QUANTITATIVE ASSESSMENT OF THE LOSS OF RESILIENCE DUE TO FRAGMENTATION OF POPULATIONS BY DAMS. CASE STUDY: BROWN TROUT IN LA RIOJA (NORTH OF SPAIN).

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In the calculation of environmental flows (*mitigation measure*) by means of habitat-based methods (IFIM) it is assumed that the greater impact caused by a dam on the population of the target species is the reduction the mean annual flow, which involves the reduction of the amount of available habitat for this species. A given population can also be affected by the presence of an obstacle, as it is split into two isolated populations each disposing of a smaller river system than the originally occupied by the non fragmented population. An increase in the environmental mean annual flow can be seen as a *compensation measure* of the impact caused by this dam. We therefore call this environmental flow *compensation flow* (Q_{comp}). A property of the population that synthesizes the resistance and recovery ability is the *resilience*, ρ. Knowing the value of the resilience of each of the populations resulting from fragmentation of the original, the intensity of impact, I, produced by the presence of the obstacle can be determined as the resilience loss (%) of the most affected resulting population (the one that has lost more resilience), $I = \rho_{fragmented} / \rho_{original}$. If passability, f_i, expresses the proportion of the population that passes through the barrier i in a reasonable time, and $F = \prod f_i$, expresses the accumulated passabilities of all the obstacles located downstream the dam whose impact is to compensate, we can quantify the compensation flow as a fraction of the natural mean annual flow, Q_{nat}, as $Q_{comp} = Q_{nat} \cdot (1- \rho_{fragmented} / \rho_{original}) \cdot e^{-\prod f_i}$. We applied this approach in an artificially fragmented population of brown trout (*Salmo trutta*) in La Rioja (Ebro basin, North of Spain), obtaining a flow rate of compensation, Q_{comp}, equal to 46% of the mean annual value of the natural flow regime.

1 INTRODUCTION

In some amphibiotic fish populations (e.g. sturgeon, eel, salmon and sea trout) the disconnection of the spawning areas from the growing areas can interrupt the species life cycle thus threatening its persistence. For a holobiotic population (e.g. resident brown trout) such a disconnection breaks it into two separate resulting populations, thus altering its temporal and spatial dynamics.

The main impact of dams on fish populations is therefore two-fold: (1) the impact derived from the function of the dam, which alter both the mean annual flow and flow regime; and (2) the impact derived from the mere presence of an obstacle, whose impact depends on the location of the dam and its degree of passability.

Here we propose both types of impacts to be considered when dimensioning measures to mitigate and compensate for the impacts of dams, designing the environmental flow according to the most relevant of both types of impact.

1.1 Rationale

The mean annual flow that is calculated following the criteria of the habitat vs. flow methods (e.g. IFIM Stalnaker *et al*. [1]) is designed to reduce the impacts caused by flow abstraction (which depends in turn upon the dam function). Since it is a true mitigation measure we shall name this environmental flow *mitigation flow* (Q_{mit}).

The impact caused by the mere presence of a dam as an obstacle for the movement of fish does not disappear by eliminating every alteration of natural stream flow, since it causes a disconnection within the river network that divides the original populations. This impact can be reduced by choosing a proper location for the dam within the river network, so as to cause the minimum impact on the population life cycle. However, other technical and economical criteria for the location of the dam may also take part in the project location decision making process. It can also be reduced by assuring the passability of the obstacle by means of a fish pass. However, there are dams whose height and location do not allow the placement of a fully functional fish pass assuring 100% passability. For these reasons, the impact derived from the presence of the obstacle cannot be often reduced by the mentioned measures. In this case an increase of the environmental mean annual flow can be observed as a compensation (instead of mitigation) measure. We shall name this environmental flow *compensation flow* (Q_{comp}).

In the following paragraphs we expose a method for the calculation of the mean annual value of an environmental flow regime to compensate the impact caused by the presence of a dam. Following this approach, if the designed environmental flow is more restrictive than the one obtained by means of habitat vs. flow methods we will assume that the impact caused by the presence of the obstacle is more important than the one derived from the alteration of the flow regime.

