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Basin influence on natural variability of rivers in semi-arid environments

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ABSTRACT

Scientific evidence indicates that freshwater aquatic ecosystems can be protected or restored by recognising that dynamic flow patterns must be maintained within the natural range of variation to promote their integrity and sustainability. An evaluation of the required conditions for healthy functioning needs to begin with a description of natural streamflow patterns.

In order to characterise the flow regimes of a group of rivers located in central Spain, data was taken from 25 gauging stations in a major river basin to establish a hydrological grounding upon which to base biological studies. A number of basin variables were also obtained, and this paper considers the relationships that exist between relevant ecohydrological indices and these basin characteristics.

Special importance has been attached to low flow characterisation, since these situations are important determining factors for the development and evolution of biological populations. The results show a significant relationship between one of the low flow indices and basin lithology, evapotranspiration and river basin size. Finally, two models have been found which allow low flow volume values to be estimated from these river basin variables. These models can be used to obtain low flow values in river basins where gauging stations do not exist.

Keywords: Hydrological parameters; basin lithology; drought management; low flow models.

Introduction

The paradigm of natural flow regimes, as described by Poff *et al.* (1997), shows the need to maintain or restore the natural range of intra and interannual variation of hydrological regimes as a fundamental element for protecting aquatic ecosystem integrity, especially in the case of fluvial ecosystems.

For this purpose it is necessary to describe several components of river regimes by means of hydrobiological indices. Processes in fluvial ecosystems are generally considered to be regulated by five components: magnitude, frequency, duration, timing, and rate of change (Poff and Ward, 1989; Richter *et al.*, 1996; Olden and Poff, 2002). River regimes and their relevant events can be described by calculating hydrological indices derived from these components, which must adequately represent the main facets of the regime and the events that determine the biological cycles of species, geomorphological processes, and the transportation of nutrients and sediment.

Since water demand for human uses increases day by day, a growing number of rivers, streams and torrents are regulated and their flows modified (García del Jalón, 2003). As a result, many of the ecological characteristics of their regimes are modified and it is necessary to know how these changes are affecting the integrity of fluvial ecosystems.

In order to maintain ecosystem integrity it is firstly necessary to carry out studies that describe each particular hydrological regime, followed by other studies that evaluate the severity of the impacts caused on our rivers by human intervention.

The literature includes a number of papers which not only describe river regimes by means of indices but also seek to establish relationships between these indices and aspects of the physical environment that affect hydrological regimes, such as the basin characteristics. There are also many papers that measure the degree of deviation from the natural state due to a particular intervention, such as a dam or water transfer; a very common situation in our country (Ibáñez *et al.*, 1996; García de Jalón *et al.*, 1992). On the other hand, research is also being carried out into the relationship between particular flow regimes and the biological communities that inhabit the river stretches where these regimes exist. Such studies serve to establish how far regimes can be deviated from their natural state without irreversibly altering the dynamics of the fluvial environment, maintaining the natural biodiversity, development potential, and the state and diversity of the fluvial habitat.

During a time the hydrologic analyses used a very few parameters and without a suitable biological relevance, something frequents in Spain (Baeza and García de Jalón, 1997; Palau *et al.*, 1998), nevertheless at the present time a great amount of hydrologic indices are available and the challenge is to choose the most suitable type to adequately describe the main aspects of the flow regime (Olden and Poff, 2002).

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Another interesting aspect to which great importance is currently being attached is the grouping of rivers or river stretches in regions that share physical qualities. This is useful for implementing common management strategies and ecosystem conservation management. These regions or ecoregions share geographical, morphological, climatic and hydrological aspects that can be defined by measurable parameters.

To classify a stretch of river in one group or another it is firstly necessary to decide what characteristics and ranges are to be used as the criteria for defining each region. Considering that these parameters must have a hydrological and an ecological base, it is necessary to address the relationship between the physical environment, the hydrological regime (Baeza and García de Jalón, 1998; O'Shea, 1995), and the affected biological populations in order to choose the most appropriate characteristics to define these ecoregions.

Cataloguing natural bodies of water in regions that share physical environmental characteristics is one of the objectives that the Water Framework Directive sets out for all European countries (Ariño *et al.*, 2002). The aim of the Directive, with regard to the conservation of fluvial ecosystems, is to improve their ecological state. For this purpose, the European area needs to be divided into ecoregions (Prat *et al.*, 2000) and reference conditions need to be established which define the good ecological state of rivers, so that all river stretches may be brought up to the ecological reference state that characterises their ecoregion. Thus it is necessary to find the physical environmental variables that define each ecoregion and subsequently to assess the degree of ecosystem naturalness from a biological viewpoint, in order to ascertain the reference conditions and the ecological state of each river stretch. Consequently, in order to fulfil this legal requirement, work must be carried out to decide what physical environmental variables are to be used and to establish relationships between the variables that determine the development of biological populations in these environments and the state of these populations.

A series of projects working in this direction are currently under way in Europe, attempting to bring together knowledge on the hydrobiology of European rivers in order to select reference factors with regard to regional ecological and hydrological conditions with which to classify the rivers of Europe. These projects seek to characterise the fluvial ecosystem and to establish relationships regarding the dependence of aquatic species on particular characteristics of this environment, with the aim of establishing a solid grounding of knowledge that allows the design of better conservation strategies and provides a response to some of the challenges of the Framework Directive.

The ecohydrology group of the UNESCO FRIEND-AMHY project aims to establish a working team to develop methods that allow the matching of different hydrological characteristics with fluvial and riparian species and to identify the relationship between hydrological variability and these species at different scales.

The FAME project seeks to establish the importance of local, geographic and ecoregional factors on fish distribution and their grouping in communities. It also aims to obtain an index that serves to evaluate reference conditions for river stretches in order to know their ecological state, based on fish community abundance, richness and diversity. This idea has been put into practice in France (Oberdorff *et al.*, 2001) and Germany (Schmutz *et al.*, 2000), countries where there are many references regarding studies on fish communities and their relationship with environmental conditions; something that Poff and Allan (1995) carried out in North America, establishing the relationship between fish communities and flow regimes.

