WHAT DO WE KNOW TO EVALUATE THE HEALTH OF BROWN TROUT (*Salmo trutta*) POPULATIONS?

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ABSTRACT

The renewed emphasis on the concept of the health of ecosystems highlights society's interest in taking measures to protect environments transformed by human activity. The criteria used for evaluating the health of fish population are rarely discussed within the scientific community. The exercise proposed here aimed to discuss these for the brown trout (*Salmo trutta*), a flagship species from the freshwater fish community typical from headwaters of watercourses which represent most of the French hydrographic network. This initiative aimed to gather the ideas of a limited number of experts on the function of these populations and on the criteria for evaluating their function. The main key parameters were identified and organised into a hierarchical

framework for each development stage. A consensus emerged on the fact that in the current stage of knowledge, the diagnosis can be established based on the analysis of abiotic parameters crucial for the biology and, with more difficulty, on the analysis of biotic parameters. For all the development stages, the identified parameters are linked to habitat (substrate, stream flow, temperature and water quality), hydrology and connectivity. Further knowledge must be acquired in order to be able to measure the biological criteria. That implies to reinforce long-term biological monitoring and research to understand the variability in biological parameters, the relevant spatiotemporal scales and the functional processes.

1 INTRODUCTION

In the context of the growing influence of global change and anthropic pressures in this beginning of the 21st century, environmental sustainability and management of water resources and natural biological resources are at the centre of social and scientific issues. Society's need to understand the ecological function of aquatic ecosystems grew and made apparent the link between environment and health. This concept of health, usually dealing with the vitality of individuals and populations of humans, and domestic and wild fauna to be characterised, has been extended to the health of ecosystems. It was developed in the course of the 90s [1] and is measured in terms of diversity, resilience and vigour. This renewed emphasis on the concept of the health of ecosystems affected by human activity reveals society's interest in taking measures for their protection.

In this context, tools for assessing and understanding the function of aquatic ecosystems must be developped. Assessment criteria are in particular necessary for assessing precisely, at the local scale (site), the function of the ecosystem. The choices of assessment criteria used by the scientific community are rarely discussed. The exercise proposed here aims to discuss them in the case of headwaters of watercourses or of rivers with a small drainage, which represent most of the French hydrographic network. A large amount of knowledge has been acquired on the biology and ecology of the brown trout *(Salmo trutta),* a flagship species from the typical fish community living in these areas. Operational tools have been developed to assess its needs in terms of physical habitat for the different development stages. This knowledge needs to be structured so as being able to draw up a hierarchical framework to assess the function of these populations.

Our approach draws on this context and proposes to collect the opinions of a limited number of experts for answering the two following questions:

- What available knowledge do we have to assess the function of trout populations?
- Do exist some criteria for evaluating the function of these populations?

2 MATERIAL & METHODS

2.1 Description of the approach

Fifteen experts gathered for a three-days seminar with the aim of determining the processes and criteria for assessing the function of trout populations. The experts discussed on the processes acting on the populations on different temporal and spatial (watershed to microhabitat) scales. The objective was to gather the experts' perception on the importance level of the parameters affecting trout populations. This perception incorporated their own work and their knowledge of the literature.

The discussions first aimed to agree on a simplified description of the biological cycle of the brown trout, which can change according to environment. The objective here was to reconstruct the scheme of the biological established by the experts from studies conducted by the participants or from the literature, in distinct physical sites with different populations. While incomplete, this view aimed to set ranges of average values that can be applied to the populations in French rivers.

Secondly, the exercise dealt with identification of the parameters influencing development stages. The objective was to gather and compare expert knowledge on the limiting and no limiting factors observed in the natural environment, at different development stages of the trout in order to provide a consensus on the predominant parameters. To do this, outlines were developed by developmental stage, distinguishing the favourable and the limiting parameters. Ranges of values of these parameters were specified when the state of knowledge was considered good.

Finally, starting from the representation of the processes previously established, the aim was to draw up a hierarchy of the processes involved and to specify evaluation criteria for these processes (direct or indirect evaluation by measurement of parameters).

The results obtained do not represent an exhaustive inventory of present knowledge, but collect the opinions and knowledge of experts and the outcome of the collective study conducted on this complex issue of evaluating the function of trout populations.

