The Spanish Experience in Determining Minimum Flow Regimes in Regulated Streams

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ABSTRACT

The state–of–the–art in habitat modelling in the context of minimum flow requirements in Spanish rivers is presented. During the last decade Spanish Water Authorities, by law, had to include evaluations of 'ecological flows' (considered as minimum instream flows) in their water planning. Most of the 'ecological flows' determinations have been based on historical flow records (10% mean annual flow or flow frequency distribution) with no serious limnological considerations. However, as environmental awareness increased, Spanish Water Authorities and natural conservation institutions have promoted studies on instream flows based on different methodologies. Palau and Alcazar (1996) proposed a method based on the application of the simple moving average forecasting model as a tool to obtain the information of minimum flows from historical daily flow records. In the Basque country, Docampo and de Bikuña (1995) developed a peculiar method based on the hypothesis that macro–invertebrate communities change along the river *continuum*. For each watershed, they have elaborated empirical relationships between the number of benthic species, the channel wetted perimeter and the instream flow, and it is assumed that the minimum acceptable flow is the one that is able to maintain at least 15 different species. Our laboratory has been working on flow requirements in streams and rivers based on habitat modelling through Instream Flow Incremental Methodology (IFIM). More than 100 stream reaches in Spain have been studied, analysing bed topography, hydraulic, substrate and refuge conditions, natural flow regime and aquatic communities composition, phenology and habitat requirements. Relationships between instream flows and potential useful habitat were established using 1 and 2–D hydraulic models, together with the habitat requirements of key indigenous fish species and macrobenthic diversity. Minimum flows were determined by selecting those flows that produced the greatest rate of habitat change. The evaluation of the potential habitat produced by natural flow regimes was used to understand the life strategy of autochthonous fishes and their flow requirements. Variability of the natural flow regime was found to be the main factor structuring stream types. In torrential Mediterranean streams, basic flows were ecologically nonsense because the stream channel is too large relative to the wetted channel produced by modal flows. Here, fisheries life strategy is migration

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and, therefore, minimum flows must be calculated at a scale larger than that of stream reach. Minimum flows, natural flow regime and the habitat requirement of native fish species at different scale, are the components used to the proposal of an 'ecological flow regime' for each river reach.

RÉSUMÉ

L'état des connaissances en modélisation des habitats dans un contexte de débits réservés en Espagne est présenté. Au cours de la dernière décennie, l'Autorité espagnole de l'eau est légalement responsable de l'inclusion de «débits écologiques» (considérés comme les débits réservés minimums) dans la planification des ressources hydriques. La majorité des débits minimums écologiques ont été estimés à partir des séries chronologiques historiques (10% du débit annuel moyen ou par analyse fréquentielle des étiages) sans qu'il n'y ait de considérations limnologiques associées à cette évaluation. Cependant, avec l'avènement d'une conscience environnemental accrue, l'Autorité espagnole de l'eau, de concert avec d'autres institutions de conservation, ont fait la promotion d'études sur les débits réservés qui utilisent d'autres méthodes. Palau et Alcazar (1996) ont proposé une méthodologie basée sur la mise en oeuvre d'un modèle simple de prévision avec moyenne mobile comme étant un outil permettant d'acquérir l'information sur les débits d'étiages à partir des séries chronologiques de débits. Dans le Pays Basque, Docampo et de Bikuña (1995) ont développé une méthode basée sur l'hypothèse que les communautés de macro–invertébrés changent en fonction du *continuum* (amont–aval) des cours d'eau. Pour chaque bassin versant étudié, ils ont élaboré une relation empirique basée sur le nombre d'espèces benthiques présentes à l'intérieur du périmètre mouillé et le débit réservé. On cherche à définir ainsi un débit réservé considéré suffisant pour permettre de maintenir au moins 15 différentes espèces. Notre laboratoire utilise la méthode IFIM pour étudier les débits réservés. Plus de 100 tronçons de rivière en Espagne ont été étudiés. La bathymétrie du lit des cours d'eau, le courant, le substrat, la disponibilité des refuges, les conditions naturelles de débit, la composition des communautés aquatiques, et les besoins en habitat ont été étudiés. Les modèles 1–D et 2–D, de concert avec les courbes de préférence d'habitat d'espèces autochtones clés et des mesures de diversité des macro–invertébrés ont été utilisés pour établir la relation entre les débits réservés et les aires pondérées utiles d'habitat. Les débits minimums étudiés sont ceux qui produisent le plus de changements d'habitat. L'évaluation du potentiel d'habitat produit par les apports naturels est utilisé pour mieux comprendre les stratégies de survie de plusieurs espèces autochtones de poissons, ce qui permet ensuite d'établir leurs besoins en terme de débits. La variabilité du régime est le fateur prépondérant qui structure les différents types de cours d'eau. Dans les cours d'eau torrentiels de la région méditerranéenne, un débit de base n'a pas de sens écologiquement puisque les débits modaux produisent des chenaux très larges par rapport au périmètre mouillé. Dans ces sites, la stratégie de survie des poissons repose sur les migrations, ce qui implique que le débit réservé doit être établi à l'échelle de plusieurs tronçons plutôt que pour un site donné. Les débits d'étiages, le régime hydrique naturel et les besoins en habitat des espèces autochtones de poisson sont les composantes utilisées afin de proposer un régime de débit écologique pour chaque tronçon de rivière.