Having identified the paradigm of the natural flow regime as one of the main determining factors for protecting the biological integrity of our rivers, and having recognised the lack of a complete knowledge (Richter *et al.*, 1997) of the hydrological behaviour of our rivers using suitable parameters, the first task in this study is to characterise the flow regime in a group of rivers located in central Spain with the aim of creating a hydrological grounding for subsequent biological work, such as the description of species, characterisation of communities, abundance, effect of introduced species, etc., and which also serves as the starting point for the selection of variables that define regions of similar river stretches.

For this purpose, the study has also identified a number of basin variables and has attempted to relate them with the representative indices of the flow regime in these rivers. The objective of this second part of the work is firstly to explain the behaviour of the rivers, and secondly to select the variables that are most influential on this behaviour and which may serve as the basis for a future regionalisation.

Special importance has been attached to the characterisation of low flow periods, since these situations are a habitat-imposed determining factor of tremendous importance for the development of biological populations. In semi-arid regions many rivers dry up naturally in the summer months for long periods of time, but in addition to this, human intervention causes many more rivers to remain artificially dry for even longer periods, and this is one of the severest of all man-made alterations to our fluvial systems. For this reason, one of the hydrological indices that has been used to characterise this period represents the magnitude and the duration of low flow periods. This index has a very particular meaning for the authors, since in other work (Baeza and García de Jalón, 1999) it has been used as an ecological flow value. In other words, this is the minimum flow that should be present in rivers during low flow periods (when the rivers are man-altered) in order to maintain the functioning of the fluvial system at close to natural values.

For the same reason, in the selection of basin variables it has been attempted to include those which best explain the low flow behaviour of the rivers. Consideration has also been made of other variables that have traditionally been used to characterise basins, such as those used in torrential flooding and high flow phenomena.

Since low flow situations differ greatly from flood situations, at least in terms of the origin of the water, a number of other variables have been included to explain the amount of water that feeds into the river during low flow periods, mainly from the geological reserve. These variables can indicate the way water is stored in the basin during rainy months and how it is slowly released over the year, i.e. the capacity to create aquifers.

This reflection has led us to include hydrogeological variables, considering that the water reserve in summer and the rate of water transmission to the basin have a clear geological base, since this is the medium where most water is stored and transported during the summer months (Gustard *et al.*, 1992; Nathan and Mc Mahon, 1991; Walton, 1965).

The groundwater that constitutes aquifers of greater or lesser importance in the study area (the Tagus basin) is responsible not only for the presence of water but also, in many cases, for the regularity of the streamflows and their fluctuation over the year and between years. Bearing in mind that the normal situation in temperate areas is that the river "gains" water from the aquifer from which it drains, it is the presence of this store of water that explains the permanent flow in these systems.

To gauge the role played by aquifers in natural inflows, it has been necessary to classify rock types according to a hydrogeological classification, and to map the surface area occupied by each type of rock in the studied basins. In this way it can be estimated how receptive a basin is to storing water underground and the relative importance of subterranean inflows in proportion to the total flows recorded in each river.

Since water inputs in these basins, in the way of rain, are minimal in summer, and considering that this is the time of year when the water demand is highest, the flows running on many of the intervened rivers will be outside the natural variation range, giving rise to situations of exceptional disturbance of the biological populations to which they are not adapted. Therefore, by assessing water inflows to the rivers from the geological reserve we will know the natural situation of low flows on these rivers, and this will serve as a reference for establishing minimum ecological flows. This will allow us to know to what point the ecosystems can be stressed during low flow periods while maintaining the biodiversity and the most interesting and specific populations of these river stretches that have long withstood extreme low flows and have developed strategies to resist them.

Finally, besides trying to quantify the influence of certain drainage basin characteristics on hydrological indices of ecological importance, it has also been attempted to find models based on the relationship between the indices describing low flows and the studied basin variables. The objective is to be able to work on other rivers with similar behaviour but for which the values of hydrological indices cannot easily be obtained, using these models to estimate them, allowing an approximation to the hydrological functioning of the rivers in basins without data in similar conditions to the river stretches for which data is available.

Methodology

This study has been structured in two parts. Firstly, recorded flow data has been used to establish a number of hydrological indices that characterise the river regimes. One of these indices, Q25d, serves as an estimator of ecological flow and, as mentioned above, has previously been used by our team in other work (Baeza and García de Jalón, 1999). And secondly, quantifiable basin variables that condition these regimes have been identified and calculated, and relationships have been established between the hydrological indices and basin variables.

The study has considered twenty-five basins in the centre of Spain, all of which lie within the Tagus basin administrative district (Figure 1). These basins and the rivers that drain them include a wide variety of types in terms of morphology, hydrological behaviour and geological composition. The main considerations in the selection of these rivers were the availability of sufficient series of flow data and that the regimes were natural, without important alterations due to human intervention.

The data for the hydrological study were obtained from the gauging station network operated by the Confederación Hidrográfica del Tajo (basin administration) (CEDEX, 2000). Complete series of daily flows for several years (from 20 to more than 40 in the rivers where more antiques record exist) were taken and used to calculate 12 parameters characterising high and low flow periods and flow variations within each year and between different years.

Since the estimation of ecological flow has been one of the few attempts to restore regimes altered by human intervention, both in Spain and abroad, the assessment methods used have been tried and tested over a long period of time, so estimates

Figure 1 The Tagus basin in Spain, showing the gauging stations considered in the study.

of ecological flow are already available for many Spanish river stretches (García de Jalón *et al.*, 1997(1); García de Jalón *et al.*, 1997(2)). There are several groups of methodologies for calculating ecological flows. One of the most widely used is that which makes a simulation of the habitat, known as the IFIM method (Bovee, 1982), in order to assess how fish habitats vary when flow changes occur. Other more or less recent methods consider the use of historic flow data recorded by gauging stations in order to identify the minimum flows running on rivers over long time periods (Palau, 1997; Baeza and García de Jalón, 1997).

