economics for energy

WP 03/2014

Hydrological management of a heavily dammed river basin: the Miño-Sil

Juan A. Añel
Mohcine Bakhat
Xavier Labandeira

info@eforenergy.org
www.eforenergy.org
ISSN nº

Hydrological management of a heavily dammed river basin: the Miño-Sil

Juan A. Añel[1,2,3], Mohcine Bakhat[3], Xavier Labandeira[3,4,5]

[1] Smith School of Enterprise and the Environment, University of Oxford, OUCE, South Parks Road, OX13QY Oxford (UK)
[2] EphysLab, Facultade de Ciencias, Universidade de Vigo, Campus As Lagoas, 32004 Ourense (Spain)
[3] Economics for Energy, Doutor Cadaval 2, 3E, 36202 Vigo (Spain)
[4] Rede, Universidade de Vigo, Facultade de CC.EE., Campus As Lagoas, 36310 Vigo (Spain)
[5] FSR-Climate, European University Institute, Via delle Fontanelle 19, 50014 Firenze (Italy)

Abstract

We herein research the potential environmental impacts of the management of dams in the Miño-Sil river basin on the natural flow of their rivers. The Miño-Sil is a transnational river basin in the north-western Iberian Peninsula, and is managed by Spanish authorities. The basin is heavily managed with more than 100 dams, which in the main are used exclusively for hydropower generation. For the period of this study (1978-2012), we analyze the repercussions of the liberalization of the Spanish energy market in 1998. Our results show that the dams in the Miño-Sil river basin years had no influence on the natural river flows over the period of interest. Moreover, despite being used so heavily for hydropower, the liberalization of the Spanish energy market did not increase the degree of intervention in river flows. Indeed for three reservoirs in particular the correlation between inflow and outflow improved. It is also clear that for the reservoirs considered, the mean water storage and monthly inflows were lower during 1998-2012 than during 1978-1997.

Keywords: water management, reservoirs (surface) dams, hydroclimatology, systems operation and management

---

Corresponding author: Juan A. Añel. Email: juan.anel@smithschool.ox.ac.uk. Phone: +44 (0)1865 614940

The authors would like to thank the Confederación Hidrográfica Miño-Sil (the Miño-Sil river Basin District Authority) for providing some of the data used for this study. We would also like to thank Carlos G. Ruiz (MSRBDA) and David A. Pérez (Gas Natural Fenosa) for their useful comments and help. The usual disclaimer applies.

The funders had no role in the design of the experiments, analysis, or interpretation of results. This study was partly funded through a contract with the Gas Natural-Fenosa Chair at the Universidade de Vigo. The funder had no role in the research, the design of the experiments, or the analysis and interpretation of the results.

1. Introduction

The presence of a dam can significantly alter the hydrological characteristics of a catchment. They are built for a range of purposes, including flood control, hydropower generation and water supply. Their environmental impact depends on their use, on geophysical factors (meteorology, climatology), and on their management strategies. There is a significant scientific literature on the effects of dams on floods [e.g., López-Moreno et al., 2002], droughts [e.g., López-Moreno et al., 2009], and the environment [e.g., Garcia et al., 2011]. The common cause of all these phenomena is the alteration of natural flows as a consequence of the existence and operation of dams [e.g., Botter et al., 2010]. Several authors have correspondingly proposed the use of operating rules to minimize the negative effects of dams [Renöfalt et al., 2010; Yin et al., 2011], although these may compromise other objectives pursued by dam builders [Barlett et al. 2012].

The 'Miño-Sil basin' is the common name for the area administered by the Miño-Sil River Basin District Authority (MSRBDA). The area comprises the basins of the Miño, Sil, Cabe and Limia rivers, and is divided into six different zones: Miño-Alto, Miño-Bajo, Cabe, Limia, Sil-Superior and Sil-Inferior (see Figure 1). The Miño-Sil is the fourth largest basin in the Iberian Peninsula in terms of annual mean flow (10570 hm3), and is thus important for hydropower generation [Lorenzo-Lacruz et al., 2012]. The Miño river flows into the Atlantic Ocean: 95% of its basin is in Spain, but its last 76 km form the border with Portugal. The Limia crosses the border with Portugal, while the Sil and Cabe lie entirely in Spanish territory. The MSRBDA manages the Spanish sections of the Miño and Limia rivers, together with the transitional and coastal waters shared with Portugal, under a bilateral agreement [Ministerio de Asuntos Exteriores y de Cooperación, 2010].

The Miño-Sil basin is economically important for the region, in the tourism, fishing, agricultural and power generation sectors. One main characteristic of the Miño-Sil basin is that most of the reservoirs are used solely for hydropower generation, with just two also used for water supply or irrigation (see Table 1). There are 106 hydroelectric stations in the basin, of which 36 are cataloged by the MSRBDA as 'big reservoirs' on the basis of their total surface areas. In 2012 the installed generating capacity reached 2773 MW. Water from the basin is also used by two thermal power plants with an installed capacity of 1629 MW, bringing the basin's gross annual production of electricity to 14143 GWh, constituting 8.58% of the Iberian Peninsula's total electrical installed power [Confederación Hidrográfica del Miño-Sil, 2012] (information available online in www.chminosil.es). Several further projects have recently been finished or are under development to increase hydropower generation, including pumped storage reservoirs for use with existing local wind power plants.

For such a complex and heavily modified basin [Martínez-Gil and Soto-Castiñeira, 2006], one which already contributes a major share of Spanish electricity generation capacity and which is due to be increased through the addition of further hydropower projects, it is very important to gain a quantitative insight into its management from an environmental point of view in order to understand the effects of hydropower as mentioned above. Accordingly, in 2009 the regional government of Galicia, where most of the dams in the Miño-Sil basin are located, introduced a tax on hydropower production. Even though the tax was probably aimed at capturing the hypothetical rents associated with hydroelectric generation [see Gago et al., 2013], it may also have reflected environmental concerns.

The operation of a hydropower system depends primarily on the availability of water resources (runoff), but it also depends on other technical guidelines (for example those provided by the operator of the grid) and the economic factors related to the alternatives to hydropower generation. In the face of scarce or non-existent information on these secondary aspects, the potential changes in electricity generation from existing hydropower plants can be considered to be a consequence of the impact of climate change for a country or region.

Instead of a single managing body, the Miño-Sil basin relies on a mix of decisions made by public authorities, including the MSRBD and Red Electrica de España (the operator of the Spanish electricity system), and several independent private companies that use the hydropower stations (see Table 1). It is likely that these decisions are motivated by a range of motivations, including economic factors, in addition to the region's climatology and hydrometeorology.

It has been shown that climatology is important, because of the link connecting the annual hydrological cycle with phenomena such as the North Atlantic Oscillation (NAO) [García et al. 2005; Gimeno et al. 2001; Trigo 2011]. In addition to the usual effects of climatic variability on the region, climate change has affected fresh water resources via changes in the hydrological cycle. The last report by the Intergovernmental Panel on Climate Change [IPCC, 2013] supported the proposition of a positive trend in precipitation for mid-latitude areas of land in the northern hemisphere. Bates et al. [2008] argued that the changes will be widespread and that: a) the quantity, variability, timing, form, and intensity of precipitation and annual average runoff will change, b) the frequency and intensity of extreme events such as floods and droughts will rise, c) water temperatures and the rate of evaporation will increase, and d) water quality in rivers and lakes will deteriorate. Despite international agreement on the threat of climate change to water resources, the nature and magnitude of these impacts are deemed to be country/region-specific. Some regions are expected to receive too much or too little water, with a higher variability in precipitation and river discharge projected to cause great damage due to an increase in floods and droughts. These problems will be further exacerbated in the second half of the 21st century [Bates et al., 2008].

Mukheibir [2013] makes a distinction between long-term impacts related to trends, and short-term impacts, which are usually linked with extreme weather events. Long-term variations in rainfall patterns could cause highly variable inflows to reservoirs, and have the potential to affect hydropower generation. This could cause the operation of some dams to become sub-optimal, either for technical or economic reasons [Iimi, 2007]. This effect could be exacerbated by increased evaporation due to the expected increase in mean global temperature, reducing reservoir water levels. Hamududu and Killingtveit [2012] states that by 2050, climate change will lead to a 1.73 TWh/yr (1.28%) decrease in hydropower production in western Europe, being up to 10% for Spain. It also states that the impacts will differ by region and must therefore be studied at a local level.

By the end of the 21st century, the water resources available for hydropower production in the Miño-Sil basin will be at best 40% less than those available for the period 1980-1999 [IPCC, 2011] . Lehner et al. [2005] predicted that by 2070, electricity production from southern European hydropower stations would be reduced by 20–50% in comparison with the period 1960-1990. Spanish hydropower generation in recent years is believed to be below historical levels for most plants, due to a series of dry years on the Peninsula [Espejo and García-Marín, 2010]. While the annual inflow generally determines the total hydropower generation [Tanaka et al., 2006], hydropower endowments can also be affected by the impact of climate change on the seasonal pattern of the hydrological cycle. In Spain, the majority of hydropower plants were built in the 1960s, in locations that were chosen based on historical records of climatic patterns that are now obsolete as a result of natural climate variability.

The research presented here is informed by a dual interest in environmental impacts: those resulting from dam operations in the Miño-Sil basin, and those related to the liberalization of the Spanish energy market. In 1998 the Spanish electricity sector went through a major transformation in the interests of this process of liberalization; this could well have affected the management strategies of the different reservoirs in the basin. We therefore split the study into two periods, before and after 1998.

We applied a number of different statistical tests together with a clustering technique to streamflow and water storage time series from the Miño-Sil basin. The remainder of this paper is structured to include a data and methods section, followed by the results for storage capacities, inflows, outflows, trends and clustering analysis, and a discussion.