INTRODUCTION: THE HISTORICAL PERSPECTIVE

Spain is a dry country where streamflow regulation is intensively managed (Garcia de Jalón, 1987) through an important hydraulic infrastructure that includes more than 1200 large dams. The traditional answer of the Spanish Water Authorities (called 'Confederaciones Hidrográficas') to the scarcity of water and water demand has been to build new dams and operate water transfers.

Initially, minimal flows were considered in 1949 in the Spanish Fisheries Law, determining for fish scales flows below dams from 1 to 30 litres per second. The 1986 *Water Act* established minimum ecological flows. This was considered as another water use, competing with traditional uses such as irrigation, urban and industrial supply. The importance of social and economic resources involving the water distribution process, together with historical water rights, has produced instream flow values without any significant consideration of environmental impacts.

The intensity of stream regulation effects (García de Jalón *et al.*, 1992) and the increase in environmental awareness of Spanish society are forcing changes. In 1999 the Water Law was modified, and minimum ecological flows were no longer considered a water use, but a general restriction imposed prior to any other use. Also, the European Water Framework Directive (WPD) in 2000 introduced changes in the way of perceiving the ecological status of water ecosystems. In this sense, WFD has the objective of obtaining a good ecological status in rivers, based on biological indicators, physico–chemical characteristics and hydro–morphological condition. The last criterion includes the river flow regime.

In Spain there is a legal requirement for ecological flows implementation but its definition, in quantity and temporal pattern, has not been accurately fixed (Manteiga and Olmeda, 1992). During the last decade 'Confederaciones Hidrográficas' had been forced by law (Ley de Aguas, 1986) to include in their Water Planning quantitative evaluations of 'Ecological Flows' considered as minimum instream flows. Due to the Confederaciones Hidrográficas' lack of personnel with limnological knowledge, most of the 'ecological flow' determinations have been based on historical flow records (10% mean annual flow, or flow frequency distribution) with no serious limnological considerations. Nevertheless, a few water managers have realized the importance of developing a methodology to determine minimum ecological flows based on biological data. Their efforts were the first attempts to apply Instream Flow Incremental Methodology (IFIM) to determine ecological flows on Spanish rivers (García de Jalón, 1990; Cubillo *et al.,* 1990), and even the development of other new methodologies (Palau, 1994; Docampo and de Bikuña, 1995).