In our opinion, these latter groups of methods have more biological sense than those based on simple percentages of the mean flow (Richter *et al.*, 1999), since it is considered that biological communities need a period of several days to restore themselves after a disturbing event that has altered their structure and composition (Ortega *et al.*, 1991; Del Rosario and Resh, 2000). Thus it is better to choose the representative flow of a period that is long enough for organisms to develop a response, rather than one single extreme value to which the populations are not adapted.

On this basis, the moving average of several days has been used to calculate the ecological flow. In previous work (Baeza and García de Jalón, 1997; Baeza, 2000) a 25-day interval has been used as the value that represents a sustained low flow situation, this being a very frequent situation in Mediterranean climates where there is no rain for a large part of the year, resulting in very little water flowing in the river for prolonged periods. Biological communities are much better adapted to flows that are sustained over a long period, such as the time that is needed for the community to reestablish itself. Thus it makes more sense to calculate a minimum ecological flow based on flows that are present in the river for a number of days than to use the very low values corresponding to one single day, as has been suggested in simpler methods.

Therefore the 25-day moving average minimum flow, is a good indicator of ecological flow in this climatic region, has been taken as one of the parameters that will characterise the regime of these rivers. There follows a description of the hydrological parameters that have been calculated:

The first three parameters identify the magnitude, duration and frequency of high water periods.

- **Q18** is the daily flow that is exceeded on only 5% of the days in the year. It is taken to represent the magnitude of high flows.
- **D > M** is the number of days in the year that the mean annual flow is exceeded. It represents the duration of high water periods.
- **N > SD** is the number of days in the year that the mean annual flow plus the intraannual standard deviation is exceeded. It represents the frequency of high water periods in the year.

The following three parameters provide a similar analysis for low flow periods.

- **Q347** is the daily flow that is exceeded by 95% of all daily flows in the year. It is taken to represent the magnitude of low flows.
- **Q25d** is the lowest mean flow value found in the year for a group of 25 consecutive days. This parameter is representative of the duration and magnitude of the lowest group of flows in the year. Its calculation is somewhat more complex and involves finding the moving average of daily flows for every 25-day period in the studied years.
- **N < SD** indicates the number of times that the daily flow is less than the mean annual flow minus the intraannual standard deviation. This parameter represents the frequency of low water periods in the year.

The next six parameters measure flow variation; the first three within the same year and the following three between the years considered in this study.

- **CVintra** is the coefficient of intraannual variation. It represents the magnitude of the dispersion of daily flow values in the year. After calculating the mean annual flow, the standard deviation is found and the quotient between the two values is established.
- **Torrential** is the difference between the flow on the day of the year that the river carries the greatest amount of water and the mean annual flow. This parameter measures the torrential behaviour of rivers (Margalef, 1983).
- **DIFannual** represents the frequency of flow tendency reversals in the year. It is calculated by counting the number of times each year that the amount of water carried by the river stops increasing and starts to decrease, or vice versa.
- **CVinter** is the coefficient of interannual variation. It characterises the magnitude of the dispersion between mean annual flows in the studied hydrological series. The mean annual flow of each river is calculated for each year, in order to subsequently find the standard deviation of these mean annual values and to calculate the quotient between the two values.
- **Irregular** is the quotient between the mean annual flows of the years with the highest and the lowest mean values of the entire series. It represents the difference between hydrologically abundant years in terms of streamflow and the driest years.
- **Drymonth** is the percentage within the studied years that the river has dried up for periods of at least one month. It represents the variability within the studied years in which a drought occurs with a sufficient duration to have biological repercussions.

We consider that with the purpose of calculate Cvinter, irregular and Drymonth we should use the same number of years that usually is used to assure that the estimations on fluvial regimes are stable and predictable, commonly they are 20 years (Gan *et al.*, 1991).

Basin variables

Fifteen basin variables have been used to explain the hydrological behaviour, flow magnitude and flow variation on the river stretches whose hydrological regime has been characterised with the above parameters.

These variables include aspects such as the substrate, climate, basin morphology and forest cover. One group of variables has been included to explain the low flow behaviour of the rivers, some of which have previously been successfully used in Mediterranean rivers for the same purpose.

Another group of variables has been taken from two classic parametric hydrological methodologies, namely the USLE method (Mintegui and Robredo, 1993) and the curve number method (USDA, 1978), which serve respectively to measure the soil erosion caused by heavy rainfall and the production of direct runoff in torrential events in the basin, respectively. The first of these two methods was applied in a project carried out by the Spanish Ministry of Agriculture some time ago and gave rise to a report from which data has been taken (Ministerio de Agricultura, 1977).

In order to implement the USDA method it is necessary to obtain a value, N, known as the curve number, which measures the way the soil complex is able to retain the effect of rain. The variables of the USLE and USDA methods used in this work are: soil loss, erodibility, forest cover, ground topography, and hydrological curve number. It is considered that some of the hydrological phenomena this study seeks to research, and which have been characterised by the aforementioned indices (magnitude, frequency), will be conditioned by these basin parameters.

The remaining variables include geomorphological values (Dirección General de Minas ITGME, 1976), topographic values (CEDEX, 2000), climatic values (Forteza, 1984), forest cover, and hydrogeological values (Table 1).

In view of the importance of groundwater inflows in these rivers, especially in the low flow season, a variable has been included to represent basin hydrogeological characteristics in more elaborate way.