The mean annual value of the compensation flow (Q_{comp}) is calculated as the mean annual value of the natural flow regime (Q_{nat}) modulated by the *intensity* of the impact (I) caused by the obstacle and the *passability* (F) of the obstacle, in case there is a fish pass.

$$Q_{comp} = Q_{nat} \cdot I \cdot e^{-F} \qquad \text{Eq. (1)}$$

To quantify the intensity of the impact the life strategy of the impacted population has to be taken into account. For amphibiotic populations the impact is absolute, and thus the passability is the only factor that should modulate Q_{nat}. For holobiotic populations the impact is due to the fragmentation of the original population into isolated populations, each of which have a shorter available river network than that originally available for the unfragmented population. If the lengths of the fragmented river networks are different, the impact caused by the obstacle may be equally different for both resulting populations. It will therefore be necessary to calculate the impact for every resulting population and to design the compensating flow using the value of the highest intensity of both impacts. The effect of an obstacle on a holobiotic population is the restriction to the dynamics of that population. The size of a population fluctuates over time around the carrying capacity, which is a stable equilibrium point defined by the ecosystem conditions. The fluctuation of the population density, N, around that equilibrium is determined by exogenous factors, such as meteorology, predator activity, prey abundance, interspecific competition, …; and endogenous factors, such as intraspecific competition, density-dependent recruitment, compensatory mortality, shelf-thinning, … This fluctuation has often been modelled by means of a deterministic skeleton (Coulson *et al*. [2]), to represent the endogenous population regulation, letting the exogenous limitation to be represented as random environmental noise, which can be in turn reduced by entering the known effects of exogenous drivers into the model. The deterministic skeleton can be built as a logistic model representing the value of the *population growth rate* at time t, r_t, ($r_t = \ln[N_{t+1}/N_t]$) for every population density at time t, N_t, with a minimum viable population density threshold, U:

$$r_t = r_0\left(1-\frac{U}{N_t}\right)\left(1-\frac{N_t}{K}\right) \qquad \text{Eq.(2)}$$

Where r_0 is the maximum potential *per capita* growth rate of the population or the intrinsic rate of population growth, that can be thought of as the genetic potential of the population; *K* is the carrying capacity; *U* is the *minimum threshold of population viability*, population density that, with a given mortality rate, supports a density of reproducers below which the probability of finding breeding pair is so low that *r* is negative and the population goes extinct.

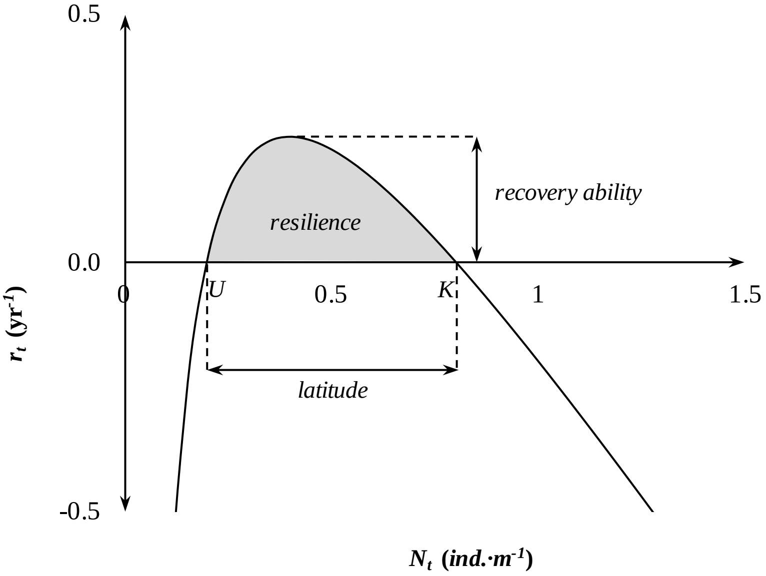

Figure 1. Graphic representation of the *r* function Eq. (2) showing the functions of latitude, recovery ability and resilience.