Palau and Alcazar (1996) proposed a method based on the application of the simple moving average forecasting model from historical daily flow records. They hypothesized that river ecosystems are organized and self–regulated in a manner similar to living organisms. As life is organized and transmitted by information arranged in DNA genetic code, streams are organized by flow time series. They found in Catalonian rivers a characteristic minimum flow, called Basic Flow, using natural stream flow time series. These minimum flows were computed applying moving averages to increasing intervals of consecutive daily flow records, up to a maximum of 100 days per year. For each day interval a mean annual minimum moving average (MAMMA) is determined; and among these MAMMA values, the one that produces a greater relative increase between day intervals was selected as the Basic Flow.

In the Basque country Docampo and de Bikuña (1995) developed a peculiar method, adapted to Basque country streams, based on the hypothesis that macroinvertebrate communities change along the river continuum. For each watershed they elaborated empirical relationships between the number of benthic species the channel wetted perimeter and the instream flow (expressed in terms of geometrical mean), and it is assumed that the minimum acceptable flow is the one able to maintain at least 15 different species. As IFIM became popular around the world, Spanish water authorities and natural conservation institutions have promoted studies on minimum instream flows based on this methodology. The experience accumulated working in about hundred stream reaches in Spain in order to evaluate their minimum ecological flows and environmental flow regimes is presented in this paper.

ECOLOGICAL FLOW REGIME VS. ECOLOGICAL FLOW

For many years and still today Water Authorities use the expression 'ecological flow' in water legislation, as a single value of flow but without any definition. In reality, the use of this concept refers implicitly to a minimum flow, which allows preserving environmental conditions. Natural regimes have flow fluctuations according to the hydrological behaviour of watersheds, and sometimes these natural annual flow variations are the main factors conditioning the geomorphological and biological characteristics of rivers.

It is clear that the term 'ecological' should be applied not to a single value of flow, but to a pool of flow values which follow a variation pattern similar to the natural regime. Accordingly, we have proposed to change the expression 'ecological flow' to one which includes natural flow fluctuations: the 'ecological flow regime'. In a similar way Petts (1996) proposed 'ecologically acceptable flow regimes' for England and Wales streams. The ecological flow regime can be defined as the 'artificial' flow regime that maintains the species composition, the communities structure and the functions of the fluvial ecosystem that exist under natural conditions. This ecological flow regime should preserve the main ecological functions that achieve natural flow regimes (Poff *et al.*, 1997), although we may be more interested in their extreme values. Minimum flows must be evaluated with precision, due to the scarcity of water and its economical importance. Maximum flows are also important for fluvial dynamics, sedimentation and fish habitat.

METHODOLOGY

In Spain, the methodology IFIM–PHABSIM has been applied in many rivers to design ecological flow regimes. This methodology is used worldwide and there are many types of software available to facilitate its application (e.g. Rhabsim (USA), Rhyahabsim (New Zealand) and River–2D (Canada), and CAUDAL–SIMUL (Mayo, 2000)).

Flow and Habitat Requirements

The habitat requirement of the aquatic community is defined by an 'indicator species' whose habitat needs represent or envelop those of the whole community. We generally select as an indicator a large native fish species of the stream reach that is at the top of the trophic pyramid (trout, barbell, salmon, nase). Only in temporary or torrential streams, which naturally do not sustain any fish species, we have used macroinvertebrates as indicator species. In the physical habitat we distinguish two main components: the channel structure, (types of bottom substratum and quality of refugee), that for a range of low flows is relatively independent of instream flows; and the hydraulic conditions (depth and velocity), which are flow dependent. As we are using this IFIM–based methodology to evaluate ecological flows, and not to predict fish densities or biomass, we are interested only in the physical habitat that is controlled by instream flows.

The density of an aquatic population in a stream reach is determined by both physical and biological factors. While flows can change almost instantaneously, changes in a population have an inertial delay due to the time of biological processes (reproduction, recruitment, growth, mortality). Thus, we consider the 'weighted useful area' as a value of the potential stream habitat independently occupied or not. Using one– and two–dimensional hydraulic simulation models and habitat requirements of the main indigenous fish species, and also macrobenthic species, relationships between instream flows and potential useful habitat (or weighted useful area) were established.