The basin aquifer capacity is represented by the value referred to as LIT. Since this information needs to be transformed into a single numerical value representing the entire basin, in order to subsequently establish mathematical relationships with the hydrological parameters, a series of transformations must be made. Firstly, the basin geological information has been simplified by grouping all the basin rock types into just ten categories (Table 2), arranged in order of increasing capacity to act as an aquifer (Gustard *et al.*, 1992; Sanz, 1996; Lacey and Grayson, 1997). After this the surface area occupied by each rock type in each basin has been measured, weighting the area corresponding to each rock type according to its groundwater storage capacity. Finally the LIT value, which represents the basin hydrogeological reserve, has been obtained by multiplying the area corresponding to each rock type by its weighted value.

For greater accuracy in the results, and to more exactly measure the area of each lithological formation, a Geographic Information System (GIS) has been used.

Analysis of data

First of all a correlation analysis of all the variables was performed, considering both the hydrological parameters and the basin variables, in order to identify any colinearity between the various hydrological parameters used and to reject those yielding redundant information, and on the other hand to determine the relative importance of the basin variables for estimating the hydrological parameters considered. The analysis has also included the standardised values of the parameters Q18, Q347 and Q25d, obtained by dividing the corresponding values by the mean flow of each river and referred to as Q18/m, Q347/m and Q25d/m, respectively.

Once the basin variables that have a relationship of statistical significance have been identified, it remains to find models that allow us to establish the relationship between two or more of these variables and the hydrological values, in order to be able to

Table 1 Meaning and units of basin variables.

Parameter	Meaning	Unit
A	**Annual Soil Erosion**	ton/ha.year
R	**Rainfall and Runoff Factor**, represents the erosivity of the type of precipitation that is recorded in a geographic locality	$J\cdot m^{-2}\cdot cm\cdot hour^{-1}$
K	**Soil Erodibility Factor**, reflects how susceptible the ground is to erosion and is calculated from its texture and organic matter content	$ton\cdot m^{-2}\cdot hour/ha\cdot J\cdot cm$
C	**Crop/Vegetation and Management Factor**, represents the cover provided by crops or vegetation to oppose erosion	–
LS	**Slope Length-Gradient Factor**, considers the slope of the river basin	%
N	**Hydrological curve number**, represents the capacity of the soil-vegetation complex to retain rainwater	mm
Permeability		%
Drainage		%
Area	Basin area	km^2
Slope	Slope of the river section from its birth to the gauging station	%
Forest cover	Percentage of the river basin covered by vegetation	%
Temperature	Annual average temperature in the river basin	^oC
ETP	Evapotranspiration	mm
Precipitation	Annual total precipitation in mm	mm

Table 2 Simplified grouping of rock types found in the basins.

Rock type order	Lithological types
1	Very consolidated clays and gypsum
2	Slates and schists
3	Granite
4	Others detritic rocks
5	Alluvial sediments
6	Sands and clay sands
7	Sands and gravels
8	Limestone and gypsum
9	Limestone with sand and conglomerates
10	Limestone and dolomites

explain or predict the magnitude of important events in the river such as the low flow season, flooding, and the variation in flow values.

The statistical tool used to find relationships between variables has been the Pearson correlation coefficient. Firstly a correlation matrix has been prepared in which all the coefficients between all the hydrological indices and all the basin variables have been calculated, in order to identify the variables that have the highest relationships and to select those that are to be used in the model. The criterion for selecting the basin variables to be used in the model has been to select those related with the index it was intended to determine with a significance level of 95%, calibrated with the t-Student.

To establish the models, a verification protocol was firstly followed to check the value distribution of the hydrological and basin variables. This included defining the kind of distribution that best fitted the values found for each variable and its proximity to a normal distribution. To begin with, simple linear regression and multiple regression models were used.

For cases of non-linearity, very small samples, or when the variable distribution showed a non-normal distribution, other strategies were used to establish the models. On the one hand what happened when one or two variables were transformed was investigated, in order to see whether their transformation led to a more linear model. Another solution was to suppose a general non-linear model $y = m(x) + n$ and to directly estimate the form of the function $m(x)$ by non-parametric regression methods. In non-normal variable distributions the transformation of variables was performed using the Box-Cox transformation family (Peña Sánchez, 1994).

Having chosen which basin variables and models to use, a step by step analysis was carried out, in which each of the variables was introduced, one by one, until the best explanation for the variability of the dependent variable was found. The variables which on the whole were not explanatory, or whose inclusion in the model did not contribute to improving it, were rejected.

In all cases, the chosen model was that which fulfilled the best linearity conditions and best explained the variance of the dependent or explained variable. The precision and validity of the model was analysed by calculating its determination coefficient. In the models that were found, the residuals were plotted against the forecast values, and this graph was used to check the linearity of the functional dependence of the two related variables.

Results

The values of 12 hydrological parameters were found (Table 2) for the studied series of flows, and the values of 15 basin variables were established (Table 3) for each of the considered basins. These values were used to perform the statistical analysis that gave rise to the correlations and models.

The results show a series of river stretches with highly different characteristics, due to the fact that the chosen rivers have very different basin sizes and therefore their mean flows are also very different (the river Tiétar at Rosarito station has a mean flow

Table 3 Range of values and rivers for which extreme values have been found for the 12 considered hydrological parameters plus the standardised values of Q18, Q347 and Q25d.

	Maximum	River Max.	Minimum	River Min.
Q18 m^3/s	107.88	Tiétar (Ros)	0.78	Guadalmejud
Q18/m	5.15	Almonte	1.97	Dulce
$D > M$ days	159	Dulce	68	Cedena
$N > SD$	12	Alberche	2	Perales
Q347 m^3/s	4.01	Guadiela	0.01	Perales
Q347/m	0.43	Escabas	0.01	Almonte
Q25d m^3/s	5.42	Guadiela	0.01	Perales
Q25d/m	0.43	Gallo	0.01	Perales
$N < SD$	8	Alberche	1	Cedena
Cvintra	2.24	Almonte	0.59	Dulce
Torrential	26.91	Almonte	3.89	Dulce
DIFannual	180	Alberche	32	Perales
Cvinter	0.78	Trabaque	0.34	Lozoya
Irregular	27.66	Trabaque	3.60	Escabas
Drymonth %	0.65	Cofio	0	several

Table 4 Results of the main studied basin variables for the 25 rivers. The table presents only those variables which the statistical analysis has shown to be most influential on the hydrological parameters.

