Martinez-capel, F.; Jose; Belmar, O.; Bruno, D.; Velasco, J. (2013). Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. Ecological Indicators. 30:52-64.

http://dx.doi.org/10.1016/j.ecolind.2013.01.042

Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin.

Oscar Belmar[1,*] (oscarbd@um.es), Daniel Bruno[1] (dbrunocollados@um.es), Francisco Martinez-Capel[2] (fmcapel@dihma.upv.es), José Barquin[3] (jose.barquin@unican.es) Josefa Velasco[1] (jvelasco@um.es).

[1] Department of Ecology and Hydrology, University of Murcia, Espinardo Campus, Murcia, 30100, Spain.
[2] Institut d'Investigació per a la Gestió Integrada de Zones Costaneres, Universitat Politècnica de València, Calle Paranimf, 1, Grao de Gandia, 46730, Valencia, Spain.
[3] Instituto de Hidráulica Ambiental, Universidad de Cantabria, C/ Isabel Torres nº 15, Parque Científico y Tecnológico de Cantabria, 39011, Santander, Spain.

[*] Corresponding author. Tel.: +34 868 88 4977

Keywords: hydrologic alteration indicators, habitat modification, riparian zone, ecological indicators.

Abstract

The Segura River Basin is one of the most arid and regulated zones in the Mediterranean as well as Europe that includes four hydrologic river types, according to their natural flow regime: main stem rivers, stable streams, seasonal streams and temporary streams. The relationships between flow regime and fluvial and riparian habitats were studied at reference and hydrologically-altered sites for each of the four types. Flow regime alteration was assessed using two procedures: 1) an indirect index, derived from variables associated with the main hydrologic pressures in the basin, and 2) reference and altered flow series analyses using the Indicators of Hydrologic Alteration (IHA) and the Indicators of Hydrologic Alteration in Rivers (IAHRIS). Habitats were characterized using the River Habitat Survey (RHS) and its derived Habitat Quality Assessment (HQA) score, whereas riparian condition was assessed using the Riparian Quality Index (RQI) and an inventory of riparian native/exotic species. Flow stability and magnitude were identified as the main hydrologic drivers of the stream habitats in the Segura Basin. Hydrologic alterations were similar to those described in other Mediterranean arid and semiarid areas where dams have reduced flow magnitude and variability and produced the inversion of seasonal patterns. Additionally, the Segura Basin presented two general trends: an increase in flow torrentiality in main stems and an increase in temporality in seasonal and temporary streams. With the indirect alteration index, main stems presented the highest degree of hydrologic alteration, which resulted in larger channel dimensions and less macrophytes and mesohabitats. However, according to the hydrologic analyses, the seasonal streams presented the greatest alteration, which was supported by the numerous changes in habitat features. These changes were associated with a larger proportion of uniform banktop vegetation as well as reduced riparian native plant richness and mesohabitat density. Both stream types presented consequent reductions in habitat and riparian quality as the degree of alteration increased. However, stable streams, those least impacted in the basin, and temporary streams, which are subject to great hydrologic stress in reference conditions, showed fewer changes in physical habitat due to hydrologic alteration. This study clarifies the relationships between hydrologic regime and physical habitat in Mediterranean basins. The hydrologic and habitat indicators that respond to human pressures and the thresholds that imply relevant changes in habitat and riparian quality presented here will play a fundamental role in the use of holistic frameworks when developing environmental flows on a regional scale.

1. Introduction

Flow regime is a major determinant of physical habitat in streams and rivers (Bunn and Arthington, 2002), and its alteration by human activities has caused serious degradation in aquatic and riparian ecosystems (Nilsson and Berggren, 2000; Richter et al., 2003). Hydrologic alteration influences habitat components such as wetted area (Froend and Van Der Moezel, 1994; Humphries et al., 1996); bars, benches and islands (Ligon et al., 1995); pools (Erskine et al., 1999); organic matter (Gawne et al., 2000); woody debris (Humphries et al., 1996); substrate composition (Sherrard and Erskine, 1991); and sediment transport, a co-determinant of physical habitat in river systems (Lloyd et al., 2003). The effects of hydrologic alteration on communities are driven by these changes (among others), given the fundamental role that physical habitat characteristics play in their structure and composition (Bunn and Arthington, 2002).

Most existing global literature focuses on the effects found downstream from dams, as they can explain up to 91% of total changes in flow and bed mobility parameters (Burke et al., 2009). However, the wide variety of effects does not allow a general quantitative relationship between flow alteration and ecological response to be developed (Poff and Zimmerman, 2010). In general, dams and their associated reservoirs impact freshwater diversity (McAllister et al., 2001) as a result of sharp decreases in riparian biodiversity downstream (Johnson et al., 1976; Ligon et al., 1995; Petts, 1980). The impact of flow modification on vegetation varies depending upon the taxonomic group considered (Bunn and Arthington, 2002), because aquatic, littoral, riparian and floodplain plants differ in flood tolerance and dependence (Blanch et al., 1999). However, despite the importance of physical habitats for communities in fluvial ecosystems (Power et al., 1988), where their characteristics can change more easily and quickly than in other ecosystems, studies on ecologically significant habitat features associated with river morphology and flow regime are scarce. Such studies are essential, as these changes are key to understanding the long-term ecological consequences of dams and other disturbances (Ligon et al., 1995).

In this context, developing flow alteration-ecological response relationships that reflect the direct and indirect influences of hydrologic alteration on both ecological processes and ecosystems by river type constitutes the basis of a holistic methodology for the assessment of environmental flows at regional scales, the “Ecological Limits of

Hydrological Alteration” (ELOHA; Arthington et al., 2006; Poff et al., 2010). Due to the combination of increasingly high demands for water (e.g. Lorenzo-Lacruz et al., 2010) and its scarcity, studying these relationships is essential for ecologically-based water management in Mediterranean areas. Human pressures in these areas have resulted in flow regulation through dams and reservoirs, water abstraction, diversion channels and inter-basin water transfers (e.g. the Tagus-Segura Transfer in SE Spain). Such infrastructures, especially those associated with agricultural demands, lead to significant modifications in flow regimes (see Belmar et al., 2010). In most rivers of the southern Iberian Peninsula, dam management to meet summer water demands has produced important changes in flow magnitude, variability and seasonality throughout the 1945-2005 period (Lorenzo-Lacruz et al., 2012). Such changes could increase globally in the coming decades, as future climate projections forecast a generalized decrease in precipitation and increased evapotranspiration in the Iberian Peninsula (Rodriguez-Puebla and Nieto, 2010) and Mediterranean areas (IPCC, 2007).

Therefore, it is essential to improve existing knowledge regarding the relationship between hydrologic alteration and ecological response, both for organisms and the physical habitat in which they live, in Mediterranean areas in general and in the most arid ones in particular. Some foundations have already been laid in Iberian Mediterranean basins. Batalla et al. (2004) defined and quantified hydrologic alteration in the Ebro River (NE Spain), where dams reduced variability in mean daily flows and caused an inversion in the monthly seasonal patterns (with reduced fall and winter peaks and summer releases for irrigation that increase baseflows). Magdaleno and Fernández (2011) studied the effect of high and low flow alterations on riparian forests and channel morphology by dams in a segment of the Ebro River. Boix et al. (2010) determined the effects of water abstraction on stream communities in some Catalonian rivers (NE Spain). Navarro-Llácer et al. (2010) revealed degradation in the ecological condition of reaches downstream from reservoirs in the Segura and Mundo rivers (SE Spain) using macroinvertebrate, fish and riparian quality indices. Garófano-Gómez et al. (2012) documented the stages of hydrologic alteration in the Júcar Basin (SE Spain) and analyzed changes in the riparian habitats. However, no author has delved into the diversity of hydrologic types present, which can be subject to different management strategies and, therefore, flow regime alterations. In this sense, no study undertaken in any Mediterranean area has characterized hydrologic alteration or defined relationships between flow alteration and physical habitat for different hydrologic types at basin scale.

The aims of this study were to: (1) characterize and quantify the main hydrologic alterations in the different river types of a semiarid Mediterranean basin (Segura River), using an indirect index and two sets of hydrologic indicators, and (2) determine the effects of flow regime alteration on fluvial habitats and riparian conditions for each type. The Segura River Basin is highly suitable for this purpose, as it presents a wide range of natural flow regimes (Belmar et al., 2011) and is also one of the most regulated basins in Europe (Ministerio de Medio Ambiente, 2004), with water demands exceeding 224% of that available and only 4% of runoff reaching the river mouth (Zimmer, 2010).

Hydrologic alteration was expected to present different patterns and effects for each river type. It was hypothesized that main stems would present the greatest hydrologic alteration due to increasing water demands and dams along their longitudinal axis, and in particular, an inversion in their seasonal pattern and a reduction in their inter- and intra-annual flow variability, as has been observed in other Mediterranean basins. However, tributaries were expected to present specific alterations associated with their individual management, dependent on natural flow regimes and land use configurations. In particular, streams with seasonal flow variations or even temporary regimes located in mid- and lowlands with large crop areas and flood control dams were expected to show a significant reduction both in flow magnitude and variability, as well as the greatest alteration in floods and droughts.

Such hydrologic alterations were anticipated to cause an overall reduction in fluvial habitat and riparian quality, although distinct effects were also expected in each river type. It was hypothesized that discharging large volumes of water from dams into main stems to address irrigation demands could produce increased channel dimensions, the homogenization of aquatic habitats, predominant turbulent flows and coarse substrates, lessen the diversity of aquatic and native riparian vegetation and increase alien species. At the opposite extreme, flow regulation by dams in more seasonal or even temporary streams should exacerbate droughts and cause a reduction of aquatic habitats and the invasion of riparian vegetation in channels.