2. Data and Methods

2.1 Data

Hydrological data were obtained from the MSRBDA. The hydrological data include the daily observed discharge (streamflow) of mountain stations, and discharge from stations along the main tributaries of the Miño and Sil rivers. Of the 36 big reservoirs in the Miño-Sil basin, 31 were included in this study. The reservoirs selected were those with the longest time series that contained less than 5% missing values. The study covers the period from 1978 to 2012, which is the maximum period of continuous data for inflows and outflows. Although the data for two of the reservoirs (IDs 1780 and 1781) cover a shorter time span, they were included because of their hydrological importance (for example, reservoir 1781 has the lowest storage capacity). The temporal coverage of the data is summarized in Figure 2. The reservoirs' locations are shown in Figure 1, and Table 1 lists additional hydrological information. The selected data represent the main reservoirs distributed over the upstream and downstream sections of the area of study. Unlike meteorological data, water storage data do not require specific tests to detect and correct inhomogeneities [Morán-Tejeda et al., 2012]; such tests are not feasible because it is not possible to establish the source of the inhomogeneity. In some cases where the data series of inflow was incomplete, we gap-filled the series using the continuity equation that relates storage capacity (St), inflow (It), and outflow (Ot): St=St-1+It-Ot [Martin et al., 1999 (page 432)]. The selected reservoirs are all used exclusively for electricity generation, except for the Bárcena and Fuente del Azufre reservoirs (ID numbers 1709 and 1710 respectively), which are also used for irrigation and water supply, respectively.

To ensure the reproducibility of this research [Añel, 2011], our computations were performed using the software R v2.15 [R Core Team, 2012], free software under the GPLv2 license (http://www.gnu.org/licenses/old-licenses/gpl-2.0.html). The 'kendall', 'boot' and 'stats' packages were used, in particular.

2.2 Impoundment ratio and correlation

To measure the influence of each dam on its downstream hydrology we follow the methodology of Morán-Tejeda et al. [2012] by computing the Impoundment Ratio (IR) and the Operational Impoundment Ratio (OIR) [Batalla et al., 2004; Morán-Tejeda et al., 2012]. The two quantities differ in the numerator, which for IR is 'storage capacity' and for OIR is the 'operational storage capacity', defined as the difference between the historical maximum and the historical minimum of the storage capacity.

$$IR = \frac{Storage \quad Capacity}{Long-term \quad Mean \quad Annual \quad Inflow}$$

In order to assess the degree to which the river flow regimes were altered, we computed the Pearson's correlation coefficient between inflows and outflows. The correlation coefficient 'r' is a measure of the rectilinear relationship between the variables, in which larger values correspond to stronger associations. At its extreme, a correlation of 1 means that the river regime downstream of the reservoir was identical to the regime at the reservoir entrance, so that there was no alteration of the natural flow regime. At the other extreme, a negative correlation of value -1 indicates that high inflows are paired with low outflows, and vice versa, indicating a reversal of the river's natural seasonality. A correlation value $|r|=0$ implies an absence of correlation between inflows and outflows, which also means a significant alteration to the river flow regime [Batalla et al. 2004; Morán-Tejeda et al. 2012].

2.3 Trends and cluster analysis

To analyze the potential trends in storage capacities and monthly outflows during the study period we used the following approaches: (i) a local polynomial regression fitting (LOESS) [Cleveland et al., 1993], (ii) a simple linear regression analysis plus boostrapping, (iii) a non-parametric Mann-Kendall test.
Because the first two tests require normality, we used Q-Q-plots to check that this condition was fulfilled by all of the series (see dynamic content 1). We note that all three variables (storage, inflow and outflow) are normally distributed for all the reservoirs except Sequeiros, Montefurado, Frieira and San Martín (ID numbers 1751, 1744, 1641 and 1740 respectively).

The LOESS procedure utilizes a nonparametric method to estimate regression surfaces and hence identifies any long-term behavior in the data. Its use is suitable when outliers are detected in the data and a robust estimation is needed.

We applied a linear regression directly to each of the time series in turn, using time as the independent variable. When interpreting the slope of the regression line, trends may be obscured by data scatter arising from multiple sources, including non-ideal hydrogeological conditions, and sampling inhomogeneities. Even though the scatter may be large, yielding a low goodness-of-fit, the overall trends in the data may still be ascertained using the confidence intervals. The null hypothesis H0 that there is no trend is tested against the alternative hypothesis H1 that there is a trend at different significance levels (1%; 5%; 10%).

To examine further the robustness of the linear trends, a bootstrapping analysis [Davison and Hinkley, 1997] with 1000 random samples was also performed. 1000 slopes were calculated and 95% confidence intervals were derived from the normally distributed slopes, to indicate the extent to which the trends are affected if the time series is relatively short.

Finally, as the selected time series in this study are not perfectly normally distributed, we also used the non-parametric Mann-Kendall (MK) test [Kendall, 1975; Mann, 1945] to double-check the validity of the results from the linear regression. The MK test is based on the rank-correlation approach, and has been widely used in hydrometeorological studies to test the validity of the null hypothesis, of no trend, against the alternative hypothesis of increasing or decreasing trend [Hamed, 2008; Fu, 2004; Moberg and Jones, 2005; Morán-Tejeda et al., 2012; Rotstayn and Lohmann, 2002; Zhang, 2009].

Clustering [Gordon, 1987; Everitt et al., 2011] allows observations to be grouped according to how similar they are, on the basis of a measure of the distance between observations. Cluster analysis techniques fall into three categories: agglomerative hierarchical techniques, k-means clustering, and k-medoids clustering. Here we used all three methods.

For the hierarchical technique, we used the Euclidean distance between objects to form the clusters, and Ward's method to determine the similarity between objects [Ward, 1963], which has previously been successfully tested [Bonell and Summer, 1992; Morán-Tejeda et al., 2012].

The k-means clustering algorithm also uses the Euclidean distance but minimizes the within-class sum of squares from a pre-specified number of cluster centers [Ripley, 2002].

The k-medoids method is very similar to the k-means method. The main differences lie in the way the center of a cluster is chosen, and that k-medoids clustering is more robust in the presence of outliers. Here we use the CLARA algorithm for k-medoids clustering, an improvement on the Partitioning Around Medoids (PAM) method, which improves the efficiency when clustering large data. In cases where the data are not clearly separated into groups, identifying the number of clusters becomes more difficult. We addressed this problem using validity indexes to measure the quality of each cluster, namely the wb, Silhouette and Dunn's indexes [Zhao, 2013].

3. Results

3.1. Dam operations and river regimes

We chose three different reservoirs with different uses and conditions to show the impacts of dam operations and reservoir management (see Figure 3). Figures for the other reservoirs are included in dynamic content 2.

The Belesar dam across the Miño River was completed in 1963 and is the largest in the Miño-Sil basin, with a storage capacity of 654 hm3 and a generation capacity of 225 MW during the study period (following construction work in November 2013 a further 20.8 MW were added). The reservoir shows high flows between December and April, and low flows for May-November. The minimum (208 hm3) and maximum (495 hm3) storage capacities are recorded in November and May, respectively. Figure 3 shows that inflows exceeded outflows from November to May, while outflows exceeded inflows from June until the end of summer season. The flows in the Belesar basin are only slightly altered by the presence of the dam, as indicated by the high correlation coefficient (0.98).

In the Sil-Superior zone the Fuente del Azufre reservoir has a smaller storage capacity and is used for hydropower and water supply. The monthly reservoir capacity has a small variation with a long-term maximum capacity in July. The flows exhibit a different pattern, with inflows having two marked peaks (note that in Figure 3 the inflow (red line) is not obvious as it is extremely similar to outflow (blue line)), one in summer and the other in winter, and with water releases dropping markedly between January and May and also between July and September. The very low storage capacity of this particular reservoir means that its management strategy is intended to keep the storage capacity at a certain level without altering river regimes. This is also shown by the high correlation coefficient of 1.

In the same Sil-Superior zone the Bárcena reservoir with 341 hm3 storage capacity is used for irrigation and electricity generation. The monthly storage capacity reaches its maximum in May and its minimum in November. The alteration of the river regime downstream of the reservoir is more pronounced than in the previous two cases. This is confirmed by a smaller correlation coefficient between the monthly inflows and outflows (r=-0.259).

Table 1 summarizes the different characteristics of the reservoirs considered in this study, including the impoundment ratio IR, its modified version OIR and the Pearson's correlation coefficient between monthly inflows and outflows. The impoundment ratio and its modified version indicate that 50% of the reservoirs had small storage capacities to contain the long-term annual inflows, with values of less than 0.05. On the other hand, Belesar, Bárcena, Albarellos, As Portas and Salas are among the reservoirs with higher impoundment ratios ranging between 0.22 and 1.10. Furthermore, by comparing the IR and OIR values it may be concluded that Bárcena does not reach its maximum storage capacity, because this variable is the only difference between both quantities. It is interesting to note that three of the five reservoirs are managed by the same company (Fenosa). Table 1 indicates also that the majority of the reservoirs with the lowest change in flow regimes tended to have lower levels of regulation. In fact, 11 of the 36 reservoirs studied have values of IR and OIR equal to zero, meaning that their storage capacity is extremely low in relation to their inflow, and the correlation between inflows and outflows is 1.0 in all cases. Ten of these eleven reservoirs are in the same cluster (see section 3.3 and table 1). Figure 4 clearly depicts these characteristics and shows how the Bárcena reservoir (id. 1709), which is used for both irrigation and electricity generation, has a high level of regulation. Most of the others lie on or near the regression line.

The two panels of Figure 5 represent the level of regulation versus the alteration of reservoir regimes for two different time periods pre- and post-liberalization (before and after 1998) of the energy market in Spain. The post-liberalization period is characterized by a better fit between the correlation coefficient and the OIR than the previous period (Rpre2=0.61; Rpost2=0.90). The low value of the correlation coefficient for the As Portas reservoir (id. 1770) before 1998 indicates a significant improvement in regime after liberalization. In contrast, the correlation coefficient of the Bárcena (1709) reservoir switched from a negative value before 1998, indicative of an inverted flow regime downstream of the reservoir, to a positive value (0.83) that indicates a very low change in the fluvial regime. For each of the remaining reservoirs there was a slight change of both OIR and correlation coefficient between the two periods.