For some Iberian endemic species, barbell (Barbus bocagei), Iberian nase (Chondrostoma polylepis) and Iberian chub (Squalius pyrenaicus), preference curves were developed (Martínez–Capel and Garcia de Jalón, 2002).

For a given species different life stages have different habitat requirements (represented by different preference or suitability curves). Thus we obtain different WUA–Instream Flow relations for each development stage. At this point a question arises: which stage must we use to determine the instream flow? Obviously the answer should be the one with the highest requirements. In order to answer this question we must compare habitat values for each flow (Figure 1a).

However, we must realize that these habitat values for adult, juvenile, fry and spawning even though all are expressed in the same unit (m^2), they are not equally needed for the maintenance of the population. An adult needs more space (home range) than other development stages, but also in a stable population they are less numerous than younger stages. Bovee (1982) has proposed a transformation coefficient for brown trout that we have adapted. An example of the transformed curves is presented in Figure 1b. Indeed, this is an area that needs further study and research. Generally, adults requirements are those of greater habitat demand. In few cases spawning habitat demands are the critical ones, and their flow requirements should be incorporated during the spawning months (December to March in salmonids, and March to July in cyprinids). In small streams inhabited by fish with migratory behaviour, adult demands are considered critical only during reproduction periods, while juvenile or fry demands are considered critical for the rest of the year.

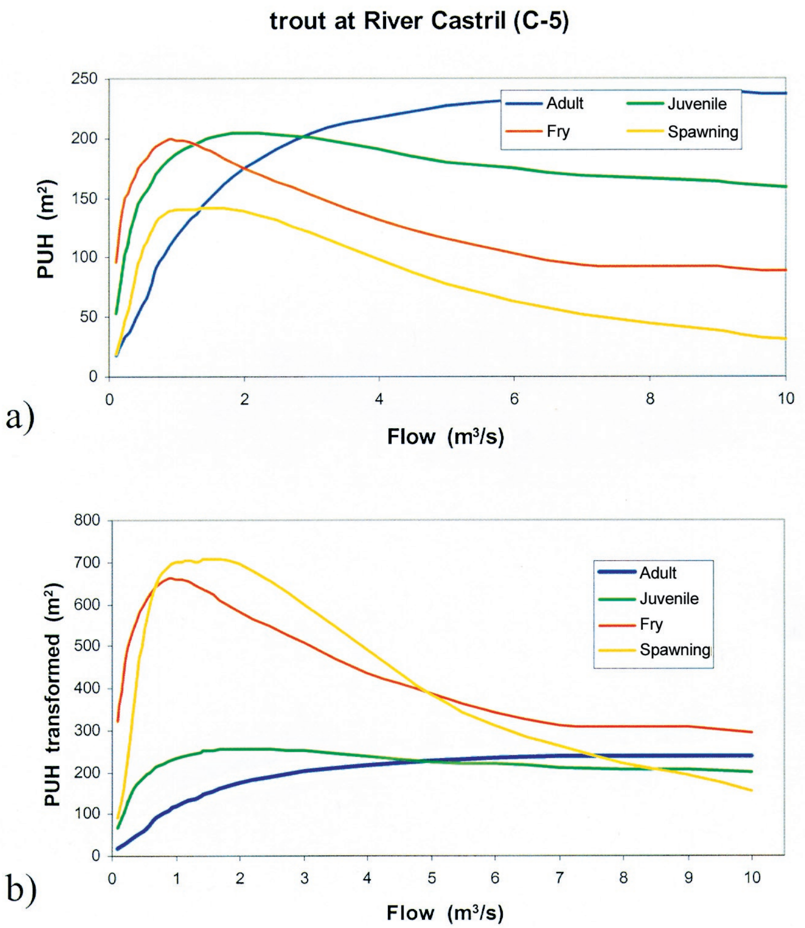

Figure 1. Curves that Relate Potential Useful Habitat (or WUA) with Instream Flow for Different Trout Development Stages: a) PUH Expressed in Different Developmental Stages. b) PUH Expressed in Adult Unit Area, After Transformation. It can be Appreciated that Adult Curve is the Most Exigent in the Adult Transformed Unities (Juvenile/Adult 0.8; Fry/Adult 0.3; Spawning/Adult 0.2).

