and  $HC(Q_{OPT}) = 0.29$ . Therefore, a multi-criteria optimal allocation of water resources among the two considered contrasting goals suggests that limiting the profitability at the 61% of the maximum economic value of the plant could increase the hydrological connectivity for salmon in

the altered river reach (from 0.08 to 0.29), setting it back to half of its natural value.

#### 4.3. Multi-objective optimization of both the plant capacity and the minimum flow discharge

Results from Section 4.2 suggest that optimizing the design of run-of-river power plants according to both economic and ecologic goals under the environmental flow constraints currently in place in Scotland can lead to sizeable losses of profitability without effectively preserving the natural hydrological connectivity. This outcome emphasizes the need for design practices that overcome considering the minimum flow discharge as a mere legal restriction, and look upon it as a decision variable (although subject to minimum values set by law) to be optimized according to the desired objectives for a given scheme.

For this reason, values of MFD during the pre-spawning season (September to November) in the range 0.04–0.23 m<sup>3</sup>/s have been tested. The lower bound is the value prescribed by law, whereas the upper bound is set equal to the value for which the fish passage function (Eq. (7)) reaches 0.99 (i.e., a value which poses no restriction to the passage of fish). This scenario rests on the idea that the Scottish Environment Protection Agency might consent to increasing the environmental flow needed to sustain adult salmon access to the Gironck Burn during the migration season, and that satisfactory economic outcomes for energy producers might still exist if these alternative operational strategies are considered during the design phase of the hydropower plant.

Fig. 4 summarizes results of the multi-objective optimization of both plant capacity and minimum flow discharge. Left charts display economic (NPV, Fig. 4a) and environmental (*HC*, Fig. 4b) performances of a run-of-river plant with increasing plant capacity  $Q$  under different minimum flow discharge scenarios, which are suitably color-coded. The lowest and the highest MFD are respectively shown in blue and green. Fig. 4a indicates that the economic value of the plant decreases with increasing MFD (i.e., moving from blue to green curves), as a larger fraction of streamflows is left in the river to support salmon migration (and hence is not processed by the plant). The economic optimal plant capacity,  $Q_{NPV}$ , diminishes as well as MFD increases (i.e., the peak of the curves shifts towards the left side). At the same time, important alterations of the natural hydrologic connectivity occurring for increasing plant capacities of a power plant complying with  $MFD_{law}$  (blue curve in Fig. 4b) are progressively damped as MFD increases (i.e., curves become flatter in the transition from blue to green). In particular, if MFD increases above the minimum flow required by salmon migrating into the considered river reach (in this case  $Q^* = 0.17$  m<sup>3</sup>/s), reductions of the hydrological connectivity are limited regardless of the choice of the plant capacity.

When both  $Q$  and MFD are considered as decision variables, the optimal MFD is equal to 0.20 m<sup>3</sup>/s and the optimal plant capacity  $Q_{OPF} = 1.02$  m<sup>3</sup>/s guarantees 0.95 M€ in 20 years with very limited alteration of the natural hydrologic connectivity (*HC* is only 3% lower than the natural condition).

The inclusion of the minimum flow discharge during the pre-spawning season among the set of design variables of the run-of-river power plant thus allows for identifying a project solution that guarantees almost unaltered hydrologic connectivity for salmon in exchange for a limited decrease of the economic profitability of the hydropower installation, especially if compared to the case of an optimized plant capacity subject to a lower (but predefined) value of the minimum flow discharge (see Table 2).

## 5. Discussion

### 5.1. Emerging optimization strategies and policy implications

When the minimum flow discharge in the pre-spawning season is free to take values larger than  $MFD_{law}$ , an optimized run-of-river power plant ensures a sizeable increase of the hydrological connectivity and a higher profitability than a plant subject to a lower (but predefined) minimum flow discharge. This counterintuitive finding proceeds from different optimization strategies emerging when MFD is set a priori or rather considered as a decision variable. In the first case, the optimal design corresponds to a small-sized power plant (i.e., with a capacity smaller than the average flow discharge). Hydrological connectivity is here mainly sustained by flows exceeding the plant capacity, which cannot be processed by the turbine and thus bypass the plant (design strategy 1). On the contrary, the optimal capacity of the power plant is significantly larger (more than twice the average flow discharge in the considered case study) if values of minimum discharge different from  $MFD_{law}$  are permitted. In this case the increase of MFD, which is mirrored by an improved hydrological connectivity, shifts the range of

workable flows to larger values. As a consequence, the optimal plant capacity increases as well, and the hydrological connectivity is now provided by the MFD and by flows that cannot be processed by the plant because lower than the cutoff value (design strategy 2).