2. Methods

2.1 Study area

The management area of the Segura River Basin, one of the most arid zones in the Iberian Mediterranean Region, presents four broad flow regime types (Belmar et al., 2011): main stem rivers, with an average annual discharge greater than 2 m^3/s; stable streams, which never cease flowing and have low seasonal flow variation; seasonal streams, which have a marked seasonal variation and eventually cease flowing (although perennial surface water persists); and temporary streams, without any flow more than 20% of the time. These river types were defined through a hydrologic classification developed using modelled natural flows and 73 indices that comprise monthly and annual measurements of flow magnitude central tendency and dispersion, as well as measurements of drought and flood duration. Moreover, they have biological significance, as they present distinct macroinvertebrate communities (Belmar et al., 2012).

Despite the relatively small size of the basin (18,870 km^2), the coexistence of these four flow regimes is explained by a strong climatic and altitudinal gradient from NW to SE. Climate ranges from wet (>1,000 mm mean annual precipitation) and cold in the NW mountains (>1,000 m.a.s.l.) to semiarid and hot in the SE lowlands (<350 mm mean annual precipitation), where autumnal storms can discharge up to 300 mm in hours. Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). This altitudinal and climatic gradient is coupled with a corresponding population density gradient. The river network has low population densities in the forested headwaters, intermediate densities in the agricultural midlands and highly populated cities in the lowlands (Mellado, 2005).

The Segura River Basin is one of the most regulated hydrologic networks in Spain and Europe. Irrigation (responsible for 90% of water demands) constitutes the main anthropogenic pressure on stream flows. The high regulatory capacity in the basin (770 hm^3, over 90% of the natural input) is provided by 24 dams that are more than 10 m in height (Grindlay et al., 2009; Grindlay et al., 2011) and 121 weirs higher than 2 m (CHS, 2007). Many small dams have been constructed in seasonal and temporary streams for flood control, but they constitute agricultural reservoirs that distribute water to irrigation channels. Additionally, two large water management infrastructures can be found in the basin. First, the Tagus-Segura inter-basin water transfer, which leads water from the Tagus River to the Talave reservoir (in the Mundo River, the main tributary of the Segura River). The transferred volumes (a mean of 325 hm^3 yr^{-1}) are used for irrigation (62%) and human supply through the *Mancomunidad de Canales del Taibilla* (24%), the entity that manages more than 90% of water for human supply in the basin (CHS, 2007). Second, the Taibilla channel, which is used to conduct the transferred volumes for human supply and additional resources extracted from the Taibilla stream.

These intense pressures on water resources have resulted in the overexploitation of surface waters and a mean groundwater extraction of approximately 478 hm^3/year (over 80% of the natural recharge), and as a consequence, water demands have created structural hydrologic deficits that cannot be mitigated even with the Tagus-Segura transfer (Gil-Olcina, 2000).

2.2 Hydrologic alteration

Hydrologic alteration was assessed using two approaches. First, an indirect index computed from variables associated with alterations in the Segura Basin provided an overall measurement for each habitat sampling site. Second, two sets of hydrologic alteration indicators were calculated from gauged records to characterize and quantify the alteration in those streams and rivers with appropriate data series.

The indirect index, based on Falcone et al. (2010b), was derived using the surface of irrigated land (%), number of dams (count) and regulatory capacity (hm^3) in the drainage area associated with each habitat sampling site, as these variables are linked to the main hydrologic alterations in the Segura Basin (Belmar et al., 2010). Sites were assigned between 0 to 8 points for each variable based on their percentile value within the data range. The 1st, 20th, 40th, 60th, 80th, 90th, 95th and 98th percentiles were calculated on “non-zero” values and used as “disturbance thresholds” for assigning the corresponding punctuation to each site. Then, those points were added for all three variables providing an index which ranged potentially from 0 (minimum flow alteration) to 24 (maximum flow alteration). This procedure allowed summing the discrete quantitative values obtained from variables of distinct natures and units and their integration into an easily-interpretable, adimensional value of overall alteration.

According to Falcone et al. (2010a), this approach constitutes the best scoring method. Variations of it are common in other studies (Host et al., 2005; Wilheim et al., 2005).

Gauged data were obtained from the Spanish Hydrographic Studies Center (CEH) database (CEH, 2012) and consisted of flow series recorded before and after the main alterations (dam construction, mainly) in rivers representative of each hydrologic type. A minimum of 15 years (Martínez and Fernández, 2006) and an optimum of 20 years (Richter et al., 1997) of records were considered for analyses to ensure the inclusion of wet, average and dry periods. Given the limited hydrologic information representing unaltered regimes in the basin, only seven gauging stations were selected, four in main stems (Mundo and Segura Rivers) and one in each tributary type (Taibilla stream, stable; Argos stream, seasonal; and Mula stream, temporary) (Table 1). In general, series conducted before the dams' construction were used as "pre-impact" data, whereas the "post-impact" data consisted of the most recent gauged series. However, given their long history of hydrological alteration, the "pre-impact" data for main stems consisted of series preceding the greatest (i.e. most recent) flow regime alteration.

The two sets of hydrologic indicators were implemented using specialized software: the Indicators of Hydrologic Alteration (IHA), developed by The Nature Conservancy (based on Richter et al., 1996), and the Indicators of Hydrologic Alteration in Rivers (IAHRIS), developed specifically for Mediterranean rivers by the Polytechnic University of Madrid (based on Martínez and Fernández, 2006). The latter has been used by the Spanish Ministry to evaluate the degree of flow regime alteration and the impact of dams in various Spanish basins and to aid the definition of environmental flows (Magdaleno, 2009).

The IHA software computes 33 hydrologic indices. As Mortenson and Weisberg (2010) proposed, and given the high redundancy of hydrologic metrics (Olden and Poff, 2003), a subset of the indices that change consistently with dam construction (Graf, 2006; Magilligan and Nislow, 2005) was selected to represent the flow regime changes for each hydrologic type (Table 2a). The IHA software enables users to implement the Range of Variability Approach (RVA) described in Richter et al. (1997). The full range of pre-impact data for each index is divided into three different percentile categories: low (≤33rd), middle (34th to 67th) and high (>67th). The program then computes the frequency with which the post-impact values of the IHA indices fall within each classification. Finally, a Hydrologic Alteration factor is calculated for each grouping as: *(observed frequency – expected frequency) / expected frequency*. A positive value means that the frequency has increased from the pre-impact to the post-impact period (maximum: infinity), while a negative value means the opposite (minimum: -1).

The IAHRIS software computes indicators based on flow magnitude, variability and seasonality: seven for habitual values, eight for flood events and seven for drought events. Alteration is assessed by dividing the altered value by the value corresponding to the natural or reference state. The variation interval is restricted between 0 (the most degraded situation or maximum alteration) and 1 (optimum situation or minimum alteration). Only indicators that complemented the IHA indices were selected (Table 2b); in particular, those associated with the intra-annual and inter-annual flow variability and extremes (floods and droughts) as well as the overall indicators for habitual, flood and drought values (which define the hydrologic conservation state).

2.3 Habitat and riparian surveys

Sites in freshwater streams (conductivity < 5,000 µS cm^{-1}) were selected both in reference and impaired conditions for each hydrologic type. Impaired sites were located in streams regulated by dams, but in the absence of other impacts. Habitat and riparian surveys were undertaken in dry-weather months (Environment Agency, 2003), when natural droughts and flow regulation are at their highest in the study area. A total of 65 sampling sites (Fig. 1) were visited between 2010 and 2011.

Physical habitat was characterized at each site using the River Habitat Survey (RHS; Environment Agency, 2003; Raven et al., 1997), adapted for the MARCE project (IH Cantabria, 2012). The RHS is the standard riverine hydromorphology survey in the UK that has also been used extensively in numerous countries across Europe and beyond for site quality appraisal, habitat feature inventories (Manel et al., 2000; Raven et al., 2010; Szoszkiewicz et al., 2006a), management planning (Raven et al., 2000; Walker et al., 2002) and in a range of ecological research applications (e.g. species' habitat suitability; Hastie et al., 2003; Vaughan et al., 2007). Designed to characterize and assess the physical structure of freshwater streams and rivers, the survey is carried out along a standard 500 m length of river channel. Flow types, substrates, channel and bank features and vegetation as well as special features such as very large boulders are considered. Observations are made at ten equally spaced spot-checks along the channel, while information on valley form and land-use in the river corridor provide additional context. General information is recorded using a sweep-up checklist that assesses the extent of features over the entire 500 m river reach. The version for the MARCE project records the channel dimensions at each spot-check, the presence of woody and leafy debris and additional mesohabitat types (areas exhibiting similar hydraulic characteristics, in terms of water depth and velocity, visually discernible). The Habitat Quality Assessment (HQA; Raven et al., 1998), a heterogeneity measure derived from RHS data to express the diversity of features considered to engender habitat "quality", was also applied. This metric allows the integration of widely-used habitat characteristics to diagnose potential impacts on biota (Balestrini et al., 2004; Erba et al., 2006; Szoszkiewicz et al., 2006b) in one score and nine sub-scores (flow type, channel substrate, channel features, bank features, bank vegetation structure, in-stream channel vegetation, land-use within a 50 m buffer, trees and associated features, and special features).

Within each 500 m reach, riparian condition was assessed using the Riparian Quality Index (RQI; González del Tánago et al., 2006, 2011) and by making an inventory of riparian woody plants and distinguishing between native and exotic species. Moreover, the RQI sub-indices provided additional information concerning longitudinal continuity, width, composition, structure and natural regeneration as well as bank condition, transversal connectivity between the riparian corridor and the river channel, and riparian soil (permeability and condition).

2.4 Habitat and riparian data analyses

A total of 64 variables were obtained from the 14 RHS attributes associated with the hypotheses (see Electronic Supplementary Material Table 3). When possible, categorical attributes were quantified by splitting their categories into new variables that were expressed as parts per unit (proportional extension), counts or semi-quantitative ("none", "present", "extensive") values along the 500 m reach. The remaining attributes were kept in their original form and units. Then, after transforming (log x+1) and standardizing all variables, a distance matrix was compiled among the sites employing the Gower Dissimilarity (Gower, 1971), which can handle the coexistence of quantitative, semi-quantitative and missing values (Gower, 1971; Legendre and Legendre, 1998; Podani, 1999).

