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STORAGE REGIMES OF THE YESA RESERVOIR, UPPER ARAGON RIVER BASIN, CENTRAL SPANISH PYRENEES

Short title: Storage regimes of the Yesa reservoir

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Abstract: Agriculture in Mediterranean countries is mainly based upon the irrigation of productive areas in the lowlands. To achieve this, it is necessary to store large volumes of water in reservoirs located in mountain headwaters. These reservoirs have a relatively simple regime of storage, increasing the water stored along the wet season (from October until May) and reaching the maximum volume shortly before the beginning of the hot, very dry season, when the water is released. This paper considers the storage regime (inflow and outflow) of the Yesa Reservoir in the Spanish Pyrenees, as an example of management of a large reservoir in a mountain Mediterranean environment, subject to a strong interannual variability. On average, the highest water storage level is achieved by retaining the high flows of the Aragón River in autumn and spring. Nevertheless, the irregularity of rainfalls and the existence of changes in the hydrological regime lead to changes in the patterns or reservoir infilling. Three patterns were identified in the Yesa Reservoir: (1) a quick increase of the stored volume in autumn, a stabilisation in winter and a new increase in spring; (2) a lower stored volume in autumn, strong increase at the beginning of winter and a new increase in spring; and (3) a continuous increase from October until May. These patterns are distributed in time over different periods since the construction of the reservoir in 1959, demonstrating the adjustment of the reservoir management to changes in the hydrological regime.

Key words: Reservoir, Water resources management, Fluvial regime, Central Spanish Pyrenees.

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1. Introduction

Reservoirs are widely used in many rivers of the world to regulate discharge, to provide water to fields, cities and industries, and to produce hydropower. During the 20th century, the number of big reservoirs (with a dam higher than 15 m) increased worldwide from 500 to more than 42,000 (Morris & Fan, 1997). More than 1242 were under construction in 1994, 6.36 % of which were higher than 100 m (Takeuchi, 1998). The current storage capacity in reservoirs is estimated to be on the order of 6,000 km^3 (Avakian, 1990), or 13 % of the total surface runoff of the planet. This strongly affects downstream river regimes (e.g. Higgs & Petts, 1988; Pircher, 1990; Jiongxin, 1990; Zsuffa, 1999), the geomorphological activity of the river beds (Brandt, 2000; Al-Taiee, 2000) and various ecological aspects (Thomas, 1996; Giers *et al.*, 1998). Reservoirs have an important impact on the environment since they directly affect both the quality and quantity of water resources (Nandalal & Bogardi, 1995). Finally, reservoirs act as large sediment traps, interrupting downstream sediment transfer, which enables the assessment of soil erosion rates in relation to different basin parameters, especially land use and plant cover (Harden, 1993; McIntyre, 1993; Valero-Garcés *et al.*, 1998; Verstraeten & Poesen, 2000).

It is well known that reservoirs undergo changes in water levels at different temporal scales as a consequence of infilling and emptying processes. In the case of reservoirs constructed for irrigation purposes, these changes tend to be seasonal, related to both the river flow regime and the demand of a large volume of water in summer (coinciding with the growing season in the irrigated areas). The regime of reservoir storage tends to reach a maximum volume shortly before the beginning of the hot season when water is released. The velocity of infilling depends on the rainfall regime and especially on the intensity and seasonality of floods. In the Mediterranean area, the concentration of a large proportion of the annual discharge in a few events explains the importance of floods for increasing the water storage (Poesen & Hooke, 1997).

This paper studies the storage regime of the Yesa Reservoir, in the Upper Aragón River Basin. Yesa is the second largest Pyrenean reservoir and was constructed to supply water to the new irrigated areas in Bardenas (60,701 ha), Central Ebro Depression, via the Bardenas Canal. As many other mountain Mediterranean reservoirs, it is affected by complex climatic influences, including snow accumulation and snowmelt processes, that are subject to large interannual and seasonal variability. Thus, the main problem for irrigation-purpose reservoirs in Mediterranean environments is that they must be filled at the beginning of the irrigation season, whereas the infilling season is characterised by a large uncertainty. This makes it so the management regime of the reservoir (especially the inflow) must adjust to the variable conditions of the discharge, that in turn depend on the variable occurrence of the seasons of rainfall and snowmelt. The main aim of this paper is to describe the storage regime of a mountain Mediterranean reservoir, stressing the different management patterns as a strategy to cope with the variability of Mediterranean discharges.