2.2 Choice of experts

Most of chosen experts were scientists or biologist people coming from research, or technical organisations or management associations. All the people chosen might get knowledge allowing them to assess the function of the aquatic ecosystem and identify the various causes of alteration (that is, to link the physical processes and the dynamics biological communities). Over half of the experts gathered had completed a thesis on the brown trout ecology.

3 RESULTS

3.1 Schematic biological cycle in brown trout

A schematic biological cycle has been established for allowing the identification of the predominant factors at each development stage. The spawning period extends from November to February; eggs hatch during January and February, and emergence occurs from March to April. The survival rate at hatching is estimated at 80% [2], with lethal thermal thresholds ranging below 1 and above 15°C and 3 mg/l for oxygen lethal rate [3]; [4]. In rivers with a good-quality habitat (no silting), the survival rate between hatching and emergence has been estimated like constant (85%). After emergence in March, density-dependent mortality (territorial species) occurrs and the annual survival rate of young of the year (0+ class) is estimated between 5 and 7% under optimal conditions while that of (>0+) juveniles and adults is estimated between 30 and 50% [5]. In most cases, life span is in average 4 years, ranging up to 7 years at some sites (even exceptionally 12 years). Males mature earlier (2 years) than females (3 years). The latter have a fecundity varying from 1000 to 2000 eggs per kg. The sex ratio in the population is most often considered to be balanced (0.5) in the first stages of life. But this sex ratio can then vary as a function of the life history strategy of individuals, which is sex-dependent [6]. Spawning migration takes place from the end of September to the end of January [7]. It require a temperature range between 6 to 12°C and depend on fluctuations in flow rates (importance of spates) [8], [7]. Spawning migration occurs in successive waves when the triggering environmental variables (water temperature and discharge) are encountered, Distances covered range from several hundred metres to several tens of kilometres. The homing phenomenon is not systematic (50 to 60%; Baglinière, personal communication). On the other hand, post-reproductive homing, namely a return of spawning fish to the habitat used before migration, is regularly observed [9]. In rivers located in the large Western Part in France, segregation is observed between the juveniles located in tributaries (nursery streams) and the adults present in river. Growth varies as a function of temperature [10] and trophic availability (the level of prey available and the type of prey).
Five development stages have been defined: laid eggs, yolk-sac alevins (incubation phase), alevins (0+), juveniles (1+) and adults (>1+).

3.2 Identification and prioritisation of the factors influencing the developmental stages

The outlines developed during the seminar were summarised in the table 1 giving an overview of the influencing factors. For each development stage previously identified a decreasing order of sensitivity to the different processes / parameters involved was established, along with criteria for evaluating these processes. The spatial scale on which the processes operate is also noted. For each developmental stage, the parameters are listed in decreasing order of importance.

Laid eggs
The nature and quantity of the substrate are considered the most major parameters for laid eggs stage. At micro-habitat scale, the current velocity conditions on the spawning areas are the second most key parameter for this development stage but depending on the type of watercourse. The current velocity measured at the substrate bottom in spawning grounds must range between determined values. The third major parameter is the ecological connectivity of the river. At the scale of the river basin, the free access by spawners to all the suitable spawning areas of the headwater is a main factor for the spawning success.

yolk-sac alevins (incubation phase)
The parameters determining the survival during subgravel phases between hatching and emergence in the redds are the quantity of fine sediment, the discharge variability and the water quality in relation to homogeneous conditions of water temperature and oxygen rate.
Large quantity of fine sediment results in silting of the spawning areas and hypoxia in redds. The impact of the fine granulometric fractions has been largely demonstrated resulting in large egg mortalities which are lower in granitic streams than schisteous rivers [11]. The quantity of deposited fine material can be simply assessed by

screening. A proportion of fine material in sediment higher than 20-25% (20%), corresponds to a very critical threshold for this stage [12], [4].

The depth of burial has no direct impact on survival at hatching, but could influence the dynamics of emergence.

Variations of water flow during low water periods can induce redds dewatering leading to egg mortalities. Furthermore, the number and the intensity of floods and their timing are major important pressure factors in the spawning success [13], [11]. Strong floods that disrupts the substrate decrease the under gravel survival through destruction of spawning grounds (notably floods with a frequency of recurrence of 5-10 years).