Using this distance matrix, a Principal Coordinate Analysis (PCoA) and non-parametric Multiple Analyses of Variance (PERMANOVA) were run. The PCoA was employed to examine dominant intercorrelation patterns among the RHS variables and define ordination axes that described the major sources of variation while also minimizing redundancy (i.e. multicollinearity). This ordination technique was selected because it works with any distance measure (Anderson et al., 2008). A hydrologic interpretation was assigned to each selected axis according to its correlation (Spearman) with the habitat variables and location of the sampling sites in the plot, considering their hydrologic type and condition (reference or altered). The PERMANOVA analyses were used to test the overall discrimination of habitat features by hydrologic type in reference and altered conditions. PERMANOVA performs distance-based multivariate analyses of variance, and hypotheses are evaluated with permutation tests. It can be used to analyze complex experimental designs, and therefore, is considered to be a robust analysis (Anderson et al., 2008; Quinn and Keough, 2002). First, a one-way PERMANOVA was computed to test the effect of natural flow regimes on habitat characteristics. Then, a PERMANOVA with hydrologic conditions (reference or altered status) nested in the hydrologic types was used to test the existence of habitat differences between reference and altered sites by hydrologic type. Randomization tests were run using 999 permutations.

Finally, Mann-Whitney U tests were performed to explore differences between reference and altered sites in individual RHS variables, HQA and RQI scores and sub-scores, as well as the number of native and exotic riparian plants, which allowed sets of indicators that change with hydrologic alteration to be obtained. An adjusted p-value was computed to correct the effect of the number of samples (Siegel, 1956; Siegel and Castellan, 1988) and avoid family-wise errors (Tukey's adjustment; Tukey, 1953).

Gower dissimilarities were performed with the FD (v. 1.0.11; Laliberté and Shipley, 2011) package for R (R Development Core Team, 2011). PCoA and PERMANOVA were carried out using PRIMER software (v. 6.1.12; Clarke and Gorley, 2006). Mann-Whitney U tests were developed in STATISTICA (v. 6.0; Statsoft, 2001).

3. Results

3.1 Hydrologic alteration

The indirect alteration index provided values that ranged between 0 and 5 at reference stations and between 6 and 12 for hydrologically altered stations. The greatest values were obtained in main stem rivers and the lowest in stable streams, whereas seasonal and temporary streams presented intermediate values (Table 3). However, the hydrologic alteration analyses (Electronic Supplementary Material Table 1) presented a different alteration gradient, with seasonal streams as the most altered.

Main stem rivers

In the Segura River, the Fuensanta dam caused a reduction of flows throughout the year except in August, when a slight inversion in the natural pattern occurred (Fig. 2a). There was a decrease in minimum, maximum and base flows, as well as an increase in the zero-flow duration (Electronic Supplementary Material Table 1). A great reduction in the number of high pulses was also registered, as well as an increase in the duration of low pulses. Both the rise rate and the number of reversals decreased. Moreover, there was a relevant reduction in the coefficients of variation of habitual flows, especially in the monthly volumes. Floods presented the greatest overall alteration, which was evident considering the reduction in the magnitude of maximum daily flows and the effective discharge. However, the connectivity discharge showed a huge increase, and the overall conservation status was moderate for habitual values and droughts and poor for floods as a result (Electronic Supplementary Material Table 2). Downstream, the construction of the Cenajo dam exacerbated the inversion of the natural flow regime produced by the Fuensanta reservoir, reducing the magnitude of flows from autumn to spring and the opposite in summer (Fig. 2b). There was also a reduction in the magnitude of minimum and base flows and an increase in the number and duration of low pulses, as well as in the rise rate and duration of the high pulses (Electronic Supplementary Material Table 1). Floods and droughts presented a poor status, emphasizing the reduction of the minimum daily flows over the year and the coefficient of variation of the maximum ones (Electronic Supplementary Material Table 2). Whereas the maximum daily flows decreased, connectivity discharge rose.

The Tagus-Segura Transfer (1978 - …) in the Mundo River produced a huge increase in flow magnitude and a great modification in the regime downstream from the Talave reservoir (Fig. 2c). Maximum flows and December and August median flows increased, whereas minimum and base flows decreased (Electronic Supplementary Material Table 1). Altered flows presented a higher number of low and high pulses (the latter more long-lasting) and a greater rise rate. Contrary to what was observed in previous cases, the coefficients of variation for habitual flows rose. Floods suffered the highest alteration again, with an important reduction in their coefficient of variation. However, droughts presented a good conservation status, despite the reduction experienced by the minimum daily flows and the increase in their coefficient of variation (Electronic Supplementary Material Table 2). Downstream, the Camarillas dam created a similar alteration pattern (Fig. 2d), with an increase in the August median flow and a reduction in minimum and base flows (Electronic Supplementary Material Table 1). High pulses became more durable, yet less frequent. Moreover, whereas the rise rate decreased, the fall rate increased. The lowest overall alteration was that for droughts, which presented a good conservation status despite the reduction in minimum daily flows and increased coefficient of variation (Electronic Supplementary Material Table 2). Habitual values and floods presented a moderate conservation status.

Stable streams

Due to its importance for the human water supply, the Taibilla stream represents the main example of flow regime alteration in stable streams, which are usually unregulated or present only small abstractions. The Taibilla reservoir was constructed in 1979 to derive water for urban use from a pumping station 4 km downstream, which desiccated the river bed and drastically changed the flow regime along the section separating the infrastructures. Water diversion was almost constant throughout the year and produced an increase in median monthly flows and a flattened flow duration curve associated with reduced flow variability (Fig. 2e). Maximum flows, the number of high pulses and the rise rate decreased, whereas minimum flows, base flows and the fall rate rose (Electronic Supplementary Material Table 1). Consequently, floods had the greatest overall alteration (“bad” status), followed by droughts (“poor” status) and habitual values (“moderate” status) (Electronic Supplementary Material Table 2).

Seasonal streams

The Argos reservoir created both a significant reduction in monthly flows and an inversion of the natural flow regime downstream from the dam (Fig 2f). There was a reduction in minimum, maximum and base flows, as well as a large increase in the zero-flow duration. A sharp decrease in the high pulse count and a slight increase in the low pulse count (more durable) were also recorded, as well as a decreased rise rate and an increase in the number of reversals (Electronic Supplementary Material Table 1). Habitual values, droughts and floods reflected a “poor” or “bad” conservation status. Within habitual values, a greater alteration in the inter-annual than in the intra-annual variation was evident. For droughts and floods, magnitude was the most altered aspect, emphasizing the huge increase in the connectivity discharge (Electronic Supplementary Material Table 2).

Temporary streams

In the Mula stream, diversion channels link La Cierva reservoir with its associated agricultural areas. Irrigation demands require large water volumes in spring and summer (Fig 2g), significantly reduce maximum, minimum and base flows and dramatically increase the zero-flow duration (Electronic Supplementary Material Table 1). As a result, the droughts presented a “bad” conservation status. The channel remains dry during most of the year downstream (Electronic Supplementary Material Table 2).

3.2 The effect of hydrologic alteration on fluvial habitats and riparian condition

With 42.31% of variation explained, only the first two axes of the PCoA were selected, because the addition of a third axis only provided an additional 8.25% and did not facilitate the interpretation of results.

The first axis (30% variance) was positively correlated with broken standing waves, cobbles, vegetated rocks, complex banktop vegetation, liverworts, mesohabitat density, very large boulders and debris. However, clay substrates as well as those river beds that were dry and choked with vegetation (extensive emergent reeds) were negatively correlated (Electronic Supplementary Material Table 3). These habitat characteristics were associated, respectively, with stable flows (headwaters and low order river sections) and variable flows (tributaries in low and arid sectors of the basin). Reference sites were distributed along a gradient from stable streams and main stem rivers, located on the positive extreme, to seasonal and temporary streams, on the negative extreme (Fig. 3).

The second axis (12.4% variance) was positively correlated with smooth flow types, uniform or bare banktop vegetation and mesohabitat density, particularly the number of glides and steps, whereas it was negatively related to channel dimensions (water and channel width as well as depth), complex banktop vegetation, broken standing waves, the number of rapids and absence of in-channel debris (Electronic Supplementary Material Table 3). Impaired sites belonging to main stem rivers that presented turbulent flow regimes as a result of large flow releases from the biggest dams were located on the negative extreme (Fig. 3). Therefore, this axis reflected habitat characteristics associated with a gradient in flow magnitude and turbulence, from relatively low and laminar flows (positive extreme) to high and turbulent flows (negative extreme).

In general, impaired sites were located on the ordination plot to the left and bottom of their respective reference sites. Consequently, the observable effects of hydrologic alteration on habitats were those associated with an increase in flow seasonality or temporality (displacement to the negative part of the first axis) and an increase in magnitude and turbulence associated with large releases from dams (displacement to the negative part of the second axis), which was especially evident for main stem rivers.

Under reference conditions there were no significant habitat differences between the main stems and stable streams, on one hand, or between the seasonal and temporary streams, on the other (Table 4a). However, when comparing reference and altered sites within each type, only main stem rivers and seasonal streams presented significant habitat differences (Table 4b). According to the Mann-Whitney U test (Table 5, Fig. 4), altered main stem rivers presented wider channels as well as a lesser proportion of step mesohabitats and submerged macrophytes than their reference reaches. These changes were supported by a reduction in the HQA sub-score for channel vegetation as well as in the RQI sub-index for bank conditions. Seasonal streams presented the greatest number of habitat features with significant changes under altered conditions, emphasizing a significant reduction in the number of mesohabitats (particularly runs, steps, pools and glides) and riparian native plant richness as well as a major proportion of uniform banktop vegetation. The HQA overall score (as well as its flow-type sub-score) and the RQI overall value (as well as all its sub-indices) also presented a reduction in altered sites (Table 5, Fig. 4). Both main stems and seasonal streams displayed a decreasing linear relationship between the overall degree of hydrologic alteration (indirect index) and the quality scores (RQI and HQA) (Fig. 5). A hydrologic alteration equal to six (the minimum value detected in altered sites) constituted the threshold between “very good” and “good” riparian quality (RQI) for main stems and between “good” and “moderate” for seasonal streams (Fig. 5). However, in-stream habitat quality (HQA) was “moderate” at this degree of alteration in main stems and changed from “moderate” to “poor” in seasonal streams (Fig. 5).