2. The study area

The Upper Aragón River Basin has an area of 2,181 km^2 (Fig. 1). The highest altitudes are located in the north of the basin (Collarada Peak, 2886 m). The Aragón River runs north-south across the paleozoic area (limestone, shale and clay), the Inner Sierras (limestone and sandstone) and the flysch sector. Finally, it arrives to the Inner Depression (marls) and runs westward.

Precipitation increases toward the north along the altitudinal gradient, and to the west because of the Atlantic influence. The average annual precipitation in the northernmost sector of the basin reaches values above 1500 mm, and around 800 mm in the Inner Depression.

The mean annual temperature decreases from north to south (8º in Canfranc and 11º in Jaca). The 0ºC isotherm occurs at 1549 m a.s.l. during the cold season (from November to April; García-Ruiz *et al.*, 1985), indicating the importance of snow accumulation. The whole area is occasionally subject to very intense rainstorms, which can cause serious damage by flash floods (White *et al.*, 1997).

Plant cover has been strongly affected by human activities. As a result of changes in land use during the 20th century, most cultivated fields have been abandoned, except in the Inner Depression, where cutting meadows and cereal crops prevail. Natural forests occur above 1400 m a.s.l. The subalpine belt (over 1800 m) is composed of grasslands and small forests of *Pinus uncinata* and the alpine belt begins at around 2300 m.

3. Methods

Information on the storage fluctuations of the reservoir water was provided by the Ebro River Hydrographic Administration (*Confederación Hidrográfica del Ebro*), specifically daily discharge data from gauging stations in the Aragón River and its main tributaries (Fig. 1). Average monthly and annual discharges were calculated using these data. Floods were defined as the discharge surpassing at least 5 times the average annual discharge. Table 1 summarises the length of different series of data.

Special importance was given to the inflow and outflow data of the Yesa Reservoir. In order to estimate the total inputs, data from the gauging station on the Aragón River at the Yesa Reservoir Tail was added to the station on the Esca River at Sigüés, both immediately before the reservoir (Fig. 1). The remaining inputs were small, non-gauged ravines and direct precipitation, together representing a very small percentage of the total inflow. The outflow was calculated by adding the data from the Aragón River at the foot of the reservoir and the diversions through the Bardenas Canal. Evaporative losses were not considered since they were low compared to the discharge. The evaporation tank from Jaca (1949-1973) gives an annual average loss of 1217 mm, and average precipitation at Yesa is 833 mm, that is, a total loss of 364 mm. The maximum area impunded by the reservoir is 2089 ha, and consequently the maximum water loss by evaporation is 7.61 hm^3 per year. This figure represents 1.7% of the total capacity of the reservoir and 0.55% of the discharge inputs. Besides, no statistically significant trends in evaporation were detected during the study period.

Finally, monthly data on water volume stored in the Yesa Reservoir were analysed. As Yesa Reservoir management is conceived in a yearly basis, it can be described by monthly data on inflow, outflow and storage. For every hydrologic year, a total of 36 variables were collected considering the inflow, outflow and total storage in every month. A cluster analysis (hierarchical classification) has been performed on this data set, to identify different groups of years according to their differences in the regime of inflow, outflow and storage. Prior to the cluster analysis, the data were standardised by substracting the average of the variable and dividing by the standard deviation. The Ward's cluster extraction method was used. This procedure tends to produce clusters with a similar number of elements. The selection of the final number of clusters includes a certain level of subjectivity. The premise has been to obtain a low number of groups to facilitate the interpretation. A frequent rule is to determine, by the analysis of the dendrogram, the step at which the distance between groups is much bigger than in previous steps. The solution (number of groups) in this step is then used. The centroids represent the mean values of the variables for each group. They can be used to characterize the mean regime of the three groups. The attribution of each year to one of the groups allowed to study the temporal distribution of the three management patterns.