Minimum Flows Determination

Criteria for minimum flows were determined by selecting in the habitat–flow curves, those flows where the greatest rate of habitat change occurs for the more exigent stage development (García de Jalón, 1990; Mayo *et al.*, 1995). Analyzing the curves that represent these relationships between potential habitat and instream flows, we have frequently found a typical shape shown in Figure 2a. The potential habitat value increases with flow very rapidly, until the stage where the slope smoothes and the curve eventually reaches its maximum value.

Two flow values can be defined in these curves, with ecological meaning (see Figure 2a):

- **Basic Flow:** is the minimum flow needed for the conservation of the communities. At lower flows than basic flow, the potential habitat decreases sharply, while for greater values the habitat increases only slightly. Different development stages with particular habitat requirements may lead to basic flow variations through the year.

- **Optimum Flow**: is the instream flow that produces a maximum value of potential habitat. Obviously, it is the reference flow for ecological enhancement.

Often it is difficult to fix a single basic flow because there is a transitional segment of the curve between the high gradient part and the low slope part of the curve. In these cases it is useful to determine segment extreme values, designated as low and high basic flows. We will use this distinction later, in order to determine ecological flows in humid and dry years.

As a practical approach we use three criteria in order to select a Basic Flow value:

i. **Relative changes in slope:** searching for the point from which the slope decreases. This can easily be analyzed using the derivative curve (Figure 2b).

ii. **Minimum absolute slope:** searching for the flow that corresponds with a slope value (derivative) significantly low (100 s/m). This criterion generates a value of the Basic Flow that can be considered as a minimum threshold.

iii. **Optimum flow proportion:** often Basic Flows generate a WUA value close to the maximum value reached by this curve. Taking into account that native species have evolved in the stream in which they live, adapting their habitat requirements to those conditions provided by most frequent flow range, this should not be surprising. For practical purposes, we have defined a criterion as the minimum flow value that produces a WUA that is 75% of the maximum value of the curve WUA/Q (Figure 2).