Despite the overall lack of differences between the habitats in reference and altered sites within stable and temporary streams, significant reductions in specific features such as riparian quality (bank conditions and transversal connectivity), for the former, and the presence of submerged fine-leaved macrophytes, for the latter, were also detected (Table 5).

4. Discussion

4.1. Hydrologic alteration

Rivers and streams in the Segura Basin experienced changes in flow regimes similar to those described in other Mediterranean arid and semiarid areas. In general, dams reduce flow magnitude and variability and invert seasonal patterns (Graf, 2006; Walker et al., 1995). However, it is acknowledged that the effects of such water infrastructures on flow regime are more pronounced in Mediterranean areas than in other temperate zones due to storage needs and great reservoir capacities that respond to naturally scarce water resources (Batalla et al., 2004; Lopez-Moreno et al., 2009; Lorenzo-Lacruz et al., 2010). In fact, in the Ebro Basin (NE Spain), floods have been described to be more affected by reservoirs in its southern Mediterranean tributaries than those in the Atlantic zone, even with similar impoundment levels (Batalla et al., 2004). In the Segura Basin, the significant alteration observed in flow regimes is mainly due to water demands that exceed the available resources (Gil-Olcina, 2000), creating a structural deficit that has been further accentuated in recent decades by decreasing precipitation trends (CHS, 2005).

Differences arose depending on the tool used to define hydrologic alteration. With the proposed indirect index, main stem rivers presented the greatest hydrologic alteration, due to the higher regulatory capacity of their reservoirs, whereas stable streams showed the lowest (except the Taibilla stream), as most of them did not include dams or any other notable human pressures in their watersheds. Seasonal and temporary streams displayed an intermediate degree of alteration, with lower storage capacities in their reservoirs but large agricultural areas in their basins. However, the indicators of hydrologic alteration (IHA, IAHRIS), which take into consideration all aspects of flow regime (habitual, drought and flood values), concluded that seasonal streams experienced the greatest hydrologic alteration. As a consequence, the management regulations in dams (not only their capacity) also play a fundamental role when quantifying hydrologic alteration in streams and rivers.

As expected, the applied indicators revealed different patterns of hydrologic alteration by stream type. Alterations mainly included changes in flow magnitude (maximum, minimum and base flows), in the inter- and intra-annual variability as well as in drought and flood regimes. Main stem rivers demonstrated a progressive inversion in their flow regimes as new reservoirs appeared along the channel, producing a longitudinally increasing gradient of hydrologic alteration. Like other Mediterranean rivers (Batalla et al., 2004; Boix et al., 2010; Lorenzo-Lacruz et al., 2012), the Segura River displayed this inversion in its seasonal pattern due to the retention of fall and winter peaks as well as to summer flow releases by dams for irrigation. It also presented reduced flow magnitude and variability, as reported by previous studies (Gil-Olcina, 2000; López-Bermúdez, 2004; Vidal-Abarca, 1990). However, the Mundo River had a more pronounced inversion and, in particular, a large increase in flow magnitude and variability due to the Tagus-Segura transfer (intended to meet agricultural demands). The outstanding importance of this water transfer in the hydrologic alteration suffered by the Tagus, Mundo and Segura rivers has been stated (Lorenzo-Lacruz et al., 2010, 2012). Additionally, in the near future, an increase in the hydrologic alteration of the Segura River is also expected due to the recent construction of a tunnel from the Talave to the Cenajo reservoir, which will transfer water from the Mundo to the Segura River 20 km upstream from their natural confluence.

The tributaries presented specific alterations according to their water management. Stable streams with perennial and stable flows throughout the year underwent the least alteration because of the low agricultural demands in their forested watersheds. However, the Taibilla stream experienced a great alteration in droughts and floods, given the sustained derivation of flows to guarantee an almost constant discharge for urban demands.

Seasonal streams (e.g. the Argos stream) located in agricultural midlands with flood control and irrigation reservoirs presented a notable reduction in monthly flows and an inversion of flow seasonality downstream from the dam with a considerable increase in the duration of droughts and a decrease in the frequency and magnitude of floods. Finally, in temporary streams (e.g. Mula stream), droughts were intensified by the excessive water abstraction directly from the reservoir for irrigation purposes, which greatly reduced the water available downstream (see Belmar et al., 2010).

In summary, two hydrologic alteration trends were observed: increased flow torrentiality in main stem rivers and increased flow temporality in seasonal and temporary streams.

4.2 Hydrologic alteration-habitat relationships

Flow stability/variability and flow magnitude have proven to be the major determinants of fluvial habitats and riparian condition in the Segura Basin. Flow variability is related to morphological, hydraulic and biological characteristics (Jowett and Duncan, 1990). In the present study, flow stability was associated with channel morphology and vegetation, favoring coarse substrates, aquatic macrophytes (particularly liverworts and vegetated rocks), mesohabitat diversity and the complexity of banktop vegetation. Moreover, it prevented the channel from being choked with emergent vegetation and promoted the appearance of leafy and small woody debris. Its important role in determining the composition and richness of macroinvertebrates in the study area has already been shown (Belmar et al., 2012). However, low flows were associated with habitat characteristics such as smooth flow types, fine sediments, poorly developed banktop vegetation and reduced mesohabitat diversity.

Altering these determinants produced changes in the overall physical habitat in main stem rivers and seasonal streams, with decreasing habitat and riparian quality as the degree of alteration increased. In main stems, the releases from big dams to address irrigation demands involved increased channel dimensions, the homogenization of aquatic habitats and absence of in-channel debris. This homogenization reduced mesohabitat density and the presence of submerged vegetation, which contributed to a decrease in the quality of channel vegetation and banks. These habitat changes explain the negative effects described by Navarro-Llácer et al. (2010) on macrophyte, macroinvertebrate and fish communities downstream from the Talave dam in the Mundo River. In hydrologically-altered seasonal streams, the most prominent effect was a decrease in the richness of mesohabitats and riparian native species, with a reduction in the complexity of banktop vegetation and the occasional invasion of riparian or upland woody species into the channel. A reduction in the frequency and/or intensity of flood scouring leads to a terrestrialization of fluvial ecosystems. Drought intensifications and decreasing groundwater accelerate the loss of phreatophyte species, which have the lowest tolerance to dry conditions (e.g. *Salix alba* in Mediterranean rivers, González et al., 2012), and lead to the establishment of riparian vegetation that is more tolerant of long dry periods, such as *Tamarix* species (Nippert et al., 2010) and the reed *Phragmites australis* (Brock et al., 2006). Channel encroachment by riparian or upland woody vegetation has also been observed globally in semiarid and arid systems, presenting serious implications for hydrology and ecology (Huxman et al., 2005). Such vegetation patches block flows and divert them around and above their canopy. As a result, velocities decrease substantially within the vegetation patch, promoting the accumulation of fine sediments with a high nutrient content (Cotton et al., 2006; Sand-Jensen and Mebus, 1996), although they increase in surrounding open areas, tending to erode and become modified into chute channels (Schnauder and Sukhodolov, 2012; Wolfert et al., 2001).

River corridors regulated by dams represent major conduits for the invasion of alien species, favoring the spread of cosmopolitan non-native species at the expense of locally adapted native biota (Poff et al., 2007). An example in the western United States is the expansion of *Tamarix* and the contraction of *Populus* native species (Birken and Cooper, 2006; Merritt and Poff, 2010), associated with periods of extensive river damming (Braatne et al., 2008; Dixon and Johnson, 1999; Friedman et al., 1998; Johnson et al., 1995). However, contrary to expectations, there was no relationship in the Segura Basin between the richness of riparian exotic species and the hydrologic alteration by the dams, which could be due to the relatively low richness of exotic species in Mediterranean basins (e.g. Salinas and Casas, 2007; Tabacchi et al., 1996).

Despite the fact that temporary streams experience pressures similar to those suffered by seasonal streams, the effects of flow regulation by dams on habitats and riparian condition were less clear. The higher natural inter- and intra-annual flow variability that characterizes this type and communities that persist through natural disturbances of floods and droughts as well as their spatial variability (Brock et al., 2006) can mask the effects of flow regulation. Finally, in stable streams that are subject to low flow alteration (characterized by a habitual lack of dams), reduced flow magnitude only negatively affected riparian quality (bank condition and transversal connectivity).

The quantification of flow alteration-habitat relationships for main stem rivers and seasonal streams allowed the identification of those thresholds in which the degree of hydrologic alteration produced significant changes in habitat and riparian quality. The RQI was more sensitive to flow alteration than the HQA. This fact was not surprising considering that even small changes in water levels may induce observable changes in vegetation composition and structure (Nilsson and Svedmark, 2002). Additionally, the use of habitat heterogeneity as a surrogate of habitat quality in the HQA score has been questioned in other temperate basins (Barquín et al., 2011).

4.3 Concluding Remarks

The results presented here are essential for water management as well as fluvial ecosystem conservation and restoration, and highlight not only the flow regime components needed to preserve habitat features and native biota but also the physical changes produced as a consequence of their alteration.

Whereas previous research in the study area focused only on identifying the main hydrologic alteration patterns (Gil-Olcina, 2000; López-Bermúdez, 2004; Vidal-Abarca, 1990) or the effect of dams on a riparian quality index (Navarro-Llácer et al., 2010), the present study integrates different sets of hydrological and ecological indicators that allow the definition of hydrology-ecology relationships by stream type. This is essential for defining environmental flow regimes at a regional scale using holistic frameworks (e.g. ELOHA, Arthington et al., 2006; Poff et al., 2010), and therefore, water planning and improving dam operation rules.

The essential contribution of this study was identifiying the habitat indicators and quality scores sensitive to short- and long-term flow regime alterations in different river types in a highly-regulated semiarid Mediterranean basin. Such indicators can be used as monitoring tools in the implementation of environmental flow regimes in this basin and in other similar Mediterranean areas.