4. Results

4.1. The regime of the Aragón River at Yesa

Fig. 2 shows the monthly mean discharge at a selection of gauging stations of the Aragón River and tributaries.The two main rivers draining into the Yesa reservoir are the Aragón and Esca rivers. The Aragón River contributes 1,019 hm^3 per year (32.6 m^3 s^{-1}) at Yesa Reservoir Tail, with relatively high values during autumn and winter, increasing in mid-spring (maximum in May, 58.3 m^3 s^{-1}), and decreasing sharply after June, until the lowest summer values. This pattern was the result of diverse hydrological regimes prevailing in different sectors of the Aragón basin. For instance, at the headwater of the Aragón River (at Canfranc), snow retention produces low discharges in winter, whereas snowmelt and the reactivation of rainfall causes high flows in April and May (García-Ruiz *et al.*, 2001).

The Esca River at Sigüés has a clear oceanic regime (Fig. 2), with high discharges between December and April (maximum in February), coinciding with the greatest activity of fronts from the Atlantic Ocean. The discharge decreases after April until summer due to a quick exhaustion of snow reserves, an increase of evapotranspiration and a progressive decrease in rainfall (García-Ruiz et al., 2001). The mean annual contribution of this river to the Yesa reservoir is 353 hm^3 (12.1 m^3 s^{-1}).

Total annual contribution of the Aragón and Esca rivers was 1372 hm^3 (44 m^3 s^{-1}), with a maximum mean discharge in May (Fig. 2).

Table 2 shows the monthly and annual frequency of floods in both rivers. In the case of the Aragón River, floods occur especially in autumn and spring, with a decrease in winter (García-Ruiz *et al.,* 2000). The Esca River concentrates a higher frequency of floods in winter. The highest peakflow recorded in the Aragón River was 1560 m^3 s^{-1} (November, 1966), and in the Esca River, 256 m^3 s^{-1} (December, 1962).

4.2. The Yesa reservoir

The Yesa dam is 74 m high and was built in 1959 with an original capacity of 470 hm^3. By 1986 this figure had decreased to 450.3 hm^3 (according to an unpublished batimetry estimation made by the Ebro River Administration Office) due to siltation processes. The mean annual sediment siltation was 0,79 hm^3.

Fig. 3 shows the mean monthly water stored in the Yesa reservoir, including inflows and outflows. Each column indicates average levels at the end of each month. Stored levels progressively increase after September, reaching the maximum value in May (around 400 hm^3). The inflow curve exceeds outflows from October to June, allowing infilling in autumn, winter and spring. During the inflow period, the greatest differences between flows were in autumn (November) and spring (April and May), coinciding with high flow periods in the Aragón River. In winter, the differences between inflows and outflows were minimal, especially in March. Outflows exceeded inflows in summer due to water releases for irrigation purposes.

Fig. 4 shows the average monthly values of outflows throughout the year, distinguishing between the Aragón River and the Bardenas Canal. Their curves show opposite trends since the Aragón River has high downstream discharges from November to April (maximum in February), whereas the Bardenas Canal has very low discharges from October to April, and high discharges from May to August, exceeding the discharges of the Aragón River downstream the dam.

Floods from October and November are mostly retained to quickly increase the stored water. In the three following months the increase in volume practically stops and most inflows immediately become outflows. The definitive infilling is caused by the spring floods.

4.3. Fluctuations of the stored volume

Reservoir management is focused on obtaining the maximum stored volume in May to provide high water demands in summer when inflows are very low. For this reason the coefficient of variation of the Yesa reservoir storage decreases after October and reaches minimum values in winter and spring (especially in June) then increases again (Fig. 5), confirming that the spring volume was quite similar each year, due to reservoir management strategies. Nevertheless, discharges of the Aragón River varied quite highly each year, due to irregular precipitation and the volume of snow accumulated in the headwater. Fig. 5 shows that in the Aragón River the coefficient of variation of the monthly discharges was highest in October, February and August, whereas in springtime they were relatively low, ensuring high discharges year after year.