Parameter	Drainage	Erosion (A) ton/ha	Forest.cov. %	Curve Nº. (N) mm	Precipitat. mm	Temperat. °C	ETP mm	Area Km^2	Lithology (LIT)
Escabas	90	20.2	15.1	54.2	525	12.9	724	345	9.1
Navaluen.	97	18.3	4.7	58.7	619	10.8	719	698	3.0
Cofio	35	25.1	10.6	66.1	757	13.6	658	629	2.8
Cuernac.	50	13.5	7.4	73.3	639	16.4	974	120	4.4
Cuerpo H.	52	12.4	10.6	66.3	712	10.4	709	239	2.8
Dulce	25	0.5	6.8	78.7	599	10.9	735	263	6.0
Mayor	29	18.1	6.3	76.8	713	12.8	727	430	6.1
Rosarito	94	43.8	8.1	61.7	1047	16.2	881	1754	3.1
Bujalaro	37	73.4	5.9	75.1	565	12.4	798	1036	7.0
Almonte	96	9.1	12.6	57.7	900	16	920	787	2.8
Gallo	71	21.9	5.8	63.8	702	9.5	675	944	8.2
Guadalm.	32	7.8	3.8	69.5	908	10.3	638	253	7.7
Guadiela	54	13.6	5.2	76.2	525	12.9	525	3342	5.7
Jerte	64	282.4	8.3	66.2	1400	13	800	631	3.0
Perales	70	27.4	6.0	63.3	432	12.6	720	261	3.5
Tajuña	39	0.2	6.7	75.0	653	10.9	732	658	8.1
Tiétar	96	14.7	10.3	53.8	1348	16	928	730	3.0
Trabaque	54	20.8	8.0	72.8	624	13.1	740	361	7.3
Alagón	48	17.9	7.6	61.1	958	14	861	288	2.3
Alberche	98	20.7	6.1	51.3	750	9	610	1050	2.9
Ibor	97	27.8	11.4	54.1	784	14.7	892	266	5.7
Cedena	64	124.0	6.8	51.4	458	14.4	795	53	5.2
Henares	42	51.6	7.3	73.4	599	10.9	735	2597	5.9
Lozoya	72	15.8	11.7	67.3	906	9.8	626	42	3.0
Tagus	95	2.6	15.4	68.2	951	9.6	683	410	8.0

of 27.3 m^3/s, while the mean flow on the river Guadalmejud is 0.3 m^3/s). This is reflected in the highly different extreme values found for the hydrological parameters, especially those that have been used to measure magnitude in low and high flows (Q18 and Q347).

Another general characteristic of the results is the Mediterranean character of these rivers, which in general terms is indicated by the presence of very long and very dry low flow seasons and a great disparity between low and high flow values, which are related with the values of the parameters Q25d, Drymonth, CVintra and CVinter. There are 14 rivers with low flows of less than 0.5 m^3/s, 11 rivers that frequently dry up for periods of more than one month, and 12 rivers that have an interannual variation coefficient of more than 1.5, with 1.4 being the mean value found for this parameter, which indicates the strong torrential nature of these rivers and the great variation in the flows running in them over the year.

The hydrological parameters allow the rivers to be arranged in groups in order of increasing variability. At one extreme, with the lowest variability, is the river Dulce, whose high water flow values do not reach twice the mean flow, this river has the minimum CVintra (0.59) and the minimum Torrential value (3.89); along with other rivers such as the Gallo, Escabas, Trabaque, Tajuña, Mayor, Tagus and Henares. These rivers present little difference between their highest and lowest flows, and nearly always show low and high water situations with the same frequency and on the same dates, and the values of these extraordinary flows do not differ greatly from the flows generally running in the river.

The other group at the opposite extreme is characterised by the river Almonte; whose high water flows (Q18) exceed by more than five times the mean flow in the river, has the maximum CVintra (2.24) and the maximum Torrential value (26.91); along with the Alagón, Tiétar, Perales, Cuernacabras, Ibor and Alberche at Navaluenga. These rivers show great differences between their high water, low water and mean flows. This group includes rivers with very high flows, great torrentiality, and others that have very low flows and that even dry up completely.

Another group of rivers can be found in which the Alberche is the clearest representative. These rivers present many flow changes during the year, and frequent extreme flows for both high and low values.

With regard to low flows, one of the fluvial characteristics that constrain the evolution and the adaptations of the alive organisms in these semiarid regions, we have found two models, one that present rivers with low water values and very long dry periods, characteristic of temporary rivers like the Perales, and others different in which the basic characteristics is the frequency of years in which they are dried, like the Cofio, river that turn into dried practically every year. These two models must produce different strategies in the organisms that live in these rivers, and this quality must be had in consideration if a regulation projects is planned in these sections.

Many of these characteristics shared in the groups, depend on characteristics of their river basins. These groups can contribute to a more rational management of the water resources, in which the particular hydrologic behaviours of each group are considered.

The basin variables help to explain the regime variability encountered. The lithology variable, whose importance is considered in detail below, has been calibrated to yield values from 0 to 10. Four basins have been found with values over 8, namely those of the rivers Tagus, Gallo, Tajuña and Escabas, the latter having the maximum value of 9.1. At the opposite extreme are the basins of the rivers Cuerpo de Hombre and Almonte with the minimum value of 2.8. Evapotranspiration (ETP) is another of the most important variables found to explain the hydrological regimes of these basins. Most of these basins have an ETP of between 600 and 700 mm. The rivers Almonte, Cuernacabras and Tiétar have an annual value in excess of 900 mm, while the river Guadiela shows an ETP of 525 mm. The hydrological curve number, which is especially related with torrential and flood phenomena, has its maximum value in the river Dulce (78.7) and its minimum in the rivers Alberche and Cedena (51).