Storage capacity and flows were also assessed for both periods (see Figure 6 and dynamic content 3). Storage capacity is conveniently represented using a box plot. For instance, the inter-quartile range (IQR) gives a useful indication of the “spread” of the middle 50 percent of the data. Because the middle 50 percent is not affected by outliers or extreme values, this gives a more robust and less biased visualization of the data spread. The IQR of Belesar’s storage capacity decreased after 1998 for each month of the year, indicating a lower spread than during the previous period. The right plot provides a visual comparison between the two panels, which indicates similar behavior for the two periods. However, both the mean and median tend to decrease during the second period (post-1998), especially from July to October. Further, the upper whiskers indicate that monthly maximum capacities were recorded during the first period. The bottom whiskers for the months September to December are lower in the second period than the first, while greater in the second period for the other months (they are very similar in March). Thus, there is an indication of storage capacity difference between the two periods for at least 7 months of the year. Furthermore, although the maximum values of storage capacity were recorded during the first period, the minimum values were also recorded in the same period for the months from January to August. The effect of market liberalization is clear in the reservoirs corresponding to the Miño-Bajo zone. Before 1998 the reservoirs in this region were operated using maximum storage criteria to maximize power production. Moreover Albarellos is now operated using a maximum capacity 10 hm3 lower, in order to avoid inundations in its region of influence. As far as flows are concerned, the general shapes did not change between the periods, suggesting that the fluvial regime and intraannual conditions upstream were themselves unchanged.

The box plot representation shows the changes in the storage capacity of Fuente del Azufre reservoir (as in Figure 3 the blue line overlaps red line). The box size shows that the data are less dispersed in the second period than the first, and the medians also tend to decrease during the second period (post-1998), especially during the winter season. In other words, storage capacity decreased during the second period for 9 months of the year. Despite this decline in storage capacity, the whiskers show that minimum capacity values were recorded in the first period for almost every month of the year. Similarly, the pattern of the flows changed between the two periods, suggesting a relative fall in flows during the summer season.

In the same manner, the box plot representations of Barcena's storage capacity during the second period depicts a fall from April to July and an increase from October to December. The upper whiskers show that maximum storage capacity values were higher in the first period for January to July but lower for September to December. The lower whiskers of the months March to June were higher in the first period, whereas those for the rest of the year were higher in the second period.

The position of the median is in most cases indicative of a clear skewness of the data and suggests the use of statistical tests that relax the normality assumption. In the next section the Mann Kendall non-parametric (MK) test is applied to assess trends in the storage capacity and flows, with the two periods of the study assessed separately.

3.2. Trend analysis

For monthly storage capacity, linear regression results in significant trends for 72% of the cases, of which 17 reservoirs have negative trends and 4 reservoirs have positive trends. In the Sil-inferior zone, 9 of the 16 reservoirs considered have significant negative trends, as do all four reservoirs in the Miño-Bajo zone. These results are confirmed in most cases by the MK test, as indicated by the Kendall rank correlation coefficients (τ), and the corresponding p-values and bootstrapping confidence intervals (see Tables 2 and 3).

For monthly outflows, linear regression indicates significant negative trends in 52% of cases. For instance, all reservoirs in the Sil-superior zone have a significant negative trend, which is corroborated by the non-parametric MK test. Figure 7 shows the linear regression trends of storage capacity for three important reservoirs in the Miño-Sil basin (for plots of other reservoirs see dynamic content 4). By selecting different sample periods, persistent negative trends in storage capacity are shown for the Belesar and Bárcena reservoirs, while As Portas shows a significant positive trend.

A two-period analysis was performed to assess the different trends during the periods before and after 1998. Table 4 provides a concise account of the change in seasonal trends for storage capacity and flows. In summary, the main changes occurred during the summer season, especially for inflows and outflows. The most striking finding is the increased number of statistically significant negative trends in both inflow and outflow in the August of the second period. The significant positive trends in both inflow and outflow in June of the first period have almost vanished during the second period. Similarly in January, an increased number of significant negative trends was recorded in the second period. Periods of positive trends also changed between the periods. For instance, the number of significant positive trends in storage capacity decreased in 8 months of the year, with the most frequent changes occurring in the Sil superior zone, followed by Miño Alto zone.

Interestingly, it is only in November that there are more reservoirs with positive trends in storage capacity than reservoirs with negative trends.

In winter, there are at most four reservoirs with positive trends in storage capacity, which occurred for February before 1998: after 1998, such a trend is only obtained for one reservoir. In general, negative storage trends are more common than positive ones. For 7 months of the year they are more common than positive ones when considering the 'whole sample'. Before 1998, six months show a greater number of reservoirs with negative trends compared to four months where reservoirs with positive trends were in the majority.

After 1998, the numbers for trends in storage capacity are almost the same, with six months predominantly negative and five positive. Moreover for April and May there are eight reservoirs that show positive trends and eight with negative trends respectively. This compares to one and zero for the opposite trends in the same months. For the summer months this same relationship is 4-1, 0-5 and 10-1 for negative and positive trends, respectively. This suggests that the pattern is at least partly caused by the regulation of flow by dams, where in a given month a dam stores a great amount of water, which is used to generate hydropower before passing to the next reservoir downstream.

The greatest numbers of trends in storage capacity are related to high numbers of trends in inflows and outflows, always maintaining the sign of the trend. For example, in post-1998 January there is a negative trend in storage capacity for 13 reservoirs. This number matches a negative trend in the inflow for 12 reservoirs and outflow for 18. A similar behavior can be observed for August and for the whole sample for May and December. For positive trends such a link is only obvious for April post-1998.

3.3. Cluster analysis

Clustering methods are very useful to find common patterns in different data series. Several of them are commonly used in hydrological research. Each method has benefits and limitations and it can be hard to determine a priori which is the best one for a given study. Here a number of different clustering methods were used for the analysis in order to get a wider perspective of the studied problem and a more robust result. The data set of measurements used so far was extended by adding the monthly MK coefficients calculated in the previous section. Table 5 gives the average values of cluster validation indexes calculated by the clustering methods applied in this study. The distance-based measurements include the following: cluster separation (btwn); the average distances within clusters (avg within); and the average distances between clusters. Other indices considered include the Silhouette index and the Dunn index. The Dunn Index values were more varied across the cluster number domain, but in general the k-means and hierarchical clustering techniques showed the highest values, and were therefore chosen as the preferred techniques. Figure 8 plots the Dunn Index and Silhouette width as two measures of cluster number validation. Remembering that both the Dunn Index and the Silhouette Width should be maximized to obtain the optimum number of clusters, it appears that the hierarchical clustering and k-means methods perform better than the PAM method under the Dunn Index or the Silhouette width, if the number of clusters is greater than three. There are therefore 2 or 4 possible clusters. However, because 2 clusters might be insufficient to extract optimal information from the data, we opted for 4 clusters, which is highly recommended by the Dunn Index validation theory.

Looking at Table 5 it appears that storage capacity was the main factor in the cluster groupings. Cluster 1 is composed of Os Peares, Bárcena, Bao and San Esteban (see Table 1) which are reservoirs with storage capacities between 182 and 341 hm3. All the reservoirs in this cluster have significant negative trends, apart from Os Peares which has a positive trend. The corresponding outflows show significant negative trends for Bárcena and San Esteban only. Cluster 2 contains reservoirs with high storage capacities, on average almost twice those of the first cluster. Neither of the reservoirs in this cluster have any significant trend in outflow but show opposite trends in storage capacity, with As Portas having a positive trend. Cluster 3 contains most of the reservoirs considered in this study, but does not show any clear-cut characteristics, even though all the reservoirs in the Sil-inferior zone belonging to cluster 3, apart from San Martin, have significant negative trends for both storage capacity and outflow. Finally, all the reservoirs in cluster 4 are in the Miño-bajo zone and show significant negative trends for storage capacity. It is worth noting that the Montearenas, As Portas, San Martin, and Os Peares reservoirs have significant positive trends, very pronounced in the case of As Portas and Montearenas (see figure 7 and dynamic content 4).

4. Discussion

In this study we used the operational impoundment ratio, and the degree of correlation between monthly inflows and outflows, to assess the hydrological alterations and control of river flow in the Miño-Sil basin. The different values of the Pearson's correlation coefficient indicate that the reservoirs were subject to varying management strategies, due in part to the liberalization of the Spanish energy market in 1998 and the consequent management strategies of private companies. In effect, the effect on monthly flows ranged from practically no change in regime to compete inversion in seasonal pattern, due to extra outflows for irrigation in summer. The correlation between inflows and outflows ranged from 0.91 to 1 for the former type of reservoirs and from 0.027 to 0.333 for the latter. This is in fact a common characteristic of many reservoirs in the Mediterranean region, exemplified by the Spanish reservoirs [Batalla et al. 2004; Goodess and Jones 2002; Philandras et al. 2011].

It is possible that the post-1998 changes in reservoir regimes (storage, inflows and outflows) could be related to the impacts of climate change, but this is an issue to be addressed in future research.

There is a relationship between the operational impoundment ratio and the river's degree of alteration, in the sense that reservoirs with low change of flow regimes tend to be lightly regulated.

The use of a reservoir also affects the degree to which flow regimes are altered. It is of interest to highlight two contrasting characteristics: 1) reservoirs intended to produce only hydroelectricity have small values of operational impoundment ratio and are subject to minimal regime alterations, 2) reservoirs designed to supply multiple uses, such as hydropower generation and irrigation, have greater impoundment ratios and are prone to greater regime change.