A cluster analysis was used to identify the different patterns of reservoir management (Fig. 6). Three patterns were distinguished (Fig. 7), conditioned by (i) the volume of water stored at the beginning of the hydrological year, (ii) the intensity and variability of inflows between October and June, and (iii) the total contributions during the hydrological year.

Group 1 begins with a relatively high stored water volume (around 225 hm^3 in October). From October to December the volume of the reservoir increases, due to the high discharges of the Aragón and Esca rivers. From January to March the increase of the water reserves is very gentle due to an equilibrium between inflows and outflows. From April to June the volume increases again, reaching maximum values in May. This group is based upon the increase of the volume stored during two periods (autumn and spring), separated by an almost stable period (winter). During winter, inflows can also be very high, especially in the Esca River, but they are immediately exported from the reservoir, in order to establish a safety gap against possible cold season floods.

Group 2 starts the hydrological year with a stored volume less than 200 hm^3. From October to December the inflows are clearly lower than Group 1, with low levels during autumn. The greatest increase in storage starts in January. A decrease of inflows in March stabilises the stored volume. A new increase in spring leads to a maximum storage in June. Group 2 is related to an absence of heavy rainstorms in autumn, such that the pattern of storage is based upon the winter rainfalls and the springtime high flows.

Group 3 starts from a relatively low initial volume (around 141 hm^3) and remains below the other two groups during the whole hydrological year. It increases slowly from October to May, reaching a maximum volume at around 380 hm^3 and a sharp decrease in September. The evolution of the inflows shows the absence of a period with high discharges, and a slight peak in May. Contributions are very low in autumn and winter.

The frequency of each group during the period of functioning of the reservoir (Fig. 8) suggests a pronounced temporal trend. Thus, group 1 dominates during the first decade after the construction of the reservoir and progressively decreases until it disappears in the nineties. Likewise, group 2 only occurred at the beginning of the study period, whereas group 3 increased in the nineties.

This evolution indicates that the regime of infilling of the reservoir changed due to changes in the regime of the Aragón and Esca rivers. Fig. 9 shows the trends observed in the discharge of the Aragón and Esca rivers and the Bardenas Canal (1959-1996). In all cases there is a significant negative trend, except for the Bardenas Canal, which undergoes a slight, no significant positive trend, confirming that the water supply to irrigated lands remained stable or increased slightly, whereas water resources decreased. The existence of changes in the Yesa Reservoir inflow regime is demonstrated in Fig. 10, where the first and the second half of the study period is represented (1959-1977 and 1978-1995 respectively). The most important differences are: (i) a remarkable decrease in discharge affects the second half of the study period in each month, and (ii) the months with the highest discharge recession are November, February, March and May demonstrating the difficulties for increasing the reservoir storage in autumn and winter in the last decade. These difficulties can only be solved by reducing the reservoir releases from October until May, especially in March, as Fig. 11 shows.

5. Conclusions

The storage regime of a reservoir depends on the relationships between hydrological regime, reservoir size and water demand (Morris & Fan, 1997). Large reservoirs for irrigation tend to reach maximum storage levels at the beginning of the irrigation season and minimum levels at the end, as is the case of the Yesa Reservoir. However, water levels can fluctuate yearly depending on the rainfall/snowmelt seasons (García-Ruiz *et al.,* 2001), changing the periods of greatest storage increase or even the levels reached at the end of the infilling season. The Yesa Reservoir was used to study the infilling and emptying regime of a large reservoir, that must attend the water demand from irrigated lands within a context of fluctuating Mediterranean discharges. The main conclusions from this study are the following:

i) The maximum water storage is achieved by retaining the discharge of the Aragón River during the high flows of autumn and spring.

ii) Though a greater storage volume could be reached in winter, it is preferable to keep a safety margin as a precaution against possible floods. Reservoir managers depend on high spring discharges to infill the reservoir to final levels.