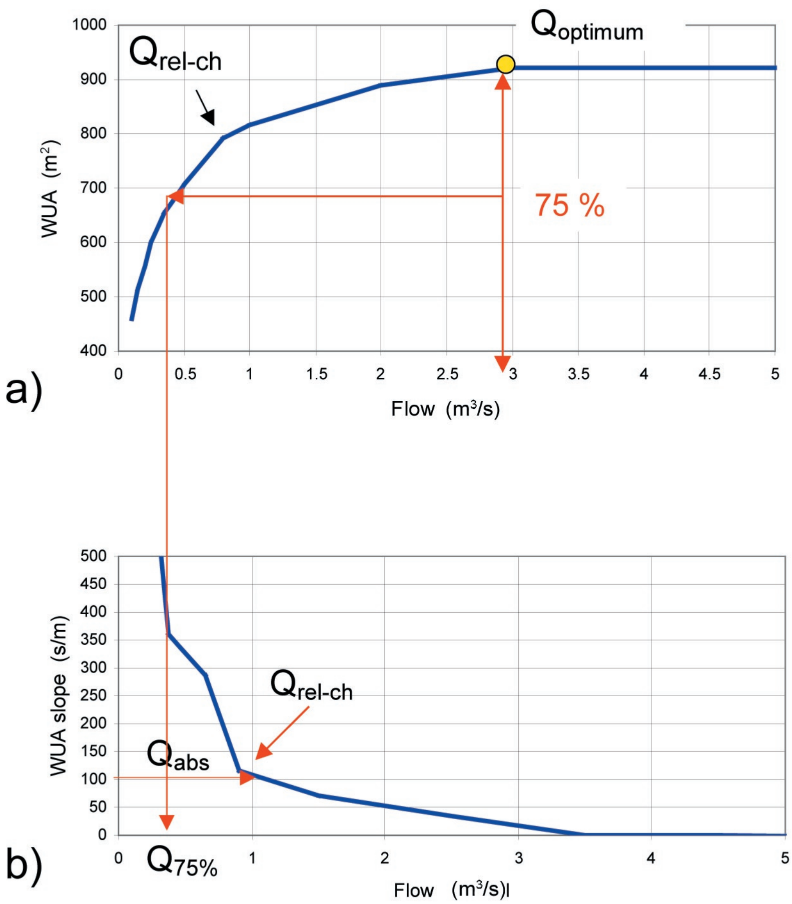

Figure 2. Criteria Used to Select a Minimum Ecological Flow or Basic Flow in the Relationship Between Potential Habitat and Flow (a). The First Criteria is the Flow (Q75%) that Corresponds to 75% of the Maximum Habitat Availability. The Derivative Curve (b), Representing the Slopes of the Former One, is Used to Jelp with the Selection Based on the Change of Slope Criteria ($Q_{rel\ ch}$) and With the Absolute Value of the Slope (100 s/m) one (Q_{abs}).

CHANNEL MAINTENANCE FLOWS

Because of flow regulation high frequency floods below the dams are usually of less importance than in natural conditions and the channel size is reduced and invaded by riparian vegetation. This implies important modifications of the physical habitat provided by the river. In order to maintain or to restore the channel dynamic processes, the ecological flow regime should include flood events that correspond to the bankfull discharges.

We determine bankfull discharge flows from natural daily flow records, analyzing annual maximum flows adjusting a Gumbel distribution. For streams in the north, centre and west of Spain, bankfull discharges have a recurrence of 1.5 to 2 years. For temporal or more torrential rivers in arid watersheds, bankfull discharges are found at larger return period (5–8 years). If the stream is slightly regulated, or is regulated recently, bankfull discharge can be estimated from cross–sections and hydraulic model application.

ECOLOGICAL REGIMES

Habitat and instream flow requirements vary with seasons. For example spawning and embryo development periods require a certain level of flows without floods. During summer with critical high water temperatures, salmonids require swift water currents (and thus higher flows) in order to compensate lower dissolved oxygen. The annual and seasonal variability of the natural flow regime was found to be the main factor structuring stream communities, especially controlling the biotic answer to minimum flow conditions.

Thus, we need to define an ecological regime of flow. This regime may be established in two ways: a) taking into account the needs of the selected indicator species, assuming different flow requirements of their development stages; b) taking into account the needs of the indicator species only for annual critical conditions in the dry season and giving a flow fluctuation proportionally to natural flow regime for the remaining seasons. This instream flow strategy of imitating nature is because of the selection for native species, and also for the maintenance of geomorphic processes and the conservation of biological integrity.

The procedure consists of using the mean monthly flows of the natural regime as the pattern of flow fluctuation, fixing the value of the basic flow to the minimum monthly flow. The flows for the remaining months in the ecological regime are adjusted by proportional reduction of the natural regime.

FLOW REGIMES IN MEDITERRANEAN STREAMS

Mediterranean streams have natural regimes with an important torrential component that is reflected in strong seasonal and interannual fluctuations. This last fact is also considered on the proposal of ecological regimes, as native species have evolved under these torrential conditions, and are adapted to them (Gasith and Resh, 1999).

Under regulated conditions Mediterranean stream species cannot compete successfully with many introduced (generalist and limnethic) species (García de Jalón *et al.*, 1992; Morillo *et al.*, 2002). In order to favour native species, we adapt the ecological flow regimes of the streams, to the characteristics of the hydrological year. During dry years the ecological regime is built using 'low basic flow' as preference for the driest month, while during humid years it is determined using the 'high basic flow'. Both regimes fluctuate in a similar manner to the natural regime (Figure 3).