The group of hydrological parameters used are easy to calculate with simple mathematical procedures if gauging data is available and have provided a good characterisation of the studied regimes, which is sufficiently broad to describe the components of the flow regime. Furthermore, it has been possible to define groups of rivers by differentiating between those of a constant and regular character and those in which many fluctuations and sudden changes in flow occur. This will be partly explained by the analysed basin variables, which will show greater correspondence with the high or low flow parameters or with the flow variation parameters depending on their particular hydrological meaning, as will be seen in the following chapter on statistical analysis.

Correlation between variables

The first step to explain the hydrological behaviour of rivers and groups of rivers consists of establishing the relationship between the mathematical parameters that have been studied to characterise the regime and the basin variables that are adopted as the determining factors of that hydrological behaviour.

To establish this relationship the values obtained were compared in the correlation analysis of the 12 hydrological parameters and the most significant variables of the studied basins. Tables 5 and 6 show the most significant results and their statistical significance.

In Tables 5 and 6 it can be seen that the hydrological parameters which have the greatest number of statistical relationships with the basin variables are the parameters Q18/m, which characterises high flows; CVintra, which represents the flow variation during the year; and the torrentiality index, which assesses the difference between the maximum annual flow and the mean flow.

With regard to the basin variables most related with the hydrological parameters, the variable representing the basin aquifer capacity (LIT) is that for which most relationships are established, followed by evapotranspiration (ETP).

Table 5 Correlation coefficients and statistical significance between hydrological parameters determining low and high flow factors and basin variables, showing only those relationships with a significance of more than 95%.

	Drainage	Curve no. (N)	ETP	Lithology (LIT)	Area	Temperature
Q18/m	0.4267*	−0.5240***	0.5052*	−0.6656***		0.5416***
D > M		0.4695*	−0.5223***			−0.5089*
N > SD						
Q25d/m				0.8463***		
Q347/m				0.8202***		
N < SD					0.5875***	

***99% significance.
*95% significance.

Table 6 Correlation coefficients and statistical significance between hydrological parameters causing intra and interannual variability and basin variables.

	Curve no. (N)	Drainage	LS	ETP	Lithology (LIT)	Temperature	Area
CVintra	−0.4444*			0.6027***	−0.5798***	0.6122***	
Torrential	−0.5579***	0.4520*		0.6658***	−0.5157***	0.6902***	
DIFannual					−0.3971*		0.5289***
CVinter							
Irregular			−0.4218*				
Drymonth	0.4865*	−0.4319∗			0.7810***		

***99% significance.
*95% significance.

It is interesting to note that the parameters $N > SD$, which measures the number of times the considered high flow threshold in each river is exceeded, and CVinter, which measures the variation between years, are not significantly related with any basin variable. Apparently these variables are more influenced by the climatology that by the geographic characteristics.

On the other hand, the hydrological parameter Q25/m, which characterises the severity of the low flow duration, is related only with the LIT variable. This is the highest relationship of all those found for all the parameters.

As has been stated in the introduction, one of the aims of this work is to try to obtain a better knowledge of the behaviour of these Mediterranean rivers during their low flow periods. For this purpose, the Q25d flow has been taken as the parameter for characterising low flows (in other studies it has served as a good ecological flow estimator), while its standardised value, Q25d/m, is the parameter that presents the highest correlation with the basin variables of all those considered. It has therefore been decided to search for a model for this value which would be useful for estimating it when the values of the basin variables that influence it are known.

To complete the information on the basin variables that can influence low flow hydrological behaviour, the mean flow of the rivers has been included in order to improve the models that were sought for both Q25d and its standardised value Q25d/m. The following table (Table 7) shows the values of the most significant relationships calculated in this new analysis of relationships with the Q25d flow.

With these results, the basin variables are selected which may be explanatory for the values of both Q25d/m and Q25d. The regression process has then been carried out in a step by step way in order to achieve the most suitable model.

Models found

For the first model, whose explained variable is Q25d/m, the values of the basin lithology variable have been used. As for the second model, which seeks to explain the Q25d values, the explanatory variables used were the mean flow, basin area and ETP.

In order to use parametric statistical methods, the results that yield information about the distribution of the variables which are to be used in the model have been checked. According to these values, the variables and parameters come close to a normal distribution with 90% significance.

Continuing with the methodology described in the statistical analysis, an attempt was made to find the best model that comes closest to the value distribution of the fitted variables, it being found that the best model is the simple linear regression model, or multiple regression model in the event that more than one explanatory variable is used.

Table 7 Correlation coefficients and statistical significance between Q25d and the studied parameters.

	Mean	ETP	Area
Q25d	0.5305***	−0.4405*	0.6191***

***99% significance.
*95% significance.

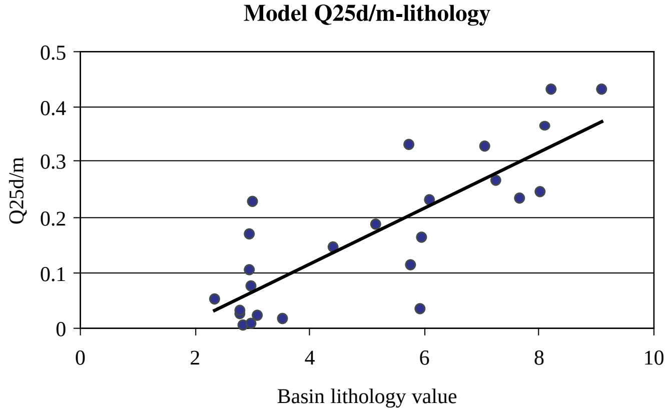

Figure 2 Q25 d/m and LIT values for each basin and the regression line obtained.