iii) Three patterns of infilling and emptying of the Yesa Reservoir were identified. The first group shows a quick increase of stored volume in autumn, slight increase or stabilization in winter and a new increase in spring. The second group implies lower stored volumes in autumn, strong increase at the beginning of winter and a new increase in spring. Finally, the third group shows a gentle and continuous increase from October to May, though the stored volumes are below the other groups.

iv) The different patterns prevail in different periods, such that the first group characterizes the sixties and seventies and the third one prevails in the eighties and nineties. This means that relevant changes have occurred in the Aragón and Esca river regimes since the outputs to the Bardenas Canal did not change substantially.

v) Given that the discharge decreased greatly along the whole year, the only possibility to reach a relatively high water reserve at the end of the spring is to retain discharges during winter, confirming the adjustment of reservoir management to changes in the hydrological regime.

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FIGURE CAPTIONS

Fig.1. The Upper Aragón River Basin, showing the location of the gauging stations.

Fig.2. Hydrological regime in several gauging stations of the Upper Aragón River Basin.

Fig. 3. Monthly average volume stored in the Yesa reservoir, and balance of the inflow and outflow discharge.

Fig. 4. Monthly evolution of the outflow discharge from the Yesa reservoir.

Fig. 5. Coefficient of variation of stored volume and discharge in the Yesa Reservoir and at the Yesa Reservoir Tail, respectively.

Fig. 6. Dendrogram from the cluster analysis.

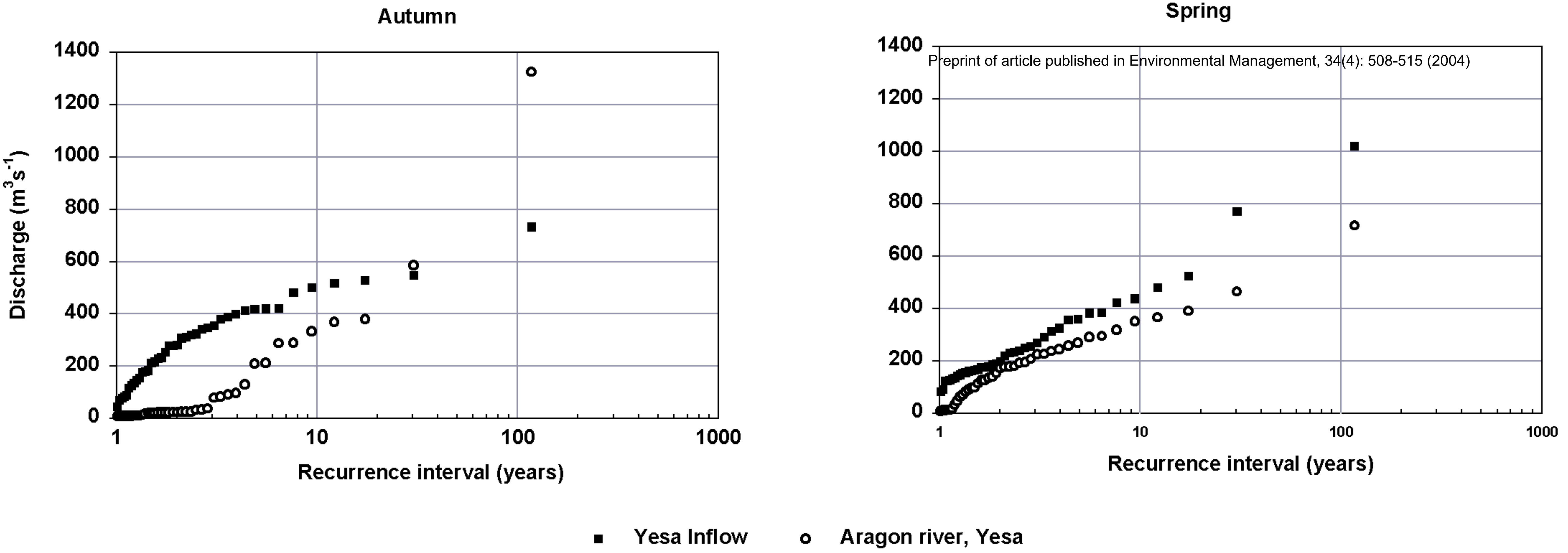
Fig. 7. Management patterns of the Yesa reservoir, from the centroids obtained by cluster analysis.