Although the procedure presented requires effort in terms of time and resources, these results encourage further research development in this field that includes other structural and functional ecological indicators. Future investigation must focus on the context of global change, not only upon determining the effects of flow and habitat alteration on aquatic communities and their implications on regional and global biodiversity, but also upon the loss of the ecosystem services that they involve.

Acknowledgements

We wish to thank the University of Murcia for the predoctoral grant to Óscar Belmar and the Ministry for Education, Culture and Sport for the predoctoral grant to Daniel Bruno. We also thank José Antonio Carbonell and Simone Guareschi for their support during the fieldwork. Finally, we are also grateful to Melissa Crim and Javier Lloret for double-checking the English.

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Table 1
Selected dams in the Segura Basin by hydrologic type, flow series analyzed and main associated uses (EP: Electric power, FC: Flood control, HS: Human supply, I: Irrigation, WT: Water transfer).

Dam	River	Hydrologic type	Year of construction	Capacity (Hm^3)	Natural series	Altered series	Main uses	Other significant impacts
Fuensanta	Segura	Main stem rivers	1933	210	1913 - 1928	1987 - 2007	I/FC/EP	
Cenajo	Segura	Main stem rivers	1960	437	1929 - 1960	1986 - 2006	I/FC/EP	Fuensanta dam
Talave	Mundo	Main stem rivers	1918	35	1943 - 1978	1979 - 2006	WT/I/FC/EP	Tajo-Segura transfer (1978 - ...)
Camarillas	Mundo	Main stem rivers	1960	36	1961 - 1978	1979 - 2006	I/FC/EP	Talave dam, Tajo-Segura transfer
Taibilla	Taibilla	Stable streams	1955,1979*	9.1	1916 - 1949	1979 - 1995	HS	
Argos	Argos	Seasonal streams	1974	10	1914 - 1929	1988 - 2008	I/FC	
La Cierva	Mula	Temporary streams	1929	7	1913 - 1927	1986 - 2006	I/FC	

* Years for the dam and water pumping station, respectively

Table 2

Selected (a) Indicators of Hydrologic Alteration (IHA) and (b) Indicators of Hydrologic Alteration in Rivers (IAHRIS) with ecological significance for habitats and riparian plants (Martínez and Fernández, 2006; The Nature Conservancy, 2007).

a)

IHA Group	Main effects	Hydrologic parameters
Magnitude of monthly water conditions	Habitat availability for aquatic plants and water resources for riparian bands	December median flow August median flow
Magnitude and duration of annual extreme water conditions	Lateral channel movement and creation of physical habitat, which involves plant colonization and the distribution of these plants in lakes, ponds and floodplains	7-day maximum flow 7-day minimum flow Base flow Zero-flow duration
Frequency and duration of high and low pulses	Influence on bedload transport, channel sediment textures and substrate grain size	High pulse count Low pulse count High pulse duration Low pulse duration
Rate and frequency of water condition changes	Stress on plants and influence on mechanical stress (e.g. incision on tributaries)	Rise rate Fall rate Number of reversals

b)

IAHRIS Aspect	Main effects	Hydrologic parameters
Habitual values (variability)	Stress on plants and influence on mechanical stress (e.g. incission on tributaries)	Coefficient of variation of annual volumes Coefficient of variation of monthly volumes **Overall Conservation Index**
Droughts (magnitude - variability)	Maintenance of water table levels or saturated sediments and encroachment of riparian vegetation into channel	Average minimum daily flows along the year (Qs) Coefficient of variation of Qs **Overall Conservation Index for droughts**
Floods (magnitude - variability)	Flush of woody debris, purging of invasive species, shaping of channel and river-floodplain connection	Average maximum daily flows along the year (Qc) Magnitude of effective discharge (Q_{GL}) Magnitude of connectivity discharge (Q_{CON}) Coefficient of variation of Qc **Overall Conservation Index for floods**

Table 3
Range and average value for the indirect alteration index by hydrologic type. Note that the number of habitat sampling sites in each type is indicated as “n”.

		Alteration index		
Hydrologic type	n	Minimum	Maximum	Average
Main stem rivers	14	1	10	7.07
Stable streams	15	1	7	2.53
Seasonal streams	24	0	12	4.83
Temporary streams	11	0	10	3.73

Table 4

PERMANOVA pair-wise tests of habitat characteristics (a) among hydrologic types in reference conditions and (b) between reference and altered conditions within each hydrologic type. Significant ($p<0.05$) pairs are indicated in bold.

a) Hydrologic types (reference conditions)	t	p
Main stem rivers, Temporary streams	**1.72**	**0.01**
Main stem rivers, Stable streams	0.95	0.49
Main stem rivers, Seasonal streams	**1.54**	**0.01**
Stable streams, Seasonal streams	**1.87**	**0.00**
Stable streams, Temporary streams	**1.87**	**0.00**
Seasonal streams, Temporary streams	0.83	0.81

b) Hydrologic type (reference, altered conditions)	t	p
Main stem rivers	**1.77**	**0.03**
Stable streams	1.25	0.13
Seasonal streams	**1.72**	**0.01**
Temporary streams	0.84	0.72

Table 5
Significant Mann-Whitney U tests for the derived RHS variables, riparian plant richness and HQA and RQI scores and sub-scores.

Hydrological type	RHS original variable/ Score	RHS derived variable/Richness/ Score meaning	Change	Adjusted p
Main stem rivers	Channel width	-	+	0.01
	Water width	-	+	0.01
	Vegetation (channel)	Submerged fine-leaved - present	-	0.01
	Mesohabitats	Number of steps	-	0.02
	HQA_5	Channel vegetation	-	0.02
	RQI_5	Bank conditions	-	0.02
Stable streams	RQI_5	Bank conditions	-	0.03
	RQI_6	Transversal connetivity	-	0.03
Seasonal streams	Flow type	Smooth	-	0.02
	Vegetation structure (banktop)	Uniform	+	0.03
	Vegetation (channel)	Emergent reeds/sedges/... - present	-	0.01
	Mesohabitats	Total number of mesohabitats	-	0.00
	Mesohabitats	Number of runs	-	0.04
	Mesohabitats	Number of steps	-	0.01
	Mesohabitats	Number of pools	-	0.01
	Mesohabitats	Number of glides	-	0.03
	HQA	Overall value	-	0.00
	HQA_1	Flow type	-	0.00
	RQI	Overall value	-	0.00
	RQI_1	Longitudinal continuity	-	0.00
	RQI_2	Width	-	0.01
	RQI_3	Composition and structure	-	0.02
	RQI_4	Natural regeneration	-	0.00
	RQI_5	Bank conditions	-	0.00
	RQI_6	Transversal connetivity	-	0.02
	RQI_7	Pemeability and condition of riparian soil	-	0.00
	-	Native riparian species richness	-	0.05
Temporary streams	Vegetation (channel)	Submerged fine-leaved - present	+	0.04

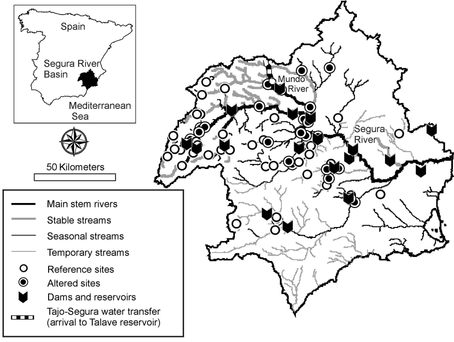
Figure 1. Study area and sampling sites (reference and altered), indicating the hydrologic types and locations of the main water infrastructures (dams and arrival of the Tagus-Segura water transfer).

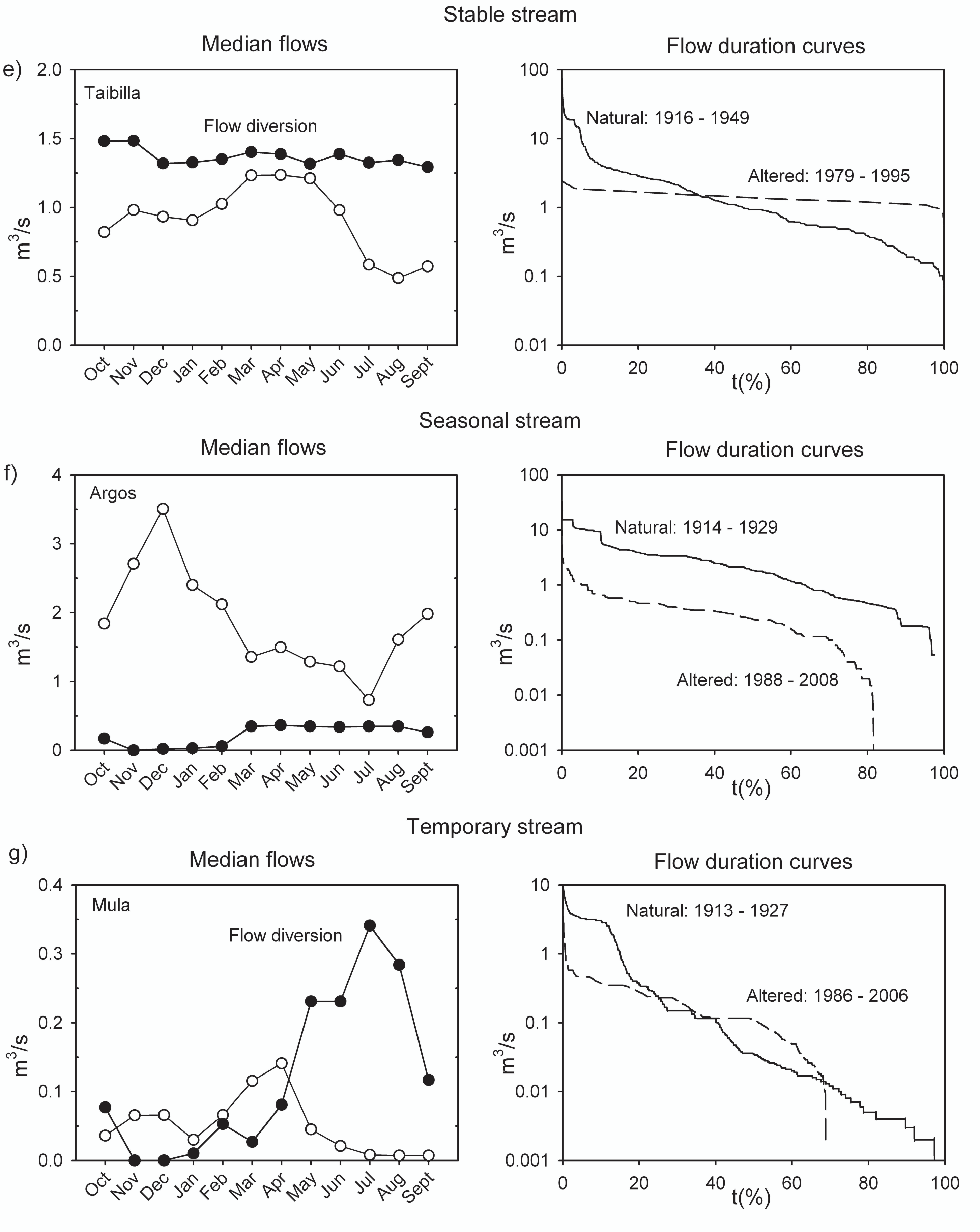
Figure 2. Hydrographs and flow duration curves for reference (white dots) and altered (black dots) flow series. Median flows (“y” axis) are in m^3/s and time (“x” axis) is shown monthly or by percentage, respectively.