Two properties of the population can be derived from this model (Fig. 1): (1) <u>*latitude*</u>, defined by Walker *et al*. [3] as “the maximum amount a system can be changed before losing its ability to recover before crossing a threshold which, if breached, makes recovery difficult or impossible”. This property enables the population to withstand random environmentally induced fluctuations around *K* without reaching the threshold *U*, and its quantitative value can be approached proportional to the distance between *K* and *U*. (2) <u>*Recovery ability*</u> (proportional to the maximum value of r_t, r_{max}) that allows population recover faster from these changes. <u>*Resilience*</u>, ρ, synthesizes both latitude and recovery ability and it can be approached proportional to the area of the curve between U and K:

$$\rho = \int_U^K r_0\left(1-\frac{U}{N_t}\right)\left(1-\frac{N_t}{K}\right)dN_t \qquad \text{Eq. (3)}$$

This expression can be simplified by likening the shape of the area to a triangle with two convex sides:

$$\rho = \frac{2}{3}(K - U)\, r_{max} \qquad \text{Eq. (4)}$$

where r_{max} is recovery ability (i.e. the maximum value of r_t for every N_t between U and K) whose value is reached when population size is N_t^*, a value that makes zero $\mathrm{d}r_t/\mathrm{d}N_t$:

$$\frac{dr_t}{dN_t} = r_0\left(\frac{U}{N_t^{*2}} - \frac{1}{K}\right) = 0 \qquad \text{Eq. (5)}$$

Then $N_t^* = \pm\,(KU)^{1/2}$, where only its positive root makes sense from a biological point of view, $N_t^* = (KU)^{1/2}$ Substituting this term in the r model Eq. (2) the value of *recovery ability*, r_{max} can be determined as:

$$r_{max} = r_0\left(1 - \frac{U}{(KU)^{1/2}}\right)\left(1 - \frac{(KU)^{1/2}}{K}\right) = r_0\left(1 - \left(\frac{U}{K}\right)^{1/2}\right)^2$$

Which can be in turn introduced in Eq. (4), thus obtaining the value of the *resilience*, ρ:

$$\rho = \frac{2}{3}(K - U)\, r_0\left(1 - \left(\frac{U}{K}\right)^{1/2}\right)^2 \qquad \text{Eq. (6)}$$

If the if the population viability threshold density, U, is considered in individuals per unit area then its value can be expressed as:

$U = (N_e / ((100 - (\%)N^{0+}) / 100)) / L \cdot A$

where N_e is the effective population size; $(\%)N^{0+}$ is the percentage population above age class 0+ (considering 1+ as the age class of first reproduction); L is the length of the river network (m); and A is the mean channel width (m).

The fragmentation of a population into two or more smaller populations reduces the available river network length, L, increasing the population viability density threshold, U, and thus reducing the latitude (K – U) of the resulting populations.

Once the resilience of every resulting fragmented population has been quantified, the intensity of the impact caused by the presence of the obstacle, I, can be determined as the maximum observed resilience loss (i.e. the resilience loss of the resulting population that has lost more resilience from the original unfragmented conditions):

$I = -\Delta\rho_{max}$

where

$\Delta\rho = [(\rho_{fragmented} - \rho_{unfragmented}) / \rho_{unfragmented}]$

The passability of the obstacle, F, can be expressed as the proportion of the population that can overcome the dam within a reasonable time lag, and it should accumulate the effect of the passabilities, f_i, of the obstacles located downstream the dam whose impact has to be mitigated:

$F = \Pi f_i$

The compensation flow can be then expressed as:

$Q_{comp} = Q_{nat} \cdot -\Delta\rho_{max} \cdot e^{-\Pi fi}$

2 METHODS

The above described rationale was applied to an artificially fragmented brown trout (*Salmo trutta*) population in the upper river Najerilla basin, (La Rioja, river Ebro basin, northern Iberian Peninsula). It is a high gradient river network whose main water course flows northwards from the Iberian System mountain range (2,400m) to the river Ebro (ca. 400 m above the sea level). River Najerilla has three impassable dams: Mansilla (altitude a.s.l. 930m), Piarrejas (850m) and La Retorna (750m). The study area comprises all water courses flowing to La Retorna dam (total river network length 222 km), and its original brown trout population is currently fragmented by the two uppermost dams into three independent subpopulations, namely: Najerilla (network length 110 km), Urbión (95 km) and Calamantío (17 km).