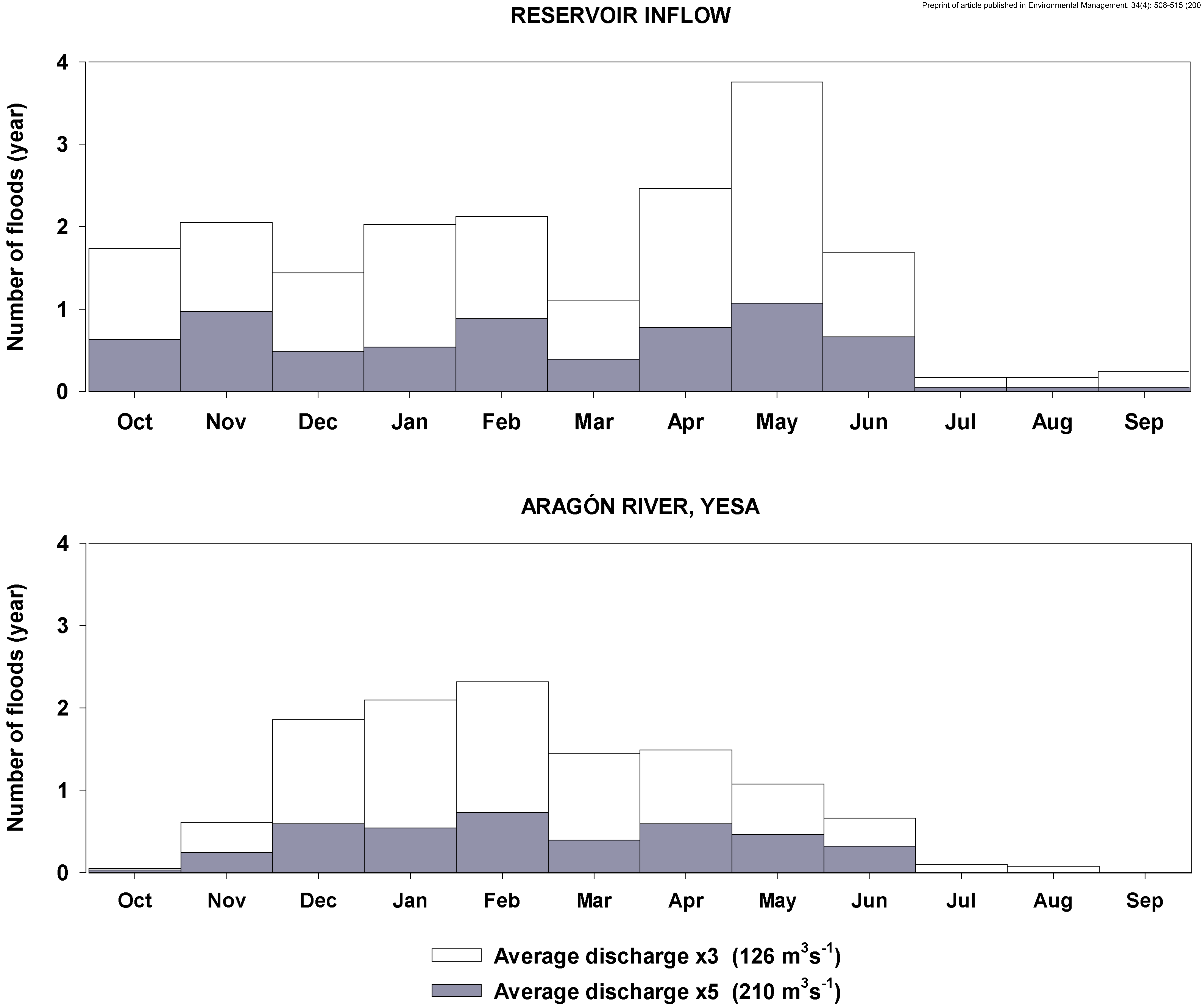
Fig. 8. Temporal distribution of the three management groups.