For the period studied, 86% of the 30 reservoirs studied were affected by decreasing inflows, a feature that also transmitted in most cases to lower storage capacity of the reservoirs. It is clear that how the inflows and outflows are managed has a direct impact on a reservoir's storage capacity. For instance, for all the reservoirs located in the Baixo-Miño zone, close to the river mouth, negative trends are detected for both flows and storage capacity. In the Sil-inferior zone where most of the reservoirs are located, 10 of the 16 reservoirs have negative trends in both storage capacity and inflow. Seasonal analysis of the trends also reveals important findings. The inflows of all the reservoirs show a negative trend for more than 36% of the cases in March, May, September and October. By contrast, 8 of the 30 reservoirs show a positive trend in April (36% of the cases). In other words, and taking 36% as an example of the percentage occurrence, seasonal negative trends are more common than seasonal positive trends.

The cluster analysis yields a first group (Cluster 1) comprising Os Peares, Bárcena, Bao and San Esteban, which are reservoirs with storage capacity between 182 and 341 hm3. Except for Os Peares which has a positive trend, all the reservoirs in this cluster have significant negative trends. The corresponding inflows exhibited significant negative trends for all except the Bao reservoir. Cluster 2 comprises the Belesar and As Portas reservoirs, which are the most important in terms of capacity. Belesar, the largest, shows a significant negative trend in storage, inflows and inflows. As Portas has had a significant increase in its storage capacity in the face of declining inflows, particularly in the spring season during the study period. This has been achieved by managing the reservoir's outflows to offset the negative impact of the dropping inflows on storage capacity. As Portas has a system installed to pump outflows back to the reservoir to improve both management and economic benefit. Cluster 3 contains most of the reservoirs, accounting for 21 of the total of 30. Significant negative trends in inflow were detected for 18 of these reservoirs, which have in turn been directly affecting the storage capacity for 10 of those reservoirs. On the other hand, the Montearenas, San Martin and Prada reservoirs have shown significant positive trends during the period of study, which is simply due to a management strategy that controls flows to maintain maximum storage. Cluster 4 comprises three reservoirs in the Miño-Bajo zone with storage capacities ranging between 17 and 91 hm3. During the period of study, each of these reservoirs showed negative trends for storage capacity, inflow and outflow, with a particular decline in inflow during spring and autumn.

References

Añel, J. A. (2011), The importance of reviewing the code. Communications of the ACM. 54 (5), doi: 10.1145/1941487.1941502.

Barlett, R., Baker, J., Lacombe, G., Doungsavanh, S., Jeuland, M. (2012), Analyzing economic tradeoffs of water use in the Nam Ngum river basin, Lao PDR. Duke Environmental Economics Working Paper EE12-10

Batalla, R. J., Gómez, C. M., and Kondolf, G. M. (2004), Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). J Hydrol 290(1–2):117–136.

Bates, B. C., Kundzewicz Z. W., Wu, S., Palutikof, J. P., eds. (2008), Climate Change and Water. Geneva: IPCC Secretariat. pp 210.

Bonell, M., and Summer, G. (1992), Autumn and winter daily precipitation areas in Wales, 1982-1983 to 1986-1987. Int J Climatol 12(1):77-102.

Botter, G., Basso, S., Porporato, A., Rodríguez-Iturbe, I., Rinaldo, A. (2010), Natural streamflow regime alterations: damming of the Piave river basin (Italy), Water Resources Research 46 (6).

Cleveland, W. S., Grosse E., and Shyu, W. M. (1993), Local regression models. In: Chambers,J.M., Hastie, T.J.(Eds.), Statistical models in S.Chapman & Hall, Boca Raton,Florida, pp. 309–379.

Confederación Hidrográfica del Miño-Sil (2012), Plan Hidrológico 2010-2015 de la parte española de Demarcación Hidrográfica del Miño-Sil.

Davison, A.C., and Hinkley, D.V. (1997), Bootstrap Methods and Their Application. Cambridge University Press.

Espejo, C., García-Marín, R., (2010), Agua y energía: producción hidroeléctrica en España. Investigaciones Geográficas, 51:107-129

Everitt, B. S., Landau, S., Leese, M., and Stahl, D. (2011), Cluster Analysis, Chichester, UK: John Wiley & Sons, 5th edition. Cited on p. 165, 166, 171,176, 180, 198.

Fu, G., Chen, S., Liu, C., Shepard, D. (2004), Hydro-climatic trends of the yellow river basin for the last 50 years. Clim Change 65: 149-178.

Gago, A., Labandeira, X., López-Otero, X. (2013), A panorama on energy taxes and green tax reforms. Economics for Energy WP 08/13.

García, N. O., Gimeno, L., De la Torre, L., Nieto, R., Añel, J. A. (2005), North Atlantic Oscillation (NAO) and precipitation in Galicia (Spain), Atmósfera, 18: 25-32.

García, A., Jorde, K., Habit, E., Caamaño, D., Parra, O. (2011), Downstream environmental effects of dam operations: changes in habitat quality for native fish species, River Research and Implications 27 (3):312-327

Gimeno, L., Añel, J. A., González, H., Ribera, P., García, R., Hernández, E. (2001), The Temperature Component of the Common-Sense Index in Northwestern Iberian Peninsula. In Brunet-India M and López-Bonillo D (eds) Detecting and Modelling Regional Climate Change. Springer, Berlin, pp 143-151.

Goodess, C. M., Jones, P. D., (2002), Links between circulation and changes in the characteristics of Iberian rainfall. Int J Climatol, 22:1593–1615. doi: 10.1002/joc.810.

Gordon, A. D. (1987), A review of hierarchical classication. J R Stat Soc A Stat, 150, 119-137. Cited on p. 165.

Hamed, K. H. (2008), Trend detection in hydrological data: The Mann-Kendall trend test under the scaling hypothesis. J Hidrol, 349, 350-363. doi:10.1016/j.jhydrol.2007.11.009.

Hamududu, B., Killingtveit, A. (2012), Assessing Climate Change Impacts on Global Hydropower. Energies, 5(2), 305-322; doi:10.3390/en5020305.

Iimi, A. (2007), Estimating Global Climate Change Impacts On Hydropower Projects : Applications In India, Sri Lanka And Vietnam. In Policy Research Working Papers, The World Bank, 40 pp. Doi: 10.1596/1813-9450-4344.

Intergovernmental Panel on Climate Change (2011), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1075 pp.

Intergovernmental Panel on Climate Change (2013), Approved Summary for Policymakers of full draft report of Climate Change 2013: Physical Science Basis, Stocker T, Dahe Q, Plattner G-K, coordinating lead authors, available: http://www.ipcc.ch/report/ar5/wg1.

Kendall, M.G., (1975), Rank correlation methods, 4th ed. Charles Griffin, London.

Lehner, B., Czisch, G., & Vassolo, S. (2005), The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 33(7): 839–855.

López-Moreno, J.I., Beguería, S., García-Ruiz, J.M. (2002), Influence of the Yesa reservoir on floods of the Aragón River, central Spanish Pyrenees, Hydrology and Earth System Sciences 6(4):752-763.

López-Moreno, J.I., Vicente-Serrano, S.M., Beguería, S., García-Ruiz, J.M., Portela, M.M., Almeida, A.B. (2009), Dam effects on droughts magnitude and duration in a transboundary basin: the lower river Tagus, Spain and Portugal, Water Resources Research 45(2).

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., Morán-Tejeda, E., Zabalza, J. (2012), Recent trends in Iberian streamflows (1945–2005), J. Hydrology, 414–415, 463-475. doi:10.1016/j.jhydrol.2011.11.023.

Mann, H.B. (1945), Nonparametric tests against trend. Econometrica 13: 245-259.

Martin, J.L., McCutcheon, S.C., Schottman, R.W. (1999). Hydrodynamics and transport for water quality modeling. Lewis Publishers, Boca Raton.

Martínez-Gil, F. J., Soto Castiñeira, M. (2006), O tempo dos ríos, Universidade da Coruña, A Coruña. 356 pp.

Ministerio de Asuntos Exteriores y de Cooperación (2010), Protocolo de revisión del convenio sobre cooperación para la protección y aprovechamiento sostenible de las aguas de las cuencas hidrográficas hispano-portuguesas y el protocolo adicional, suscrito en Albufeira el 30 de noviembre de 1998. BOE(14), 3425-3432.

Moberg, A., and Jones, P. D. (2005), Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–99. International Journal of Climatology 25(9):1149-1171.

Morán-Tejeda, E., Lorenzo-Lacruz, J., López-Moreno, J. I., et al. (2012), Reservoir Management in the Duero Basin (Spain): Impact on River Regimes and the Response to Environmental Change. Water Resources Management. doi: 10.1007/s11269-012-0004-6.

Mukheibir, P. (2013), Potential consequences of projected climate change impacts on hydroelectricity generation. Clim Change 121(1):67-78. doi: 10.1007/s10584-013-0890-5.

Philandras, C.M., Nastos, P.T., Kapsomenakis, J., et al. (2011), Long term precipitation trends and variability within the Mediterranean region. Nat Hazards Earth Syst Sci, 11:3235–3250. doi: 10.5194/nhess-11-3235-2011.

R Core Team (2012), R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Renöfalt, B.M., Jansson, R., Nilsson, C. (2010), Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems, Freshwater Biology 55 (1):49-67.

Ripley, B. D. (2002) Statistical Data Mining: http://www.stats.ox.ac.uk/pub/bdr/SDM2002/DM2002.pdf

Rotstayn, L. D., and Lohmann, U. (2002), Tropical rainfall trends and the indirect aerosol effect. Journal of Climate 15(15):2103-2116.

Tanaka, S. T., Zhu, T., Lund, J. R., Howitt, R. E., Jenkins, M. W., Pulido, M. A., Tauber, M. E., Ritzema, R. S., Ferreira, I. C. (2006), Climate warming and water management adaptation for California. Clim Change 76(3–4):361– 387.

Trigo, R. M. (2011), The Impacts of the NAO on the Hydrology of the Eastern Mediterranean, in Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region, edited by S. M. Vicente-Serrano and R. M. Trigo, pp. 41 – 56, Springer.

Ward, J. H. Jr. (1963), Hierarchical Grouping to Optimize an Objective Function, Journal of the American Statistical Association 58:236–244.