The result has relevant implications for devising schemes of feed-in tariffs aimed at supporting renewable energy production. Building a comparatively larger plant and raising the MFD (strategy 2) clearly increases river network connectivity in this hypothetical example, and could be autonomously implemented by investors, since it abides by environmental regulations and only determines a minor decrease of the profitability with respect to the purely economic optimum (see Table 2). However, run-of-river hydropower policies and incentive schemes are usually structured so as to deter the construction of large-sized installations. The rationale behind this choice is that larger plants are supposed to cause heavier impacts. Findings of this work clearly falsify this assumption, as the actual physical conditions (e.g., hydrological connectivity) required to guarantee the provision of ecosystem services of interest (in this case salmon spawning) could be in some circumstances more effectively provided by bigger plants. The identified ability of large-sized run-of-river power plants to better preserve ecosystem services is also consistent with the choice of placing them in a few most productive sites, as suggested by least-cost allocation analyzes [50], rather than according to a regionally equitable distribution.

### 5.2. The role of hydrological variability

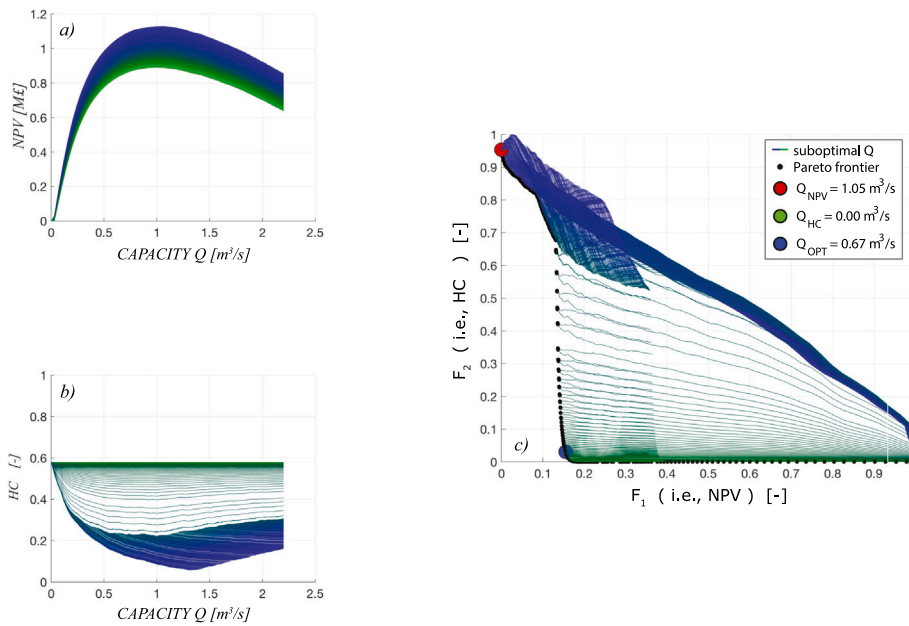
The viability of the different strategies, the gap between their optimal plant capacities and their respective impact on salmon migration depend on non-linear processes which determine variations of connectivity and profitability with increasing size of the run-of-river installation. One of the main drivers of this non-linearity is the tail of the frequency distribution of incoming flows. If the likelihood of high flows in the pre-spawning season is moderately high (i.e., for a probability distribution of streamflows with a heavier tail), discharges bypassing a small-sized plant (design strategy 1) would occur with sufficient probability to maintain a satisfactory degree of connectivity in the downstream river reaches. In fact, processing these high flows (which are potentially appealing for energy production) might not be economically convenient due to rising construction costs of larger plants. Conversely, if the likelihood of high flows is small, the connectivity in the altered river reach must rely on low-to-medium discharges that are typically processed by a run-of-river plant. Hence, increments of the plant capacity progressively remove fractions of water that are fundamental for maintaining connectivity, which must therefore be guaranteed by streamflows with long duration (i.e., a minimum flow discharge or flows lower than the cut-off value of the plant, as in design strategy 2). The optimal strategy and plant capacity result from a trade-off between these contrasting effects.

This short discussion highlights the impact of the underlying hydrological conditions on the choice of the most effective strategy to design run-of-river plants that yield satisfactory economic profitability and simultaneously preserve ecosystem services. The finding is consistent with the results of [27], who analyzed energy production and hydrological alteration in diverse flow regimes. Design practices and policies in the hydropower sector should consider these specificities and envisage adapting methodologies, regulations (e.g., dynamic environmental flows [26]) and incentives for diverse hydrological contexts.