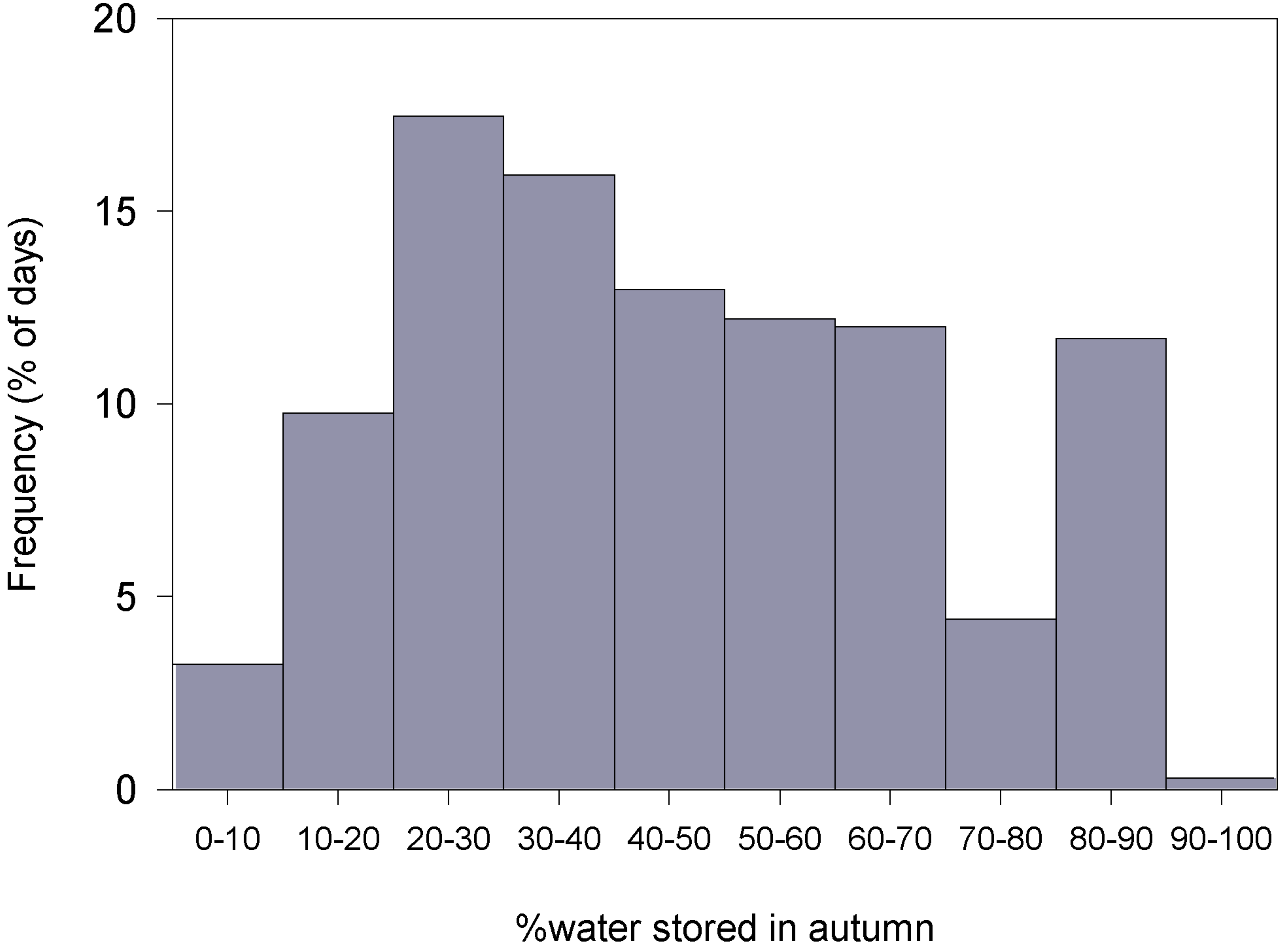
Fig. 9. Trends in discharges from 195960 to 1995-96 (α = confidence level).