Once the models were found, the residuals were represented against the values forecast by the model, and in this way it was verified that there was no linear dependence and no correlation between the residuals.

The best model, which presents the highest significance between Q25d/m and LIT, is as follows:

$$\text{Q25 d/m} = -0.1 + 0.055\,\text{LIT} \quad \text{R2} = 71.62\%;$$
$$r = 0.846; \quad \text{standard deviation} = 0.077$$

For the second model, stepwise multiple linear regression was used to examine the relationship of the Q25d low flow parameter and several basin variables. Finally a regression model was developed with two variables that exhibited statistically significant coefficients. After this it was verified that a greater number of explanatory variables did not contribute any further information to the model. The best model between the non-standardised Q25d flow and the explanatory variables of the greatest significance is:

$$\text{Q25 d} = 3.94 + 0.102 \bullet \text{mean flow} - 0.005 \bullet \text{ETP}$$
$$\text{R2} = 47.28\%; \ \text{standard deviation} = 0.941\text{m}^3/\text{s}$$

Figure 3 shows the representation of the recorded values compared with the values forecast by the model.

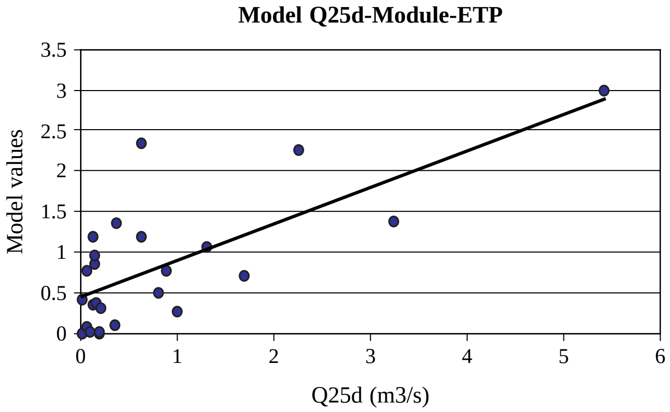

Figure 3 Observed values compared with the values obtained in the model using Q25d, mean flow and ETP.

Discussion

The hydrological parameters used in this study have served to describe river regimes in a reasonably complete way, characterising a wide variety of regime types found in a very large drainage basin with a considerable lithological and geographic variety and a notable rainfall gradient from west to east.

Some parameters have clearly identified the regularity of the rivers, and in this respect CVintra is an especially useful value. This parameter, first used in England by Gustard *et al.* (1992), clearly discriminates between regular rivers, with values of less than 1, and highly irregular rivers, with values in excess of 1.5. Gustard notes that coefficients of more than 1.5 are typical of irregular rivers and, this is the case with 12 of the 25 studied rivers in this basin.

Other hydrological parameters that characterise high flow situations (like Q18) or low flow situations (like Q25d) have correctly identified rivers in which exceptional events occur. The opposite situation are present in those where the extreme are not very different from the mean flows and situations of great stress do not occur in the hydrological systems.

On the other hand, the parameters DIFannual, $N > SD$ and $N < SD$ have been found useful for finding rivers in which situations that cause stress in the ecosystem are very frequent over the year, due to the highly fluctuating nature of the rivers. The hydrological significance of these two groups of parameters, which indicate the magnitude and the frequency of events, will have very different biological consequences. It will be interesting to take these considerations into account, for instance when planning dam discharge schedules, since the way this is done will need to be very different in rivers that have very frequent high flows of a moderate magnitude, compared with those that have very large high flows on just a few occasions during the year.

With regard to basin variables, the greatest interest lies in those that establish the highest number of relationships with hydrological parameters. These variables have been useful both for preparing the models and for explaining certain aspects of hydrological behaviour in the studied stretches that have been characterised by the studied parameters. Furthermore, those which are considered to be most influential in the functioning of the system will be those that must be taken into account when establishing guidelines for differentiating ecoregions when classifying similar fluvial systems, like those currently under way in compliance with the Water Framework Directive (Oberdorff *et al.,* 2001).

The curve number is one of the variables with the greatest number of correlations with the hydrological parameters and establishes relations with rivers of similar nature. Rivers with high values are geographically close to each other, as also it happens in three rivers with low values. This identifies similar hydrological behaviour in rivers with the same N values (curve number) and, also with a reference to the geographic location of their basins.

The negative correlations of this variable with hydrological parameters that represent high water flows, support the idea that these basins control flood flows and, also helping to avoid the occurrence of great variability over the year.

An exceptional comportment has been observed in the case of rivers situated in very large basins, their hydrological behaviour is found to be different to that of other rivers belonging to the same group and, does not show the regularity seen in the rest of the group (Prat *et al.*, 2000; O'Shea, 1995). This may be because of the tributaries that are received from basins with different characteristics and the fact that the hydrological characteristics of the receiving river are a mixture of the inflows of its tributaries, diluting the regular characteristics of other smaller rivers. Therefore it has been observed relationships with DIFannual, and with the number of times the river's flow drops below the minimum threshold ($N < SD$), whereby rivers with large basins show frequent changes in flow tendency and extreme events.

The lithological variable has been the most elaborated, since the shortage of rain in summer suggested it would bear an important weight in the low flow values of these rivers, and thus also in the parameter used as an estimator of ecological flow (Q25d). This was confirmed with the results obtained for the hydrological parameters, in which a group of rivers with high low flow values is clearly identified, and with a series of descriptors that point to a regular and predictable hydrological behaviour. All of these rivers are situated geographically close to each other and present similar hydrologeological characteristics. These rivers have flows of subterranean origin that account for more than 50% of their total inflows, and in some cases, more than 65% (López and Celaa, 1983; IGME, 1983). Apparently, the reason for these high inflows is the presence of Mesozoic aquifers in the area.