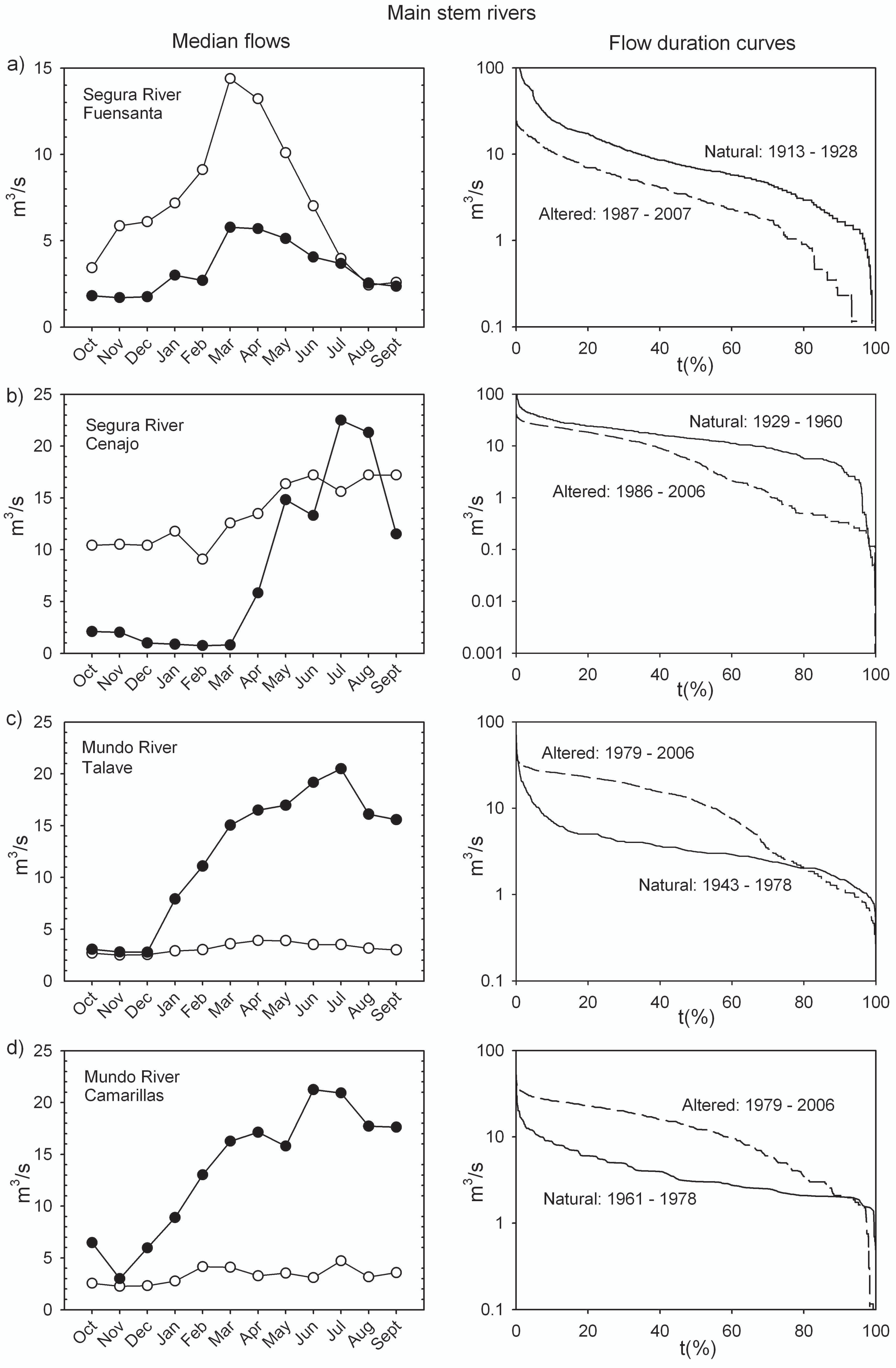
Figure 3. Biplot of the Principal Coordinate Analysis for the RHS samples by category. Note that the shapes indicate hydrologic type (circles: main stem rivers; triangles: stable streams; squares: seasonal streams; rhombus: temporary streams) and the background reference condition (white with black dot: reference, black: altered).

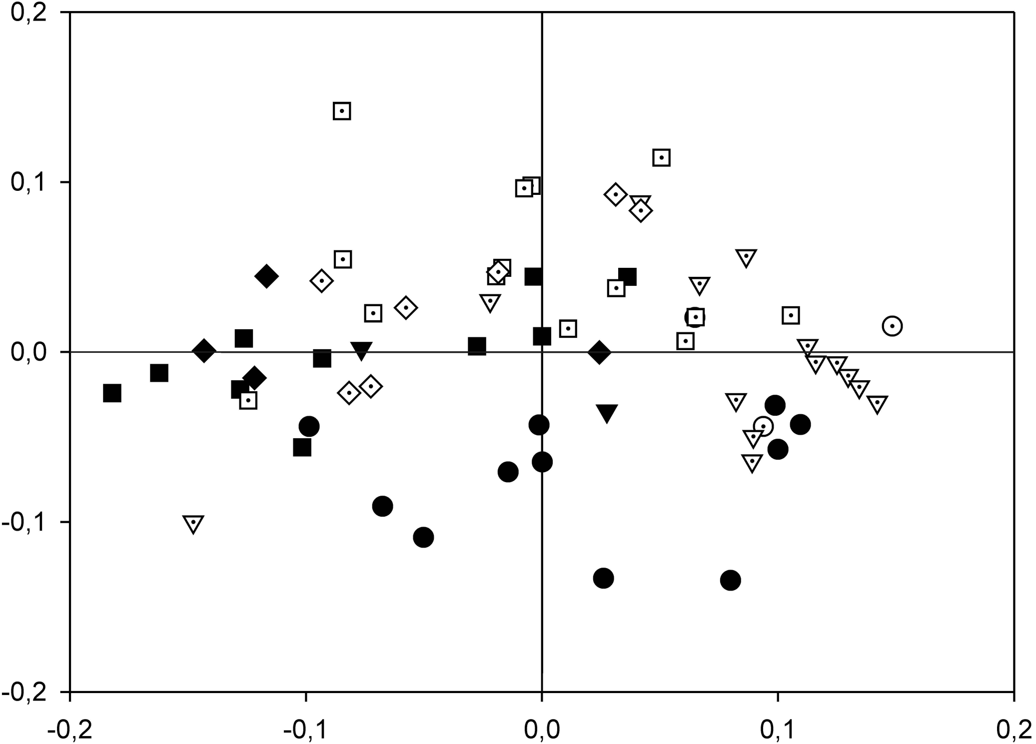
Figure 4. Box-plots summarizing the RHS variables and quality scores that significantly differ in reference and altered conditions in main stem rivers and seasonal streams. Note that the central line corresponds to the median, the box borders to the 25th and 75th percentiles, the whiskers to the minimum and maximum and the dots to outliers.