Excessive levels of nitrogen in the interstitial water can cause over mortality [11].

Alevins (0+)

The major parameters acting on the survival of alevins are the occurrence of strong spates during the post-emergence period and the amount of available and suitable habitat. The two other major parameters are ecological connectivity and temperature.

Strong spates during the post-emergence period leads to increased mortality in alevins [14], [15], [16], [17], [18], [19-21]. In addition, habitat quality measured at the base discharge (discharge before the arrival of spate) or the discharge amplitude between the spate peak and the base discharge are parameters that influence the extent of the flooding impact on this development stage of [22], [23]. These phenomena have been observed on the macrohabitat scale and are synchronous on the spatial higher scale (river stretch and region [24]).

At the scale of the catchment area, development of the 0+ stage can be impacted by fragmentation of the environment (no more connected habitats) affecting the dispersion of individuals, especially in the case of a limited carrying capacity. In fact, fragmentation reinforces the intraspecies competition (within and between age classes), could affect the habitat use [25] and modify mortality and growth that are density-dependent. At the stretch scale, instable environments and fluctuating water levels can also lead to low colonization of suitable habitats. Changing discharge has a negative effect more specifically during night and emergence time, as the alevins choose habitats with very low water depth [26].

Water temperature has a direct effect on the survival and the size in alevin since hatching, and on growth in young of the year during the first growth season [10]. Three temperature ranges have been distinguished for the growth [27-29]: an optimal range (4-19°C), a low-temperature critical range (0-4°C) and a high-temperature critical range (19-30°C). The threshold of 7°C below which growth is low is however applicable to the genus *Salmo,* in contrast to the genus *Salvelinus* (Baglinière, personal communication). The thermic preferenda curves given by Bovee [30] show that critical values for high temperatures are similar to those obtained from experiments in a controlled environment [31]. Effects of this parameter have been observed at the stretch scale in trout populations in Lower Normandy rivers [32].

Juveniles (1+)

The major parameters used for characterizing this development stage are the cohort abundance of the previous year and the ecological connectivityt.

In river including successive spawning and growing habitats, 1+ fish densities are strongly dependent on the 0+ fish densities present the previous year. In river where the spawning and growing zones are separate and/or the growth rate is high (notably Normandy and Brittany rivers), density between the two age classes is still correlated [33]. Nonetheless, this relation can be less apparent for two reasons: *i)* migration within the river system and/ or into to the sea, and *ii)* the contribution of the age class to the recreational fishing during their second year of life due to a high growth rate.

Ecological connectivity plays an important role in the dispersion and level of abundance as many movements or migration in brown trout within and outside (estuary, sea) river system occur at the 1+juvenile stage[5].

Adults (>1+)

Major parameters affecting abundance at this stage are: suitable habitat conditions, presence of shelter and the ecological connectivity. However, high rate of suspended matter, water temperatures above 20°C, poor water quality and significant fishing pressure also could impact this development of this stage, but have not been considered here.

Parameters type	Spatial scale	Parameters	Characteristics	Eggs	Yolk-sac alevins	Alevins 0+	Juveniles 1+	Adults >1+	Anthropic factors
Physical chemistry	Reach	Temperature			1-15°C	<17°C	<17°C	<21°C	Change in water quality
		Water quality	Oxygen		> 10 mg/l				
			Nitrogen		NQ				
Physical environment	Micro-habitats	Gravel substrate	Diameter	1-10 cm					Interruption of solid transport, cladding, deepening
			Thickness	5-10cm					
			Surface	Optimum ≥5%					
			Mobility	NQ					
		Fine sediment	Diameter		> 2 mm				
			Level of fines		< 20%				
		Suspended matter							
		Burial depth			NQ				Flow change
		Shear force			10-100 N/m2?				
		Substrate							Change in flow and solid transport
		Water height		10-50 cm					
		Speed		15-70 cm/s					
	Facies	Variation of water level				NQ			
	Sequence	Habitat				Habitat at the base flow rate			
	Reach	Shelter							Rectification
	Catchment area	Connectivity		Potential reproductive area		NQ	NQ		Fragmentation of the habitat
Hydrology	Reach	Flooding	Frequency		5-10 years	Daily max. rate during post-emergence			Climate change
			Amplitude		NQ				
			Seasonality		NQ				
	Reach	Low water	Duration						Climate change
			Amplitude						
Fisheries management	Reach	Fishing pressure							
		Restocking							
Biotic parameters		Competition/Predation							
		Population dynamics	Cohorts the previous years				NQ		