Yin, X., Yang, Z., Petts, G. (2011), Reservoir operating rules to sustain environmental flows in regulated rivers, Water Resources Research 47(8).

Zhang, Q., Xu, C-Y., Gemmer, M., Chen, Y-D., Liu, C. (2009), Changing properties of precipitation concentration in the Pearl River basin, ChinaStoch. Environ. Res. Risk Assess. 23:377-385. doi: 0.1007/s00477-0080225-7.

Zhao, Y. (2013), R and Data Mining: Examples and Case Studies. Academic Press.

Table 1. Characteristics of the reservoirs in the Miño-Sil basin (H: hydroelectric power; I: irrigation; W: water supply). ID and R.O.E.A. numbers identify the measurement stations

ID	R.O.E.A.	Name	Zone	Storage capacity (hm^3)	Use	Ir	OIr	Year of construction	Operator	Cluster	Correlation monthly inputs/releases
1627	E001	Belesar	Miño Alto	654	H	0,220	0,220	1963	FENOSA	2	0,985
1629	E002	Os Peares	Miño Alto	182	H	0,060	0,050	1955	FENOSA	1	1,000
1709	E007A	Bárcena	Sil Superior	341	H+I	0,440	0,400	1960	Public state	1	-0,259
1710	E008	F. del Azufre	Sil Superior	3	H+W	0,000	0,000	1949	Public state	3	1,000
1718	E009	Montearenas	Sil Superior	2	H	0,010	0,000	1966	ENDESA	3	1,000
1712	E011	Peñarrubia	Sil Superior	12	H	0,010	0,010	1961	ENDESA	3	1,000
1740	E013	San Martin	Sil Inferior	10	H	0,000	0,000	1956	IBERDROLA	3	1,000
1741	E014	San Sebastian	Sil Inferior	46	H	0,300	0,300	1959	ENDESA	3	0,960
1745	E015	Pias	Sil Inferior	10	H	0,060	0,050	1961	ENDESA	3	0,999
1770	E016	As Portas -	Sil Inferior	536	H	1,090	1,090	1974	IBERDROLA	2	0,040
1781	E016D	Azud de Edrada	Sil Inferior	0,2	H	0,000	0,000	1976	IBERDROLA	3	1,000
1743	E018	Bao - Presa	Sil Inferior	238	H	0,250	0,250	1960	IBERDROLA	1	0,967
1791	E019	Prada - Presa	Sil Inferior	121	H	0,690	0,690	1958	ENDESA	3	0,528
1792	E020	Santa Eulalia	Sil Inferior	11	H	0,050	0,050	1966	IBERDROLA	3	0,997
1790	E021	Chandrexa	Sil Inferior	61	H	0,290	0,290	1953	IBERDROLA	3	0,878
1748	E022	Guistolas	Sil Inferior	5	H	0,020	0,020	1952	IBERDROLA	3	1,000
1744	E023	Montefurado	Sil Inferior	11	H	0,000	0,000	1954	IBERDROLA	3	1,000
1751	E024	Sequeiros	Sil Inferior	11	H	0,000	0,000	1951	IBERDROLA	3	1,000
1795	E025	Leboreiro - Mao	Sil Inferior	4	H	0,060	0,060	1949	FENOSA	3	0,999
1780	E026	Edrada / Mao	Sil Inferior	11	H	0,180	0,180	1978	FENOSA	3	0,977
1768	E027	San Esteban	Sil Inferior	213	H	0,040	0,050	1955	IBERDROLA	1	1,000
1769	E029	San Pedro	Sil Inferior	5,7	H	0,000	0,100	1959	IBERDROLA	4	1,000
1631	E030	Velle	Miño Bajo	17	H	0,000	0,000	1966	FENOSA	4	1,000
1634	E031	Castrelo	Miño Bajo	60	H	0,010	0,010	1969	FENOSA	4	1,000
1637	E032	Albarellos -	Miño Bajo	91	H	0,200	0,200	1971	FENOSA	4	0,986
1641	E033	Frieira	Miño Bajo	44	H	0,010	0,000	1970	FENOSA	3	1,000
1808	E035	Conchas	Limia	78	H	0,130	0,130	1949	FENOSA	3	0,991
1807	E036	Salas	Limia	87	H	0,530	0,530	1971	FENOSA	3	0,972
1711	E350	La Campañana	Sil Superior	14	H	0,020	0,020	1963	ENDESA	3	0,995
1713	E570	Santiago	Sil Inferior	2	H	0,000	0,000	1968	IBERDROLA	3	1,000
1716	E571	Pumares	Sil Inferior	4	H	0,000	0,000	1970	IBERDROLA	3	1,000

Table 2. Slopes of linear regression with their P-values. boot.ci1 and boot.ci2 are the corresponding 95% bootstrapping confidence intervals using 1000 replicates

	Storage capacity				Inflows				Outflows			
ID	Estimate	P-value	boot.ci1	boot.ci2	Estimate	P-value	bias	boot.ci2	Estimate	P-value	boot.ci1	boot.ci2
1627	-0.2218	0.0000	-0.29453	-0.14670	-0.1174	0.0505	-0.001865	0.00548	-0.1061	0.0377	-0.234391	0.003412
1629	0.0090	0.0133	0.00203	0.01592	-0.1364	0.0085	-0.000554	-0.02255	-0.1299	0.0118	-0.256423	-0.017666
1709	-0.0251	0.1384	-0.05834	0.00830	-0.0132	0.2908	0.000159	0.01261	-0.0133	0.2076	-0.039768	0.012375
1710	0.0000	0.9888	-0.00011	0.00012	-0.0420	0.0004	-0.000231	-0.01973	-0.0421	0.0004	-0.063900	-0.019129
1718	0.0012	0.0000	0.00108	0.00130	-0.0564	0.0000	0.000053	-0.03838	-0.0565	0.0000	-0.074733	-0.038006
1712	0.0000	0.9489	-0.00067	0.00073	-0.0807	0.0741	-0.000745	0.00739	-0.0806	0.0744	-0.161855	0.006821
1740	0.0010	0.0000	0.00062	0.00132	-0.1810	0.0002	0.002310	-0.07464	-0.1807	0.0002	-0.289191	-0.076835
1741	0.0019	0.3158	-0.00222	0.00604	-0.0052	0.0557	0.000114	0.00038	-0.0053	0.0235	-0.010716	0.000256
1745	-0.0027	0.0000	-0.00350	-0.00187	-0.0065	0.0212	0.000220	-0.00126	-0.0065	0.0222	-0.012069	-0.001156
1770	0.4929	0.0000	0.41696	0.56412	-0.0087	0.4941	0.000105	0.01675	0.0189	0.0590	-0.034907	0.017009
1781	0.0000	0.6397	-0.00002	0.00001	0.0018	0.5167	0.000114	0.00674	0.0019	0.4801	-0.003283	0.006882
1743	0.0273	0.0050	0.00514	0.04910	-0.0126	0.3453	-0.000402	0.01567	-0.0020	0.8694	-0.040695	0.016668
1791	0.0283	0.0000	0.01734	0.03911	-0.0101	0.0017	-0.000195	-0.00332	-0.0098	0.0004	-0.016518	-0.003706
1792	-0.0015	0.0000	-0.00211	-0.00078	-0.0154	0.0000	-0.000106	-0.00809	-0.0122	0.0010	-0.022749	-0.008003
1790	-0.0247	0.0000	-0.03171	-0.01759	-0.0130	0.0004	-0.000013	-0.00493	-0.0117	0.0000	-0.020854	-0.004948
1748	-0.0015	0.0000	-0.00175	-0.00128	-0.0094	0.1045	-0.000153	0.00322	-0.0090	0.1212	-0.021936	0.003877
1744	-0.0005	0.0478	-0.00092	-0.00016	-0.1321	0.0000	0.000245	-0.09085	-0.1319	0.0000	-0.171756	-0.089943
1751	0.0001	0.4653	-0.00017	0.00037	-0.2642	0.0000	0.003206	-0.12883	-0.2642	0.0000	-0.403995	-0.126921
1795	-0.0017	0.0000	-0.00219	-0.00120	0.0013	0.5670	0.000133	0.00631	0.0017	0.4277	-0.004177	0.006517
1780	0.0000	0.9674	-0.00240	0.00223	-0.0127	0.0000	0.000024	-0.00870	-0.0145	0.0000	-0.016683	-0.008786
1768	-0.0114	0.0182	-0.02119	-0.00146	-0.3847	0.0000	-0.003109	-0.20003	-0.3779	0.0000	-0.569130	-0.210742
1631	-0.0198	0.0000	-0.02118	-0.01844	-0.0005	0.9976	0.011537	0.28824	0.0035	0.9824	-0.302626	0.314217
1634	-0.0387	0.0000	-0.04261	-0.03482	-0.0550	0.7329	0.003556	0.26274	-0.0518	0.7476	-0.370664	0.263605
1637	-0.0488	0.0000	-0.06092	-0.03707	-0.0326	0.0156	0.000055	-0.00886	-0.0212	0.0942	-0.057580	-0.008798
1641	-0.0470	0.0000	-0.05014	-0.04395	-0.0541	0.7709	0.004618	0.29035	-0.0533	0.7739	-0.414748	0.285951
1808	-0.0290	0.0000	-0.03703	-0.02092	-0.0090	0.3756	0.000336	0.01055	-0.0070	0.4589	-0.029990	0.012077
1807	-0.0127	0.0422	-0.02656	0.00106	-0.0085	0.0744	-0.000223	0.00115	-0.0043	0.2864	-0.017703	0.000628
1711	0.0010	0.2113	-0.00057	0.00263	-0.0555	0.0000	-0.000688	-0.02992	-0.0544	0.0000	-0.079558	-0.031516
1713	-0.0018	0.0000	-0.00189	-0.00175	-0.1099	0.0534	-0.004037	-0.00240	-0.1099	0.0535	-0.208807	-0.004201
1716	-0.0003	0.0000	-0.00041	-0.00016	-0.0898	0.1028	-0.001152	0.01683	-0.0900	0.1021	-0.192175	0.012620