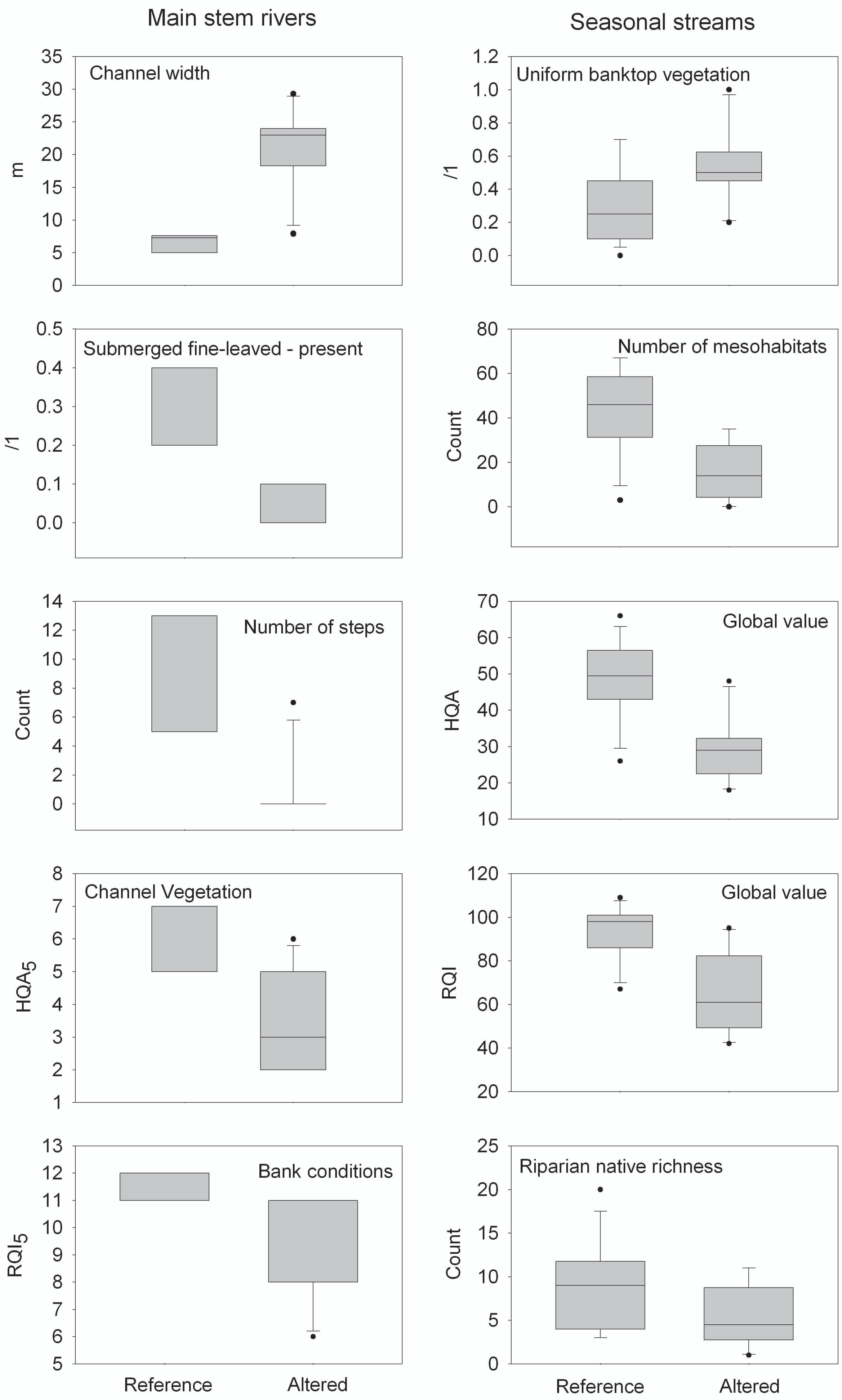
Figure 5. Regression ($p<0.05$) of the Riparian Quality Index (RQI) and Habitat Quality Assessment score (HQA) on the indirect index of hydrologic alteration for main stem rivers and seasonal streams.


Spain
Segura River Basin
Mediterranean Sea
50 Kilometers
Mundo River
Segura River
Main stem rivers
Stable streams
Seasonal streams
Temporary streams
Reference sites
Altered sites
Dams and reservoirs
Tajo-Segura water transfer (arrival to Talave reservoir)


Stable stream
Median flows
e)
Taibilla
Flow diversion
m³/s
0.0
0.5
1.0
1.5
2.0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Flow duration curves
Natural: 1916 - 1949
Altered: 1979 - 1995
m³/s
0.01
0.1
1
10
100
0
20
40
60
80
100
t(%)
Seasonal stream
Median flows
f)
Argos
m³/s
0
1
2
3
4
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Flow duration curves
Natural: 1914 - 1929
Altered: 1988 - 2008
m³/s
0.001
0.01
0.1
1
10
100
0
20
40
60
80
100
t(%)
Temporary stream
g)
Median flows
Mula
Flow diversion
m³/s
0.0
0.1
0.2
0.3
0.4
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Flow duration curves
Natural: 1913 - 1927
Altered: 1986 - 2006
m³/s
0.001
0.01
0.1
1
10
0
20
40
60
80
100
t(%)


Main stem rivers
Median flows
Flow duration curves
a)
Segura River
Fuensanta
m^3/s
0
5
10
15
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
100
10
1
0.1
Natural: 1913 - 1928
Altered: 1987 - 2007
0
20
40
60
80
100
t(%)
b)
Segura River
Cenajo
m^3/s
0
5
10
15
20
25
Natural: 1929 - 1960
Altered: 1986 - 2006
100
10
1
0.1
0.01
0.001
t(%)
c)
Mundo River
Talave
m^3/s
Altered: 1979 - 2006
Natural: 1943 - 1978
t(%)
d)
Mundo River
Camarillas
m^3/s
Altered: 1979 - 2006
Natural: 1961 - 1978
t(%)


0,2
0,1
0,0
-0,1
-0,2
-0,2
-0,1
0,0
0,1
0,2


Main stem rivers
Seasonal streams
Channel width
m
35
30
25
20
15
10
5
0
Uniform banktop vegetation
/1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Submerged fine-leaved - present
/1
0.5
0.4
0.3
0.2
0.1
0.0
Number of mesohabitats
Count
80
60
40
20
0
Number of steps
Count
14
12
10
8
6
4
2
0
Global value
HQA
70
60
50
40
30
20
10
Channel Vegetation
HQA_5
8
7
6
5
4
3
2
1
Global value
RQI
120
100
80
60
40
20
Bank conditions
RQI_5
13
12
11
10
9
8
7
6
5
Riparian native richness
Count
25
20
15
10
5
0
Reference
Altered
Reference
Altered

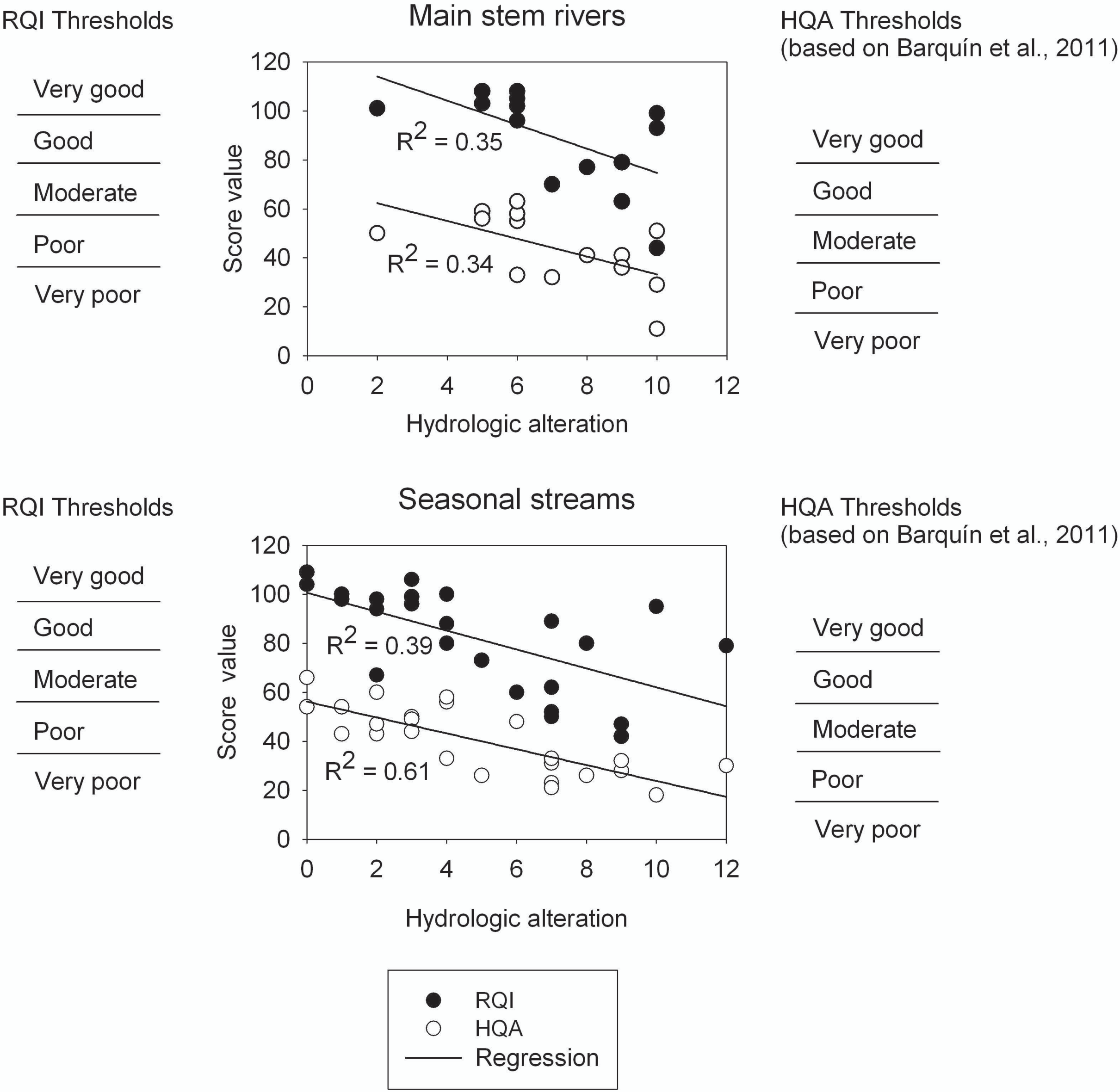

RQI Thresholds
Very good
Good
Moderate
Poor
Very poor
Main stem rivers
HQA Thresholds
(based on Barquín et al., 2011)
Very good
Good
Moderate
Poor
Very poor
120
100
80
60
40
20
0
Score value
$R^2 = 0.35$
$R^2 = 0.34$
0
2
4
6
8
10
12
Hydrologic alteration
RQI Thresholds
Very good
Good
Moderate
Poor
Very poor
Seasonal streams
HQA Thresholds
(based on Barquín et al., 2011)
Very good
Good
Moderate
Poor
Very poor
120
100
80
60
40
20
0
Score value
$R^2 = 0.39$
$R^2 = 0.61$
0
2
4
6
8
10
12
Hydrologic alteration
● RQI
○ HQA
Regression

Table 1

Indicators of Hydrologic Alteration (IHA) for the flow series associated with each dam. Note that the IHA include the results for the three percentile categories: low (≤33rd), middle (34th to 67th) and high (>67th). A positive value means that the frequency has increased from the pre-impact to the post-impact period (maximum: infinity), whereas a negative value means the opposite (minimum: -1). Blank cells indicate indetermination.