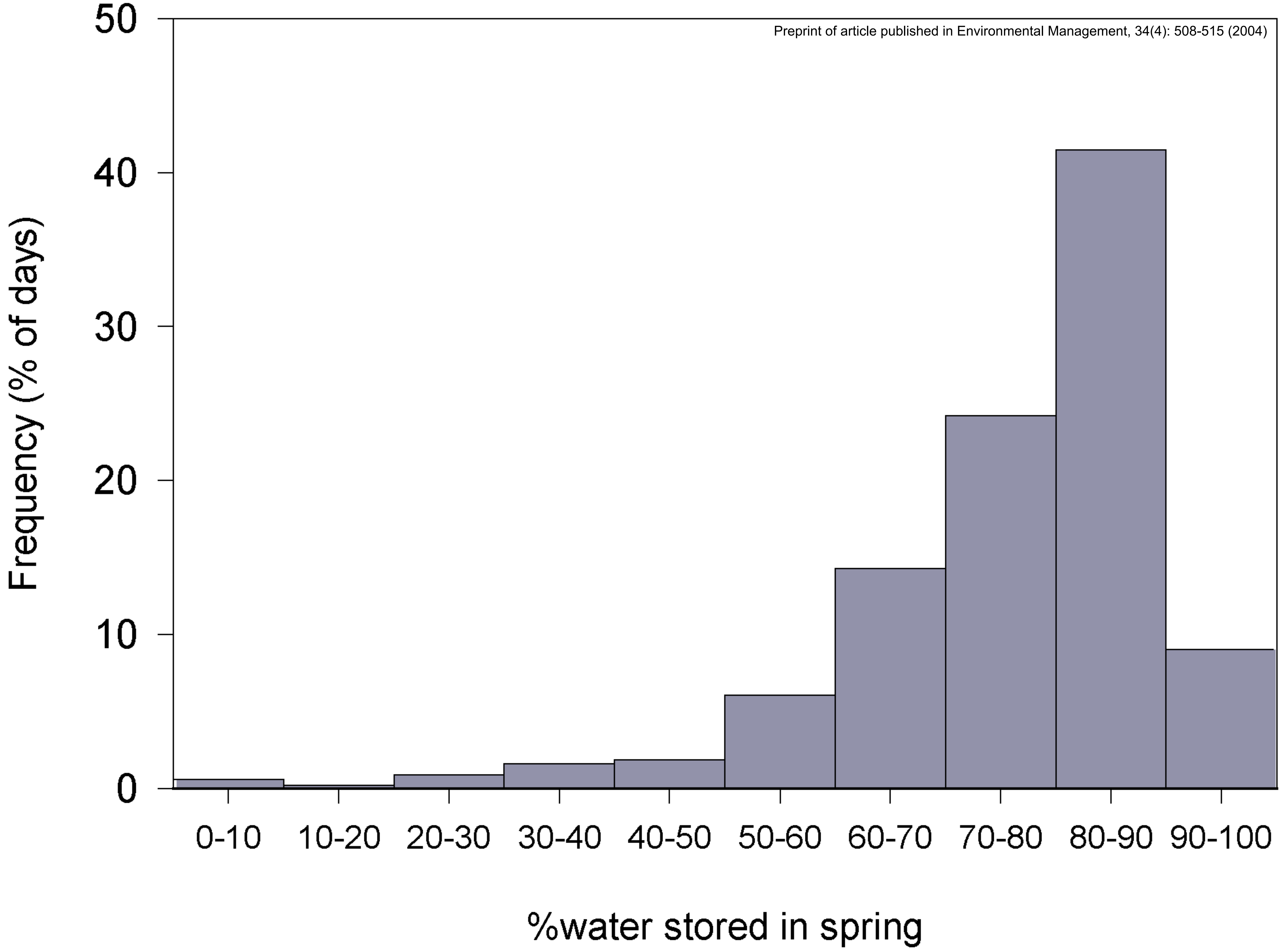
Fig. 10. Mean monthly regime of the Yesa Reservoir inflows calculated for two different periods