Table 3. Mann-Kendall tests with their P-values. Bootstrapping confidence intervals as in Table 2

	Storage Capacity				Inflows				Outflows			
ID	tau	P-value	boot.ci1	boot.ci2	tau	P-value	boot.ci1	boot.ci2	tau	P-value	boot.ci1	boot.ci2
1627	-0.2198	0.0000	-0.554688	-0.31737	-0.1298	0.0000	-0.35784	-0.15926	-0.0786	0.0044	-0.25958	-0.051086
1629	0.1651	0.0000	0.222811	0.43407	-0.0523	0.0465	-0.19326	-0.01405	-0.0461	0.0789	-0.18999	0.005318
1709	-0.1007	0.0002	-0.295250	-0.11110	-0.1313	0.0000	-0.36316	-0.16598	-0.0853	0.0020	-0.25424	-0.083249
1710	-0.0601	0.0278	-0.257487	0.02203	-0.1529	0.0000	-0.40462	-0.20975	-0.1528	0.0000	-0.40345	-0.200560
1718	0.4890	0.0000	0.828256	1.13726	-0.4172	0.0000	-0.98074	-0.68743	-0.4167	0.0000	-0.98399	-0.677259
1712	-0.0174	0.5541	-0.125579	0.05817	-0.1644	0.0000	-0.42869	-0.21886	-0.1625	0.0000	-0.42604	-0.217505
1740	0.1112	0.0000	0.119786	0.33256	-0.1516	0.0000	-0.39570	-0.21299	-0.1504	0.0000	-0.39653	-0.212008
1741	0.0169	0.5272	-0.064309	0.13950	-0.0906	0.0007	-0.25602	-0.10804	-0.1048	0.0001	-0.28847	-0.132313
1745	-0.2952	0.0000	-0.734945	-0.43449	-0.1144	0.0000	-0.31128	-0.14695	-0.1120	0.0000	-0.30560	-0.140987
1770	0.3805	0.0000	0.579937	0.94017	-0.0489	0.1184	-0.22690	0.02907	0.0353	0.2605	-0.03814	0.173329
1781	-0.0640	0.0614	-0.229388	-0.03433	0.0374	0.2742	-0.01429	0.17034	0.0350	0.3057	-0.01389	0.157755
1743	-0.0189	0.4813	-0.130027	0.05766	0.0400	0.1348	-0.01440	0.18108	0.0174	0.5155	-0.04453	0.124521
1791	0.1522	0.0000	0.198009	0.41806	-0.1462	0.0000	-0.38758	-0.19571	-0.1247	0.0000	-0.32541	-0.167720
1792	-0.1309	0.0000	-0.383658	-0.13994	-0.1783	0.0000	-0.45894	-0.24245	-0.1356	0.0000	-0.36548	-0.167971
1790	-0.2371	0.0000	-0.588558	-0.35691	-0.1874	0.0000	-0.45864	-0.29275	-0.1152	0.0000	-0.30608	-0.147734
1748	-0.3385	0.0000	-0.800027	-0.54989	-0.1262	0.0000	-0.33057	-0.17321	-0.1216	0.0000	-0.31830	-0.161396
1744	-0.1418	0.0000	-0.375784	-0.18722	-0.2392	0.0000	-0.58266	-0.36389	-0.2391	0.0000	-0.58343	-0.357137
1751	-0.1903	0.0000	-0.477858	-0.2809	-0.1833	0.0000	-0.46757	-0.26026	-0.1836	0.0000	-0.47455	-0.265496
1795	-0.3059	0.0000	-0.757207	-0.47927	-0.0331	0.2843	-0.19168	0.05799	0.0135	0.6619	-0.09696	0.146389
1780	-0.0192	0.5753	-0.138786	0.07525	-0.2946	0.0000	-0.71842	-0.45036	-0.3274	0.0000	-0.81463	-0.482939
1768	-0.0516	0.0495	-0.193989	-0.02751	-0.2110	0.0000	-0.53034	-0.31974	-0.1984	0.0000	-0.50256	-0.290285
1631	-0.4735	0.0000	-1.132986	-0.76819	-0.0653	0.0285	-0.25261	-0.01642	-0.0613	0.0399	-0.24223	-0.002873
1634	-0.3887	0.0000	-0.938915	-0.60965	-0.0946	0.0015	-0.31143	-0.07581	-0.0942	0.0016	-0.30918	-0.076694
1637	-0.3078	0.0000	-0.751764	-0.47173	-0.2122	0.0000	-0.52951	-0.31741	-0.0997	0.0011	-0.28881	-0.114622
1641	-0.4324	0.0000	-1.032467	-0.70167	-0.0941	0.0016	-0.31614	-0.06304	-0.0936	0.0017	-0.30405	-0.074281
1808	-0.2765	0.0000	-0.666141	-0.43866	0.0091	0.7278	-0.07962	0.11869	-0.0400	0.1282	-0.17922	0.020938
1807	0.0365	0.2378	-0.079999	0.23499	-0.1507	0.0000	-0.41224	-0.20333	-0.0061	0.8433	-0.10874	0.084704
1711	0.0451	0.1257	-0.001923	0.17050	-0.1679	0.0000	-0.44706	-0.22853	-0.1651	0.0000	-0.42641	-0.227470
1713	-0.6252	0.0000	-1.422752	-1.07007	-0.1785	0.0000	-0.46078	-0.25291	-0.1783	0.0000	-0.46071	-0.253738
1716	-0.2737	0.0000	-0.685371	-0.41620	-0.1668	0.0000	-0.43588	-0.22501	-0.1657	0.0000	-0.43943	-0.226827

Table 4. Frequency of monthly trends for the whole sample, and for periods pre- and post-1998

Periods		Trend	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Whole Sample	Storage capacity	Negative Trend	4	5	4	7	12	5	8	4	3	4	3	10
		Positive Trend	2	1	4	1	5	5	3	4	2	4	6	1
	Inflow	Negative Trend	0	1	6	2	14	3	0	1	1	6	0	14
		Positive Trend	2	3	0	4	1	0	3	4	0	0	1	0
	Outflow	Negative Trend	1	1	6	2	15	1	0	1	2	7	0	14
		Positive Trend	2	4	0	5	2	0	3	2	0	0	1	0
Pre-1998	Storage capacity	Negative Trend	4	3	6	2	5	4	3	5	5	3	4	3
		Positive Trend	3	4	2	1	2	6	2	5	5	6	6	0
	Inflow	Negative Trend	1	0	1	7	1	2	10	0	0	1	2	0
		Positive Trend	0	0	4	0	2	11	0	5	0	2	3	0
	Outflow	Negative Trend	0	1	1	8	1	3	11	1	0	1	2	1
		Positive Trend	1	2	7	0	2	13	1	5	0	2	6	0
Post-1998	Storage capacity	Negative Trend	13	2	1	1	8	4	0	10	0	0	3	2
		Positive Trend	0	1	3	8	0	1	5	1	2	4	2	2
	Inflow	Negative Trend	12	0	0	0	2	0	0	29	0	0	1	0
		Positive Trend	0	1	0	5	0	1	0	0	4	4	0	0
	Outflow	Negative Trend	18	0	0	1	4	1	0	27	0	0	3	0
		Positive Trend	0	2	0	8	0	0	1	0	6	8	0	0

Note: Only trends that are statistically significant at the 5% level are included. Seasons are highlighted with different colors.

Table 5. Validation statistics calculated for the different clustering methods used.

	Cluster	2	3	4	5	6	7	10
K-mean	Avg within	162	108	79	56	42	52	31
	Avg-btwn	547	424	392	309	308	272	267
	wb ratio	0.2970	0.2557	0.2039	0.1831	0.1534	0.1462	0.1138
	Avg silwidth	0.6125	0.6054	0.6670	0.5773	0.5680	0.5823	0.4746
	Dunn	0.2180	0.2923	0.6645	0.2526	0.1488	0.1488	0.1207
PAM	Avg within	141	91	79	56	42	34	30
	Avg-btwn	1 422	391	392	309	274	273	272
	wb ratio	0.3337	0.2330	0.2039	0.1831	0.1534	0.1266	0.1125
	Avg silwidth	0.5973	0.6390	0.6670	0.5773	0.5847	0.5823	0.4978
	Dunn	0.2829	0.2829	0.6645	0.2526	0.1488	0.2046	0.3622
Hierarchical	Avg within	176	133	79	78	52	52	30
	Avg-btwn	2 628	421	392	388	308	307	272
	wb ratio	0.2803	0.3171	0.2039	0.2013	0.1717	0.1691	0.1125
	Avg silwidth	0.6937	0.5460	0.6670	0.6449	0.5680	0.5338	0.4978
	Dunn	0.4668	0.3781	0.6645	0.5302	0.3473	0.3941	0.3622

Note: Avg within: average distances within clusters; Avg-btwn: average distances between clusters; wb ratio: ratio of the average distances within to the average distances between clusters; Avg silwidth: average Silhouette width; Dunn: Dunn index.