In order to verify the impact of aquifers on hydrological variables, it has been considered in the basin variables only the surface occupied by water-bearing and the its capacity to lodge water, due to the lack of information on transmissivity and other physiographical aspects (appearance of folding, escarpment, encased valleys, etc.), these aspects will have to be including in future models to improve them.

The next variable with a great impact on several parameters is evapotranspiration (ETP), which has an important influence on low water flows. It is interesting to see that the effects due to extreme ETP values in the basins depend on the type of woodlands present in the basin. When this variable is studied in relation with the forest area the results for low water flows seem to be conditioned by the kind of trees predominant in the basin (Prat, 1997). Thus, in rivers where the basins possess a high proportion of woodland areas consisting largely of deciduous species, low water flows are found to be very low. In contrast, basins, which possess larger woodland areas but in this case corresponding to pinewoods, low water flows are acceptable. This suggests a more in-depth investigation, not only to the total value of water lost by evaporation but also to the kind of forest cover, must be development.

In contrast with this idea, it is seen that the forest cover percentage is not significantly related with any hydrological parameter, not even those that measure or represent low water flows. We have also found that the total precipitation is not determining in the behavior of these rivers; we should take into account the possibility of including a value to measure intensity, or the amount of precipitation in critical months, or the difference between rainy and dry seasons. This idea is supported by instance by the flow that presents some rivers in the dry period, basins with low rainfall levels maintain high low water flows; which reinforce the argument to consider the importance of aquifers in these basins and, the order in which the received precipitation has been flowing to the river throughout the year.

The models

Two models have been obtained which may be applied without excessive fieldwork to calculate low water flows, which could also serve as ecological or maintenance flows, from easy-to-get basin variables. In the first model a standardised ecological flow value (ecological flow divided by medium flow) is obtained. This is an interesting index for characterising the river regime, for which it is necessary to know the basin lithological composition. In the second model the values of ETP and the mean flow must be entered as explanatory variables.

While ETP is a variable that is widely used in many models, and is normally available from weather stations, the LIT variable from the first model is an original contribution of this work. To obtain it, it is necessary to have a good geological classification of the basin. A Geographic Information System (GIS) is a very useful tool for achieving greater precision in the measurement of basin areas. In similar studies, relationships were found between the river size and the quotient of the value used as an estimator of ecological flow and mean flow (O'Shea, 1996; Orth and Leonard, 1990). This quotient was also clearly related with the area where the basin was located and especially with its lithological constitution.

The first model has a considerably higher determination coefficient, $R^2 = 71.62\%$, than the second model, $R^2 = 47.28\%$, indicating that the first model explains a much higher percentage of the variance of the explained variable than the second model. Either of the models would serve to obtain the characteristics of the flow regime of the rivers in the absence of flow data records, a situation that is fairly frequent in many basins where gauging stations do not exist.

In both of the two calculated models a series of pairs of values has been observed for the variables in certain basins which correspond to unusual values or which differ greatly from those obtained by the model. These values were obtained in rivers that have in common basins that cover very large areas. This contradictory behaviour, in rivers with large area basins, has also been seen in relation with other parameters. The same results have been obtained in Australia (Lacey and Grayson, 1997), in a study that sought to establish a model between a ecological flow and the basin lithology, finding that the model also failed in large basins but was very effective in basins smaller than 100 km^2.

The determination of these models was found to have two immediate applications: one is to obtain hydrological parameters that may serve as an estimator of ecological flows in basins without flow gauging. The second is to gain a deeper knowledge of the variables that influence low flow periods on these rivers and their values. Similar variables have been compared in different ways on other rivers, obtaining good results, limited in some basins, either because of their size or for other morphological reasons that are yet to be researched.

Conclusion

The hydrological regimes of 25 rivers in central Spain have been characterised using variables that provide information on the behaviour of these rivers in the so-called components of the natural regime of rivers: magnitude, duration, frequency, timing and rate of change. This group of variables has also allowed groups of rivers to be identified whose regimes present similar behaviour. For some of the variables and some groups of rivers, a relationship has also been found with their geographic location within the Tagus basin. On the other hand, consideration has been made of a number of basin variables that condition the hydrological response of rivers, and finally ETP and lithology have been chosen as the most useful variables which explain several of the most important events of the hydrological regime in these rivers. The total precipitation is not a highly determining factor, especially in those basins where the aquifers are very thick, and it may perhaps remain to carry out research on the influence of rainfall distribution.

Another of the proposed objectives was to find variables that served as potential discriminators of groups of rivers with similar hydrological behaviour, with a view to obtaining fluvial ecological regions for the purposes of future management and assessment of their quality. This point has been partially addressed by finding a number of basin variables that have many relationships with many of the hydrological parameters, and therefore, at least statistically, have a great influence on the regimes of these rivers.

The models found, work fairly well in small basins, and can be very useful for estimating low flow or maintenance flow values in basins without gauging data. This may serve to establish recommendations regarding basin management and to establish a series of particular maintenance flows for each basin, considering the relationships and influences of the environment on the rivers.

In order to improve the model in future applications we must incorporate the knowledge on water-bearing. This means the need to obtain data on the infiltration coefficient, aquifer permeable area, thickness, effective porosity, transmissivity and permeability, as well as certain geomorphological features that indicate flow directions. On the same form, also we will have to incorporate other parameters that explain the regularity found in some rivers, such as the accumulation of precipitation water in the form of snow, or the role that the detrítics rocks play in the water accumulation, since also some rivers with part of their river basins in these formation present regular character.

The environmental flow results obtained with these models can be compared with those calculated by other methods. Finally, it remains to implement those recommended flows in real river stretches and to maintain the components of the natural flow regime within the organisation of natural variation in regulated rivers, in order to verify their validity. Experiments need to be carried out to evaluate the biological response in these river stretches when a management programme based on the proposed flow values and their variation is implemented.

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