### 5.3. The role of target ecosystem services

The choice of the most suitable design strategy also depends on the biological species and life stage of organisms considered (i.e., the specific values of  $Q^*$  and  $\sigma$ ). If hydrological conditions that thoroughly comply with their biological requirements are already secured by  $MFD_{law}$  (i.e., if  $Q^* \ll MFD_{law}$ ), run-of-river plants can be optimized





**Fig. 4.** (a) Economic (NPV) and (b) environmental (HC) performances of a run-of-river plant in the Girnock Burn with increasing plant capacity  $Q$  and different values of the minimum flow discharge. The latter are represented by the color of curves, and range from MFD =  $d_{95}$  (the lowest value prescribed by law, blue curve) to the value of MFD for which the fish passage function reaches 0.99 (the highest boundary set equal to a value that is not limiting for fish passage, green curve). (c) Efficient (black dots, i.e. the Pareto frontier) and non-efficient (dashed colored lines) plant capacities obtained for the considered case study. Notable capacities are highlighted with red (economic optimum), green (ecologic optimum) and blue (multi-objective optimum) markers.

**Table 2**

Results of the multi-objective optimization performed for one (i.e., the plant capacity  $Q$ ) or two (i.e., the plant capacity  $Q$  and the minimum flow discharge MFD) decision variables, compared with the results obtained when only the economic profitability of the hydropower plant is considered. The latter have been obtained within Section 4.2 by applying F1 as sole objective function (i.e., by only considering the optimum identified in Fig. 3a and represented with a red marker in Fig. 3c). Noticeably, if  $Q$  and MFD are simultaneously optimized according to economic and ecologic requirements, almost unaltered hydrologic connectivity is guaranteed at the expense of a 14% reduction of revenues with respect to the economic optimum. If only  $Q$  is optimized, instead, a reduction of profitability equal to the 38% only ensures 50% of the natural hydrological connectivity.

	Single-objective (economic) optimization	Multi-objective (economic and ecologic) optimization with predefined MFD	Multi-objective (economic and ecologic) optimization with optimized MFD
Objective function	F1	F1, F2	F1, F2
Optimized variable	$Q$	$Q$	$Q$ , MFD
$Q_{OPT}$ [m³/s]	1.05	0.25	1.02
MFD [m³/s]	0.04	0.04	Dec-Aug: 0.04
MFD <sub>OPT</sub> [m³/s]			Sept-Nov: 0.20
NPV [ME]	1.10	0.68	0.95
HC / HC <sub>nat</sub> [-]	0.14	0.50	0.97

to pursue maximum profitability only. When more demanding organisms are concerned, a trade-off between economic and ecologic goals might suggest the construction of either small or large-sized plants, depending on the actual availability of streamflows. For intermediate values of  $Q^*$  and  $\sigma$ , comparatively larger plants that guarantee hydrological connectivity through the minimum flow discharge and the cutoff flows (i.e., design strategy 2) are economically feasible and ecologically efficient (especially if high flows occur frequently in the considered catchment and are therefore appealing for energy production). When the biological requirements grow further (or high flows are unlikely), increasing the plant capacity no more compensates for revenues losses linked to downstream release of low flows. The optimal strategy thus becomes the construction of small-sized plants (i.e., design strategy 1).

The control exerted by ecological parameters on the most suitable design strategy for run-of-river power plants stresses the importance of clearly defining target species and ecosystem services which are deemed especially significant and should thus be preserved in the considered river basin. If multiple ecosystem services are simultaneously

considered, their potentially contrasting needs will in fact compete to define the optimal design of the hydropower installation. A clear prioritization of ecosystem services, which arises from stakeholder consultation regarding specific riverine environments, is therefore pivotal to develop sustainable hydropower exploitation schemes.

Although the analyses presented here have been performed for a specific location and a hypothetical example for a single fish life stage, the case study is emblematic of challenges arising in river basins where current or anticipated hydropower exploitation of water resources threatens the provision of ecosystem services. The proposed generic analysis is suited to other case studies, provided that hydrologic data are available and sensible hypotheses can be made concerning the economic and ecologic parameters of the model. Likewise, the identified flaws and improvements suggested for incentive schemes used to promote the growth of renewable energies hold beyond the specific case study addressed in this paper, and constitute valuable general recommendations towards optimal design and policy for run-of-river hydropower.