Figure 1. Location of the Miño-Sil basin in the Iberian Peninsula, and reservoir locations (triangles) indicated by ID number

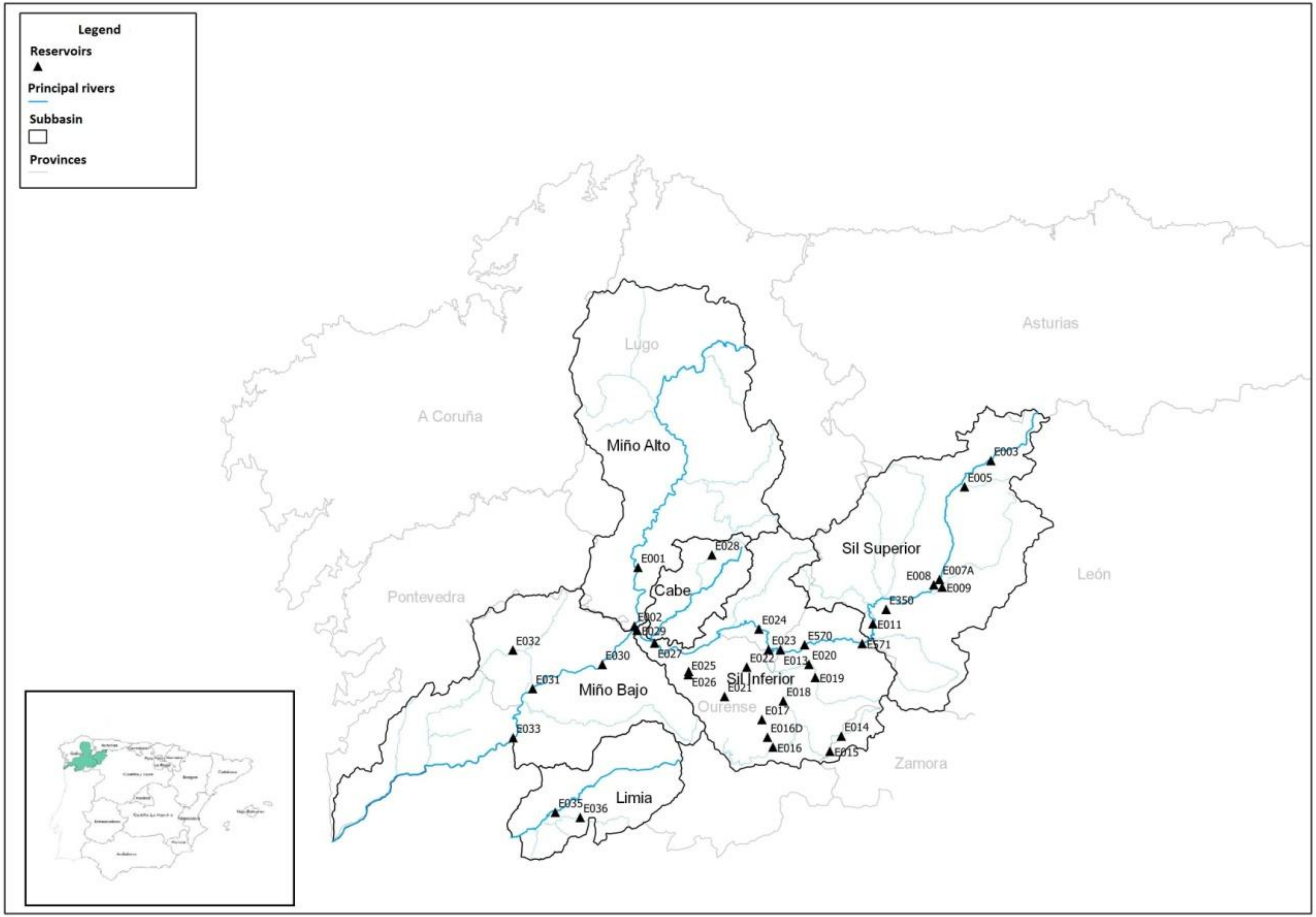
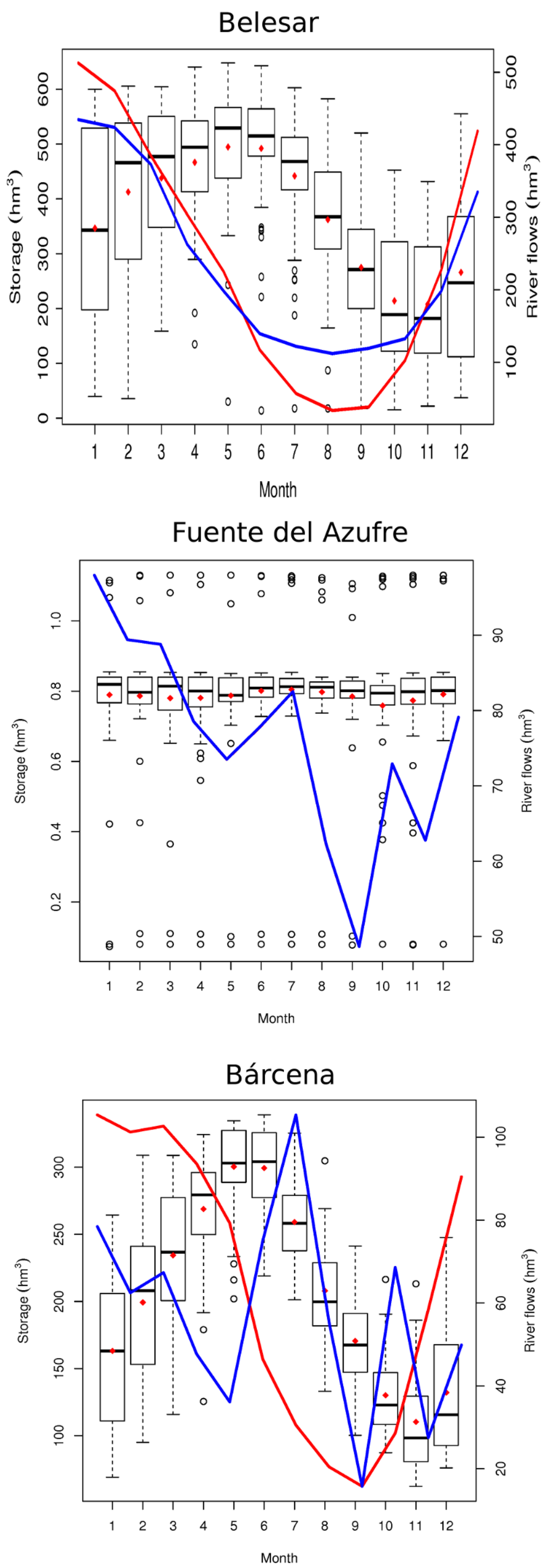


Figure 2. Temporal coverage of inflow/outflow data series for the selected reservoirs indicated by ID number

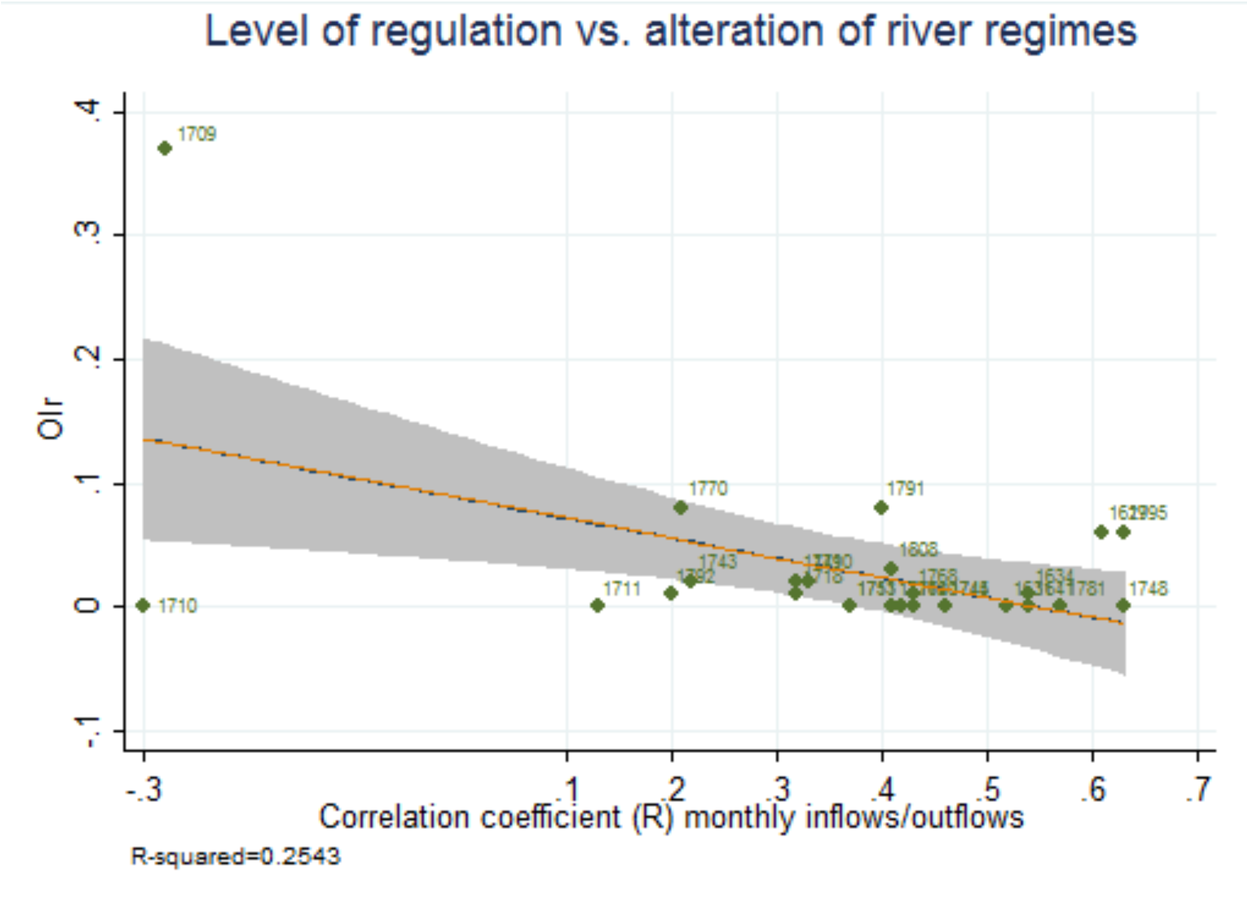
	E001	E002	E003	E005	E007A	E008	E009	E011	E013	E014	E015	E016	E016D	E017	E018	E019	E020	E021	E022	E023	E024	E025	E025	E026	E027	E028	E029	E030	E031	E032	E033	E035	E036	E350	E570	E571
1959		X							X									X	X	X	X				X							X				
1960		X							X									X	X	X	X	X	X		X							X				
1961		X							X	X					X	X		X	X	X	X	X	X		X		X					X				
1962		X			X				X	X	X				X	X		X	X	X	X				X							X				
1963		X			X				X	X	X				X	X		X	X	X	X				X		X					X				
1964	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1965	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1966	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1967	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1968	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1969	X	X			X	X			X	X	X				X	X		X	X	X	X				X		X					X				
1970	X	X			X	X	X	X	X	X	X				X	X	X	X	X	X	X				X		X					X		X	X	
1971	X	X			X	X	X	X	X	X	X				X	X	X	X	X	X	X				X		X	X	X		X	X		X	X	
1972	X	X			X	X	X	X	X	X	X				X	X	X	X	X	X	X				X		X	X	X		X	X		X	X	X
1973	X	X			X	X	X	X	X	X	X				X	X	X	X	X	X	X				X		X	X	X		X	X		X	X	X
1974	X	X			X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1975	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1976	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1977	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X	X	X	X
1978	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1979	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1980	X	X			X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X
1981	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1982	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1983	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1984	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1985	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1986	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1987	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1988	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X
1989	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1990	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1991	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1992	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1993	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1994	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1995	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1996	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X
1997	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1998	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
1999	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2000	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2001	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2002	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2003	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2004	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2005	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
2006	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2007	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2008	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2009	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2010	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2011	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2012	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 3. Alteration of river regimes by dams