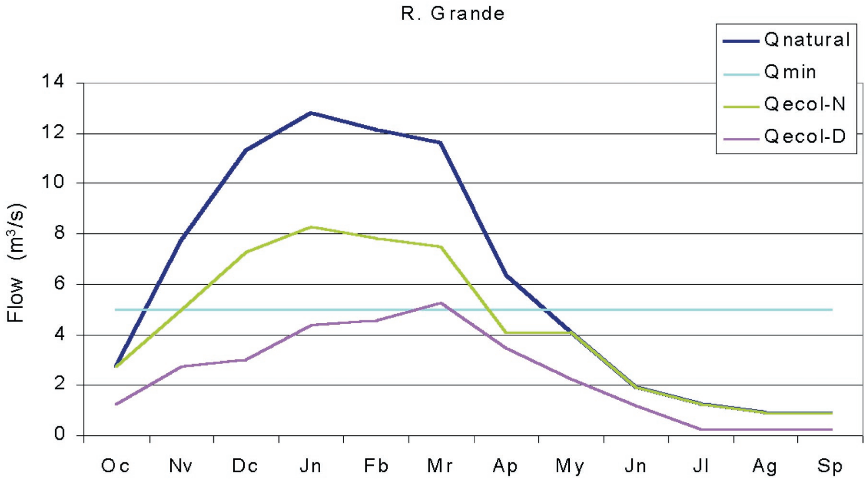

Figure 3. Mean Monthly Flow Regimes in River Grande at Cartama (Malaga) Describing: Natural Regime; Basic Flow; Ecological Regime for Humid and Dry Years. This is a Torrential Temporary Stream with a Large Channel and its Basic Flow is Greater than Natural Flows during Summer Months. Therefore, Its Ecological Regimes Coincide with Natural Ones during those Months. In order to Conservate the Composition, Structure and Function of the Stream Native Communities Drought Conditions Must be Maintained.

Streams with very intense torrential characteristics in the semi–arid regions of southeast Spain) have a natural seasonal flow fluctuation during dry years that follows different patterns than in normal years. Generally this fluctuation is less marked and their maximum values tend to be delayed from February–March in humid years to March–April in dry years. Thus, in this type of stream we design Ecological Regimes for dry years following a fluctuation pattern proportional to that occurring in dry years. We define dry years in these streams, as those with a mean annual flow less than half of the average for whole series. On stream reaches below dams, the consideration of dry years may be done by the evaluation of the reservoir–stored water quantity.

The natural flow regime in the streams that drain semiarid basins present marked summer low flows and frequently the channel is completely dry during one or several months. In these streams monthly average flows during summer are lower than basic flows. This is possible because the channel size is a consequence of bankfull discharge, while basic flows are calculated through the channel morphology and the amount of habitat represented. As bankfull discharge is relatively huge compared to the normal or modal flows, the stream channel is too large to be wetted by modal flows. Thus fish living in these rivers have a life strategy based on temporal migration and, therefore, minimum flows must be determined from a scale larger than the stream reach.

In these semiarid streams we have defined the ecological regime leaving the natural flows for the months in which values are lower than the basic flow. For the remaining months the ecological regime imitates natural fluctuation but the monthly mean values are reduced by the coefficient obtained from the ratio of basic flow to mean annual natural flow.

LOOKING AHEAD

The design of ecological flow regimes allows the implementation of environmental water planning related to water abstraction schemes or inter–basin water transfers. Spanish water authorities are planning to establish these ecological flow regimes downstream of the main dams, according to the methodology presented above.

Due to the fact that we are not able to apply this methodology to every stream reach, an extrapolation tool was developed. Baeza and García de Jalón (1997, 1999) have classified stream reaches of the Spanish Tajo basin according to their hydrological, geological, climatic and topographic characteristic. For each stream type class, models for predicting minimum ecological or basic flows were developed.