Time series of quantitative data were collected by the regional fisheries administration (Consejería de Medio Ambiente de La Rioja) in a network of 6 monitoring stations scattered throughout the study area. The data represent the annual variation of the density and the age structure of brown trout (*Salmo trutta* L.) between 2001 and 2006 (Unzu *unpublished data*). Data were obtained by three pass electrofishing removals in closed reaches of ca. 500 m^2 comprising the whole river section. The correction of Carle and Strub [4] was applied to estimate total abundance. All captured trouts were individually measured (1mm) and weighed (1g). The age of every 5 mm size class was determined by length frequency analysis and scale reading.

The parameterization of the population dynamics model and, therefore, the expression of resilience Eq. (6) was carried out using qualitative approaches and quantitative determinations (Berryman [5]). The threshold of population viability, *U*, was estimated by means of qualitative approaches. This issue has been addressed by several authors, and considering a rough number put forth by Lande [6] and Lynch and Lande [7] a threshold 2,500 fish age 1 and older at any time (Hilderbrand [8]) can be set in order to being conservative. Although Frankham [9] and Franklin and Frankham [10] think that the number can be even lower.

The intrinsic population growth rate, r_0; and carrying capacity, *K*, were quantitatively determined from the collected time series for every fragmented population. A weighted averaging of the observed parameters was used to approach the values for the original unfragmented population.

3 RESULTS

The results obtained from the application of the exposed methods are shown in Table 1.

Table 1. Case study results: r_0, intrinsic rate of population growth; K, carrying capacity (ind.$\cdot m^{-1}$), *L*, available river network length (km); *U*, threshold population density (ind.$\cdot m^{-1}$); ρ, population resilience (ind.$\cdot m^{-1}\cdot yr^{-1}$) of the original (unfragmented) and the current (fragmented) brown trout populations in upper Najerilla basin.

	unfragmented					*fragmented*					
Population	r_0	*K*	*L*	*U*	ρ	r_0	*K*	*L*	*U*	ρ	$\Delta\rho$
Najerilla	1	0.14	222	0.0023	0.0744	0.9	0.12	110	0.0068	0.0399	-46%
Calamantío						1.3	0.28	17	0.0521	0.0654	-12%
Urbión						1.1	0.13	95	0.0060	0.0548	-26%

The resilience of the original unfragmented population was estimated $\rho_{unfragmented}$ = 0,074 ind.$\cdot$m$^{-1}\cdot$yr^{-1} and the most impacted population showed a resilience of $\rho_{fragmented}$ = 0,040 ind.$\cdot$m$^{-1}\cdot$yr^{-1}. The intensity of the impact is therefore:

$I = -\Delta\rho_{max} = 0{,}46$

Considering a passability of 0% in the three dams that currently divide the original population, the compensation flow, Q_{comp}, should be:

$Q_{comp} = Q_{nat} \cdot -\Delta\rho_{max} \cdot e^{-\Pi fi} = Q_{nat} \cdot (0{,}46) \cdot e^{0}$

$Q_{comp} = Q_{nat} \cdot 0{,}46$

The compensation flow, Q_{comp}, in the upper Najerilla reach should be at least the 46% of the mean annual flow. Applying the above exposed approach, if the mitigation flow, Q_{mit}, obtained by habitat based methods (i.e. IFIM) was smaller than the compensation flow, the latter should be chosen.

4 DISCUSSION

The concept of resilience in ecological systems was first introduced by Holling [11]. He used it to describe the persistence of natural systems to changes in ecosystem variables, due to natural or anthropogenic causes. Walker *et al*. [3] define ecological resilience as: “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks”. Resilience loss can be used as a measure of the impact of the presence of a dam on the integrity of the dynamics of a brown trout population.

The main difficulty of this approach is to quantify the value of the resilience. Here we propound a simplified expression for the calculation of the resilience that is described elsewhere (Alonso *et al*. [12]), and therefore it should not be considered an accurate measure of it. However, the exposed approach can be used as an easy-to-calculate quantification of the compensation measures of the impacts on the integrity of brown trout population dynamics due to its fragmentation by dams.

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