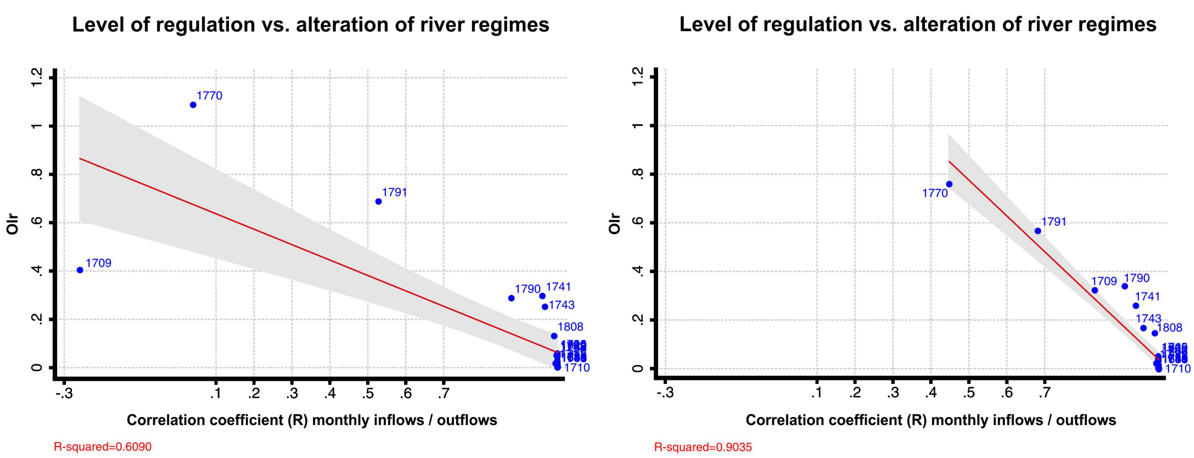
Note: The boxplots represent the distribution of the stored capacity, the red dot inside the box is the mean, the red lines are the inflows and the blue lines are the outflows.

Figure 4. A linear regression of the level of regulation against the correlation coefficient.



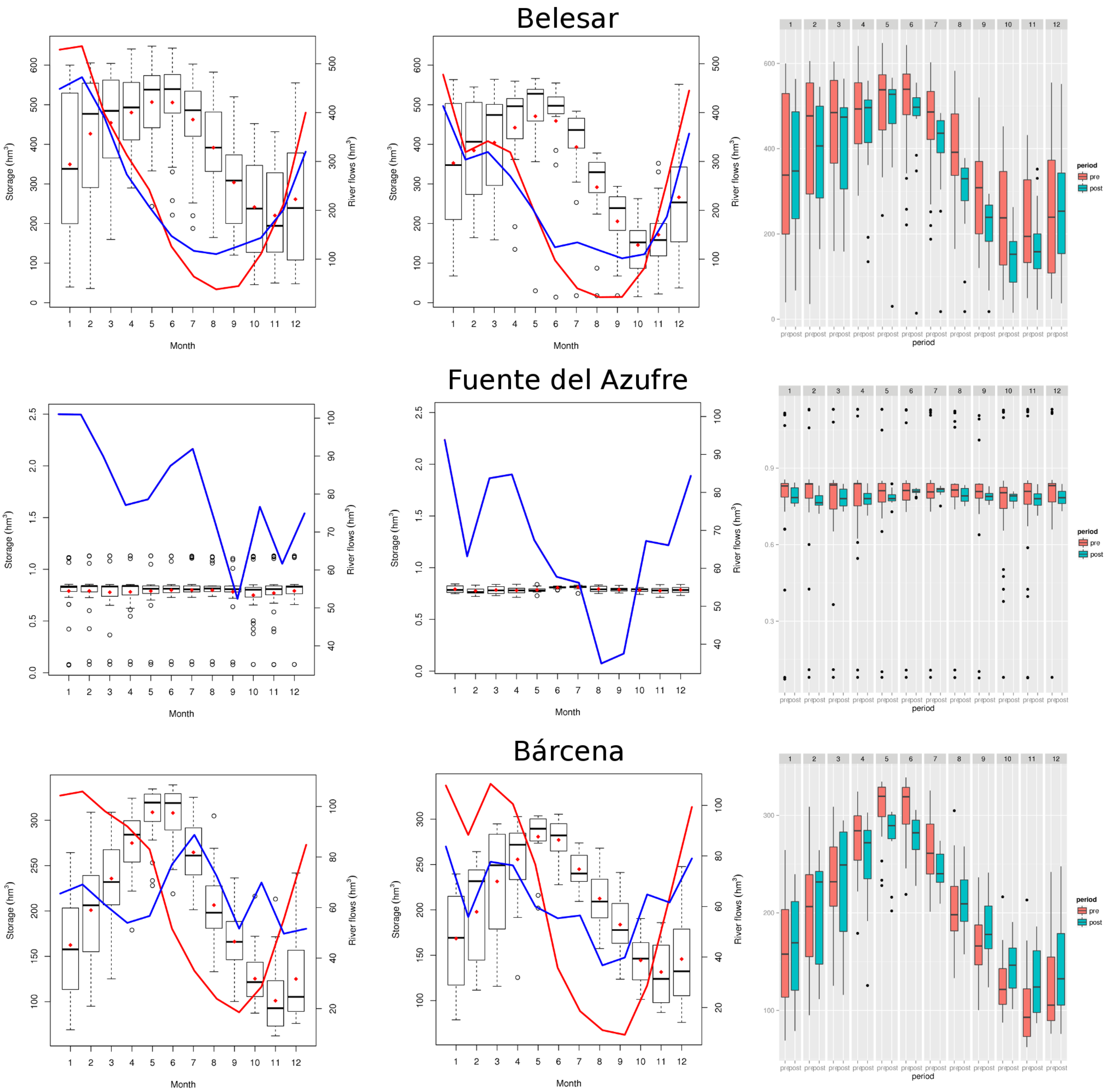
Note: The shadowed region shows confidence intervals at the 5% significance level.

Figure 5. Similar to figure 4 but for the periods before (left) and after (right) 1998



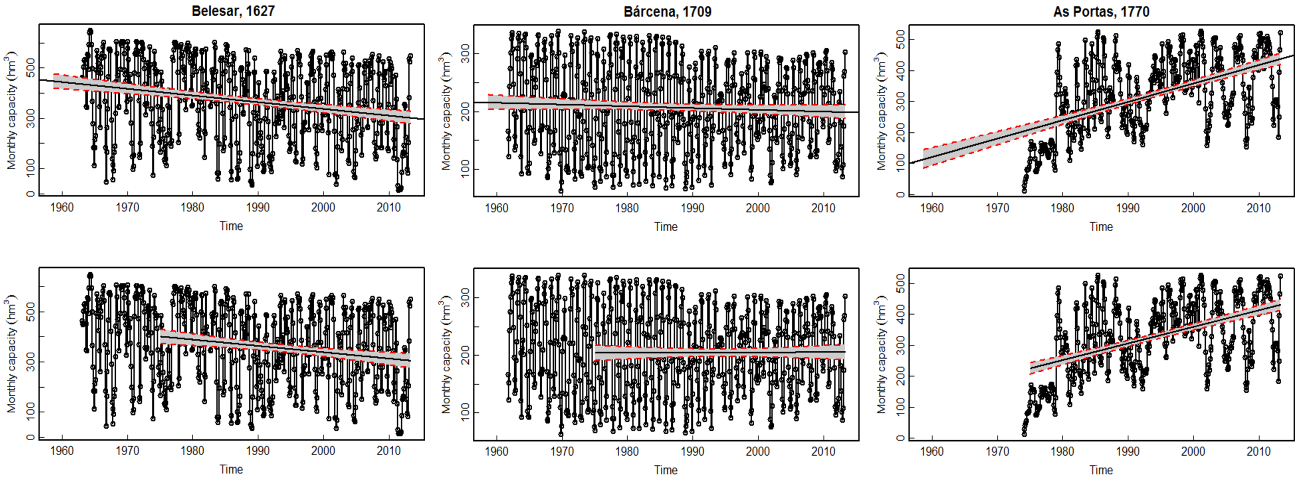
- A - - B -

Figure 6. Alteration of river regimes by dams and period (left panel for the pre-1998 period and middle panel for post-1998)



Note: The right panel in green and red shows the stored capacity data (hm3) from the two periods.

Figure 7. Trends in storage capacity for the Belesar, Bárcena and As Portas reservoirs calculated over two different sample periods



Note: Grey shaded area indicates the 95% confidence intervals.

Figure 8. The performance of the k-means, PAM, and hierarchical methods using the Silhouette and Dunn Validation measures