Table 1: Factors influencing the different development stages in the function of the Brown trout populations

3.3 Criteria for overall function of populations

A global consensus emerged on the difficulty for identifying robust criteria allowing the precise assessment of the function of trout populations in terms of abundances, biomasses, population structure, and habitat use (occupation rate). There is the same incertitude for assessing the viability of the population, namely the minimum number of fish necessary to ensure the self sustanaibility of a population. However, independently of the demographic / life strategy adopted by the trout population or its individuals (migration vs. residency) , a density of (0+) juveniles between 30 and 50 ind/100 m² in the apical areas of headwaters has been proposed as a criterion for suitable function or for good health of the population (Baglinière, personal communication). Criteria on for the distribution of size-structured abundances are also necessary to get a “functional” picture of the “metapopulation”.
Otherwise, it emerges that, whatever the type of environment, the most vulnerable stages are the young stages. In fact, adult fish abudance (>1+) is mainly limited by the available and suitable habitat when recruitment is significant.
Conversely to biological criteria, current knowledge allows ecosystem function to be assessed through the selection of physical environment criteria. This selection must be based on the physical determinants that are necessary to explain the dynamics and function of the population. Although thresholds cannot be defined for all the key environmental parameters identified, knowledge is available for some major parameters and its unfluence level on populations.

4 CONCLUSION

4.1 Methodological limits

The limits of the exercise come undoubtedly from the fact that the criteria have been defined by a handful of experts and reflect the opinions of only a part of the scientific community. Nevertheless, the approach has the advantage to do emerge a consensus from a large amount of scientific results available in the literature on the biology of the trout and the major function parameters, and more particularly those necessary for assessing the function of a trout population.
In a subsequent phase, it should be envisaged:
i) to submit the chosen criteria to other French and foreign scientists (consultation by post or during a wokshop). As the experts present here are specialist on the influence of physical parameters on biology, the approach should be supplemented with experts in other areas (physiology, genetics, etc.). The results could also be compared to the views / opinions of managers charged to assess the function of ecosystems in order to incorporate a broader spectrum of basic and applied knowledge.
ii) to carry out an experimental approach for testing the chosen criteria and for checking its reliability in natural conditions

4.2 Nature of the criteria obtained

It emerges from the seminar that, in the present state of knowledge, a diagnosis can only be established based on the physical parameters crucial for biology (and with greater difficulty, on the biological parameters). For all development stages, the parameters identified are the habitat (with special attention given to the substrate, discharge, water temperature and quality), the hydrology conditions and the ecological connectivity.

However, in a first step, the same exercise could be carried out using a shared analysis on biological monitoring implemented over sufficient periods (>5 years) and in varied physical environments. Such a exercise should probably allow to obtain quantitative criteria for these biological parameter..
In a second step, the environmental parameter values unfavourable for the populations might be identified via multi-site analyses to complete this type of diagnosis. While the trends in population evolution in relation to these parameters are known at present, general models have to be developped to known ing thresholds values of some major acting parameters such as amplitude and gradients of disturbing spates thermal tolerances, habitat fragmentation level, etc.
Comparison between physical processes reflecting various degrees of alteration and population structures might improve our understanding on function of the populations. New information is essential to improve the diagnosis based on physical parameters, which does not reflect the variability in responses of populations as a function of the degree of alteration, the importance of the physical context and the compensatory phenomena that emerge. Acquisition of this more detailed understanding of mechanisms is necessary to identify the foundations for restoration activities. This is why the Water Framework Directive puts biology at the centre of the initiative. In order to meet this challenge, it is ultimately necessary to establish biological criteria and not restrict only to the physical criteria even crucial for biology. Further research must be initiated to understand the variability in biological parameters, the spatiotemporal scales involved and the functional processes.

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