However, today in Spain there are many reaches without enough instream flows, and it is not possible to implement ecological flows there because the water rights have been given. These water concessions are often excessive and their capacity is long term (duration time is more than 60 years). Therefore, these water rights are incompatible with any ecological flow regime, and only through public expropriation an ecological regime can be applied. Only in unregulated streams, under new planned reservoirs and water abstractions works it would be possible to apply these ecological flow regimes. In fact, at present no ecological flow regime has been applied in Spanish river or stream reaches.

When exploitation schemes produce flows that are higher than minimum ecological flow regime (in certain stream reaches below dams), the real flow conditions (observed regime) present great differences with natural flows (Figure 4). The effect of high summer flows in rivers with natural dry or very low natural flows have completely changed fluvial communities, favouring introduced species that have especially impacted native fish species. Therefore, it is not only a question of minimum instream flows that must be maintained following the ecological regime, but also a question of maximum instream flows that should not be reached, especially during the natural dry season.

One may conclude that theory and practice differ and we must consider a different approach. In order to achieve more water flowing in the rivers, it would be more efficient to evaluate the actual instream flows, compare them with the natural flow regime, and apply the principle of 'who regulate flows must pay'. Richter *et al.* (1997) proposed different quantitative parameters that can be used to characterize a natural flow regime from their biological significance. These parameters can be used to quantify the deviation of the regulated stream flow regime from its natural one. This is an alternative environmental method for managing instream flows as it includes a negative feedback mechanism: the greater the flow regulation intensity, the more must be paid.

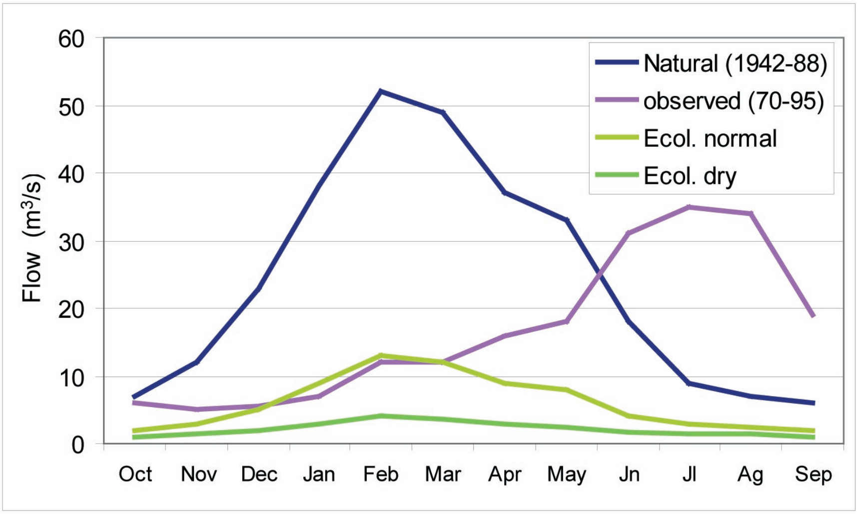

Figure 4. Mean Monthly Flow Regimes in River Genil at Puente Genil Describing: Natural Flows (Simulated); Natural Dry Years (Simulated); Observed (1979–1995); Ecological Regime for Humid and Dry Years. It Shows the Great Difference Between Real Conditions (Observed Regime) and Natural Flows, Even Though Ecological Regimes are Complimented. The Effect of High Summer Flows have Completely Changed Fluvial Communities and Native Fish Species have been Impacted by Introduced Ones.

Finally, it must be considered that the resilience of fluvial systems (the capacity to recover from disturbance) diminishes as their flow regulation intensity increases. And, thus, the ecological flows that must be maintained below a reservoir or on diverted reaches should be increased if new reservoirs and water transfers are built in the basin.

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