Table A.1

List of symbols used in the manuscript. Their meanings and units are reported. For terms that intrinsically have no units (e.g., indices) or that assume the units of the variables they contain (e.g., vectors), - is indicated in the column for units.

Symbol	Meaning	Unit
$\alpha_C$	Cutoff fraction	Unitless
$\alpha_M$	Fraction of plant capacity for which turbine efficiency begins to decrease	Unitless
$\Delta T$	Time period over which energy production is calculated	days
$\Delta z$	Topographic difference between intake and outflow	m
$\eta$	Turbine efficiency	Unitless
$\eta_M$	Turbine efficiency at plant capacity	Unitless
$\eta_P$	Plant efficiency	Unitless
$\eta_0$	Turbine efficiency at cutoff flow	Unitless
$\rho$	Water density	kg/m <sup>3</sup>
$\sigma$	Vulnerability of fish to flow reductions	m <sup>3</sup> /s
$a$	Coefficient of the cost function	£/( $\frac{m^3}{s}$ ) <sup>b</sup>
$A$	Contributing area	m <sup>2</sup>
$b$	Exponent of the cost function	Unitless
$C$	Construction costs	£
$E$	Overall energy production of the plant	MJ
$E_i$	Annual energy production of the plant	MJ
$e_p$	Energy price	£/MJ
$f$	Fish passage function	Unitless
$F$	Vector of objective functions	-
$F_j$	Objective function	Unitless
$F1$	Objective function for the economy	Unitless
$F2$	Objective function for the hydrological connectivity	Unitless
$g$	Standard gravity	m/s <sup>2</sup>
GHP	Gross hydropower potential	W
$H$	Hydraulic head	m
$HC$	Long-term hydrological connectivity downstream of the plant intake	Unitless
$HC_{max}$	Maximum hydrological connectivity	Unitless
$HC_{min}$	Minimum hydrological connectivity	Unitless
$HC_{nat}$	Hydrological connectivity under natural streamflow conditions	Unitless
$i$	Index of each year during the plant lifetime	-
$j$	Index of each objective function	-
$k$	Friction coefficient	Unitless
$L$	Length of the penstock	m
$m$	Number of objectives	-
MFD	Minimum flow discharge	m <sup>3</sup> /s
MFD <sub>law</sub>	Minimum flow discharge set by law	m <sup>3</sup> /s
MFD <sub>NPV</sub>	Optimal minimum flow discharge when only the economic objective is considered	m <sup>3</sup> /s
MFD <sub>OPT</sub>	Optimal minimum flow discharge resulting from a multi-criteria optimization	m <sup>3</sup> /s
$N$	Plant lifetime (i.e., duration of the feed-in tariff)	years
NPV	Net present value	£
NPV <sub>max</sub>	Maximum net present value	£
NPV <sub>min</sub>	Minimum net present value	£
$p$	Probability distribution of streamflow available at the plant intake	s/m <sup>3</sup>
$p_{ds}$	Probability distribution of flow released downstream of the plant intake	s/m <sup>3</sup>
$q$	Streamflow available at the plant intake	m <sup>3</sup> /s
$\langle q \rangle$	Mean streamflow at the plant intake	m <sup>3</sup> /s
$\langle q_s \rangle$	Mean specific (i.e., per unit catchment area) streamflow at the plant intake	m/s
$q_{ds}$	Flow released downstream of the plant intake	m <sup>3</sup> /s
$q_w$	Workable flow (i.e., flow processed by turbines)	m <sup>3</sup> /s
$q_{10}$	Streamflow with a cumulative exceedance probability of 0.10	m <sup>3</sup> /s
$q_{90}$	Streamflow with a cumulative exceedance probability of 0.90	m <sup>3</sup> /s
$q_{95}$	Streamflow with a cumulative exceedance probability of 0.95	m <sup>3</sup> /s
$Q$	Plant capacity	m <sup>3</sup> /s
$Q_C$	Cutoff flow (i.e., minimum workable flow)	m <sup>3</sup> /s
$Q_{HC}$	Optimal plant capacity when only the ecologic objective is considered	m <sup>3</sup> /s
$Q_{NPV}$	Optimal plant capacity when only the economic objective is considered	m <sup>3</sup> /s
$Q_{OPT}$	Optimal plant capacity resulting from a multi-criteria optimization	m <sup>3</sup> /s
$Q^*$	Minimum flow allowing for fish immigration	m <sup>3</sup> /s
$r$	Discount rate	Unitless
$R_N$	Revenues from energy selling	£
$x$	Vector of decision variables	-
$x_{opt}$	Vector of multi-objective optimal solutions	-