Hydrologic type	Main stem rivers												Stable streams			Seasonal streams			Temporary streams		
River/stream	Segura River						Mundo River						Taibilla stream			Argos stream			Mula stream		
Dam	Fuensanta			Cenajo			Talave			Camarillas			Taibilla			Argos			Mula		
Indicator	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High
December median flow	1.59	-0.62	-0.85	1.74	-0.74	-1.00	-0.14	-0.04	0.18	0.38	-0.91	0.73	-1.00	2.00	-1.00	1.86	-0.86	-1.00	2.10	-0.88	-1.00
August median flow	-0.54	0.52	-0.09	0.11	-0.09	-0.02	-0.79	-1.00	1.79	-0.88	-1.00	2.11	-1.00	-0.65	1.65	1.29	-0.29	-1.00	-1.00	-1.00	2.25
7-day maximum flow	2.20	-1.00	-1.00	-0.15	1.15	-1.00	-1.00	-0.79	1.79	-1.00	-1.00	2.22	2.00	-1.00	-1.00	1.86	-0.86	-1.00	1.48	-0.50	-0.85
7-day minimum flow	2.43	-0.67	-1.00	2.00	-1.00	-1.00	1.14	-0.46	-0.68	1.65	-0.72	-0.77	-1.00	-1.00	2.00	2.00	-1.00	-1.00	1.63	-0.75	-0.69
Base flow	0.83	-0.62	-0.09	2.00	-1.00	-1.00	2.00	-1.00	-1.00	2.22	-1.00	-1.00	-1.00	-1.00	2.00	2.00	-1.00	-1.00	1.63	-0.50	-1.00
Zero-flow duration		-0.07	0.52		-0.04			-0.04			-0.25			0.00			-0.76	3.05			5.50
High pulse count	3.00	-1.00	-1.00	0.30	0.47	-0.80	-0.77	0.19	0.50	0.29	-0.25	0.48	2.00	-1.00	-1.00	5.43	-0.82	-0.86	-1.00	-0.90	2.10
Low pulse count	-0.39	0.74	-0.81		-0.44	1.20	-0.74	-0.26	0.71	-0.74	-0.14	0.84		0.50	-1.00		-0.29	0.79	-1.00	-1.00	3.33
High pulse duration		-1.00	0.52	-0.43	-0.61	1.45	-0.86	0.29	1.29	-1.00	-1.00	2.50	-1.00	-1.00	-1.00	-0.46	-1.00	-1.00	1.68	-0.07	-0.59
Low pulse duration	0.02	-0.39	1.29	-0.67	-0.10	2.59	-0.23	1.22	-0.74	-0.11	0.68	0.21	-0.53	-1.00	-1.00	-0.05	0.43	1.14	3.33	-1.00	-1.00
Rise rate	1.59	-0.49	-1.00	-1.00	-0.15	1.15	-1.00	-0.36	1.36	-1.00	-1.00	2.22	2.00	-1.00	-1.00	1.71	-0.86	-0.86	-1.00	-1.00	2.25
Fall rate	0.52	-0.62	0.22	0.57	0.43	-1.00	0.39	0.38	-0.88	2.22	-1.00	-1.00	-1.00	-1.00	2.00	-0.86	0.29	0.57	2.25	-1.00	-1.00
Number of reversals	2.24	-1.00	-0.39	1.61	-0.61	-1.00	-0.89	1.89	-1.00	1.88	-0.72	-1.00	-1.00	-1.00	2.43	-1.00	-0.86	1.86	-1.00	-0.88	2.10

Table 2
Indicators of Hydrologic Alteration in Rivers (IAHRIS) for the flow series associated with each dam. Note that asterisks (*) indicate inverse values (i.e. the value of the indicator is higher in altered than in reference conditions).

Hydrologic type	Main stem rivers				Stable streams	Seasonal streams	Temporary streams
River/stream	Segura River		Mundo River		Taibilla stream	Argos stream	Mula stream
Indicator	Fuensanta dam	Cenajo dam	Talave dam	Camarillas dam	Taibilla dam	Argos dam	Mula dam
Coefficient of variation of annual volumes	0.23	0.26	0,43*	0.34*	0.14	0.11	0.61
Coefficient of variation of monthly volumes	0.75	0.82	0,79*	0.66	0.85	0.71	0.81
Overall Conservation Index for Habitual Values	0.19	0.33	0.28	0.30	0.26	0.05	0.46
Hydrologic status for Habitual Values	Moderate	Moderate	Moderate	Moderate	Moderate	Bad	Good
Average minimum daily flows along the year (Qs)	0.24	0.05	0.51	0.79	0.50*	0.02	0.00
Coefficient of variation of Qs	0,87*	0.56	0,83*	0,33*	0.30	0,39*	0.00
Overall Conservation Index for Droughts	0.20	0.12	0.57	0.43	0.10	0.07	0.02
Hydrologic status for Droughts	Moderate	Poor	Good	Good	Poor	Poor	Bad
Average maximum daily flows along the year (Qc)	0.08	0.28	0,76*	0.59*	0.07	0.27	0.60
Magnitude of effective discharge (Q_{GL})	0.27	0.39	0.91	0,96	0.20	0.56	0.86
Magnitude of connectivity discharge (Q_{CON})	0.00*	0.00*	0,18*	0.40*	0.00*	0,01*	0,51*
Coefficient of variation of Qc	0.67	0.15	0.20	0.18	0.13	0,75*	0,65*
Overall Conservation Index for Floods	0.06	0.09	0.14	0.18	0.02	0.13	0.47
Hydrologic status for Floods	Poor	Poor	Poor	Moderate	Bad	Poor	Good

Table 3

Correlation between the RHS variables derived (“New variable”) or the RHS original attributes and the two first Principal Coordinates/PCoA axes (“PCo1” and “PCo2”). Units: “/1”, parts per unit; “m”, meters; “Count”, number of features; “SQ”, semi-quantitative value (“none”, “present”, “extensive”); “P/A”, presence/absence value.

Original variable	New variable	Units	PCo1	PCo2
Channel substrate	Bedrock	/1	-0.07	0.50
	Boulder (≥256 mm diameter)	/1	0.45	-0.10
	Cobble (64-256 mm diameter)	/1	0.71	-0.13
	Gravel/Pebble (2-64 mm diameter)	/1	0.32	0.18
	Sand (0.06-2 mm diameter)	/1	0.18	0.05
	Silt (≤0.06 mm diameter)	/1	-0.30	-0.03
	Clay (≤0.06 mm diameter)	/1	-0.58	0.46
	Earth	/1	-0.33	-0.21
Flow type	Broken standing waves	/1	0.62	-0.32
	Smooth	/1	-0.05	0.55
	No perceptible	/1	-0.48	0.22
	Dry (no water)	/1	-0.48	-0.10
	Rippled	/1	0.31	-0.24
	Unbroken standing waves	/1	0.37	0.01
Marginal & Bank Features	None	/1	-0.46	0.14
	Cliffs	/1	0.37	-0.06
	Bars	/1	0.37	0.10
Channel features	None - Channel	/1	-0.57	-0.11
	Exposed bedrock	/1	-0.06	0.36
	Exposed rock	/1	0.63	0.18
	Mature island	/1	0.32	-0.28
	Vegetated rock	/1	0.69	-0.10
Channel width	-	m	-0.05	-0.38
Water width	-	m	0.42	-0.45
Water depth	-	m	0.54	-0.40
Vegetation structure (banktop)	Complex	/1	0.70	-0.42
	Simple	/1	-0.03	-0.17
	Uniform	/1	-0.47	0.41
	Bare	/1	-0.07	0.42
Vegetation (channel)	None - Channel vegetation	/1	-0.07	0.02
	Liverworts/mosses/lichens - present	/1	0.74	0.15
	Liverworts/mosses/lichens - extensive	/1	0.47	0.03
	Emergent broad-leaved herbs - present	/1	0.20	0.30
	Emergent broad-leaved herbs - extensive	/1	-0.21	0.09
	Emergent reeds/sedges/rushes/grass/... - present	/1	0.40	-0.07
	Emergent reeds/sedges/rushes/grass/… - extensive	/1	-0.51	0.32
	Submerged broad-leaved - present	/1	0.13	0.25
	Submerged broad-leaved - extensive	/1	-0.03	0.24
	Submerged linear-leaved - present	/1	0.11	0.06
	Submerged linear-leaved - extensive	/1	-0.09	0.19
	Submerged fine-leaved - present	/1	0.05	0.21
	Submerged fine-leaved - extensive	/1	-0.13	0.17
	Filamentous algae - present	/1	0.23	0.17
	Filamentous algae - extensive	/1	0.00	0.09
Debris (channel)	None - Debris	/1	-0.41	-0.29
	Large woody debris - present	/1	0.12	-0.02
	Small woody debris - present	/1	0.53	0.25
	Leafy debris - present	/1	0.50	0.33
	Leafy debris - extensive	/1	0.02	0.22
Mesohabitats	Total number of mesohabitats	Count	0.67	0.51
	Number of waterfalls	Count	0.23	0.23
	Number of cascades	Count	0.36	0.18
	Number of trench flows	Count	-0.01	0.43
	Number of rapids	Count	0.74	-0.30
	Number of riffles	Count	0.57	-0.05
	Number of runs	Count	0.56	0.13
	Number of steps	Count	0.57	0.55
	Number of pools	Count	0.43	0.41
	Number of dammed pools	Count	0.29	0.30
	Number of glides	Count	-0.12	0.73
Physical features (channel)	Sedimentary deposits	SQ	0.32	0.22
Features of special interest	Very large boulders	SQ	0.60	-0.04
	Floodplain boulder deposits - present	SQ	0.27	0.07
Choked channel	Choked channel - present	P/A	-0.56	0.28