## 6. Conclusions

A set of tools to assist design and management of run-of-river power plants when competing economic and ecologic objectives must be jointly maximized has been presented in this paper. The approach has been tested in a hypothetical study of a Scottish river catchment where an interest to increase hydropower production would compete with a minimal need of securing hydrological connectivity, which enables

salmon access to migration routes. The following findings and policy recommendations are worth emphasizing:

- A tradeoff between economic profitability of hydropower production and preservation of river connectivity for ecological purposes exists. This tradeoff implies a strong reduction of profitability (equal to 38% of the maximum economic value of the plant in this case) without effectively preserving the natural hydrological connectivity of the stream;

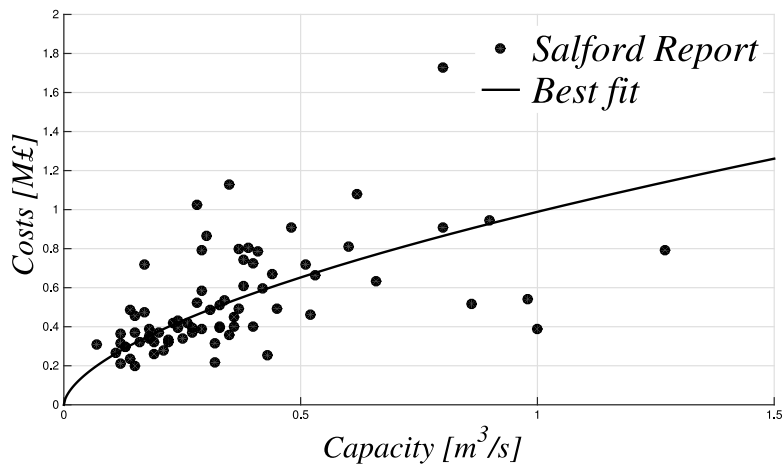


Fig. A.1. Construction costs ( $C$ ) versus plant capacities ( $Q$ ) are displayed with black dots for a set of run-of-river installations from [43]. A power-law relation (solid line) has been fitted to these data to estimate the parameters of the cost function,  $C = aQ^b$ . The resulting values ( $a = 0.91$  [ $\text{M}\text{£}/(\frac{\text{m}^3}{\text{s}})^b$ ] and  $b = 0.48$  [-]) are reported in Table 1. Please refer to Section 3.2.4 for further details concerning their estimation.

- An alternative solution arises when the residual flow is regarded as a decision variable that can take values higher than the minimum flow discharge currently set by law. In this case, a trade-off which guarantees almost unaltered hydrological connectivity and only a minor decrease of the profitability compared to the economic optimum is identified;
- Distinct strategies for designing run-of-river power plants that are economically profitable and effectively preserve ecosystems services emerge when interactions between design and policy are allowed. The first strategy consists in building small-sized installations and sustaining hydrological connectivity through bypass flows larger than the plant capacity. The second approach relies on the construction of comparatively larger plants that guarantee ecological needs by means of a minimum flow discharge and of flows lower than the cutoff value of the turbines;
- Local hydrological conditions and target ecological requirements defined by the actual ecosystems of interest determine the most effective strategy for specific case studies. Environmental regulation should therefore define target species and ecosystem services which are particularly relevant for specific river basins. Design practices in the hydropower field should account for these indications and adapt to diverse hydrological contexts;
- Policy to support renewable energies should avoid incentive schemes that penalize a priori relatively larger run-of-river installations, thus deterring investors from pursuing this strategy. In fact, our analysis reveals that in some cases a larger plant capacity could be the most effective way to effectively preserve concerned ecosystems services through an economically viable project.

#### CRediT authorship contribution statement

**S. Basso:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **G. Lazzaro:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Validation, Writing - original draft, Writing - review & editing. **M. Bovo:** Software, Formal analysis, Investigation. **C. Soulsby:** Conceptualization, Supervision, Resources, Writing - review & editing. **G. Botter:** Conceptualization, Methodology, Supervision, Writing - review & editing.

#### 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. List of symbols

A list of the symbols used in the manuscript, together with an explanation of their meanings and units, is provided in Table A.1.

#### Appendix B. Cost function

The cost function resulting from fitting a power law to the database of economic data employed in this study is displayed in Fig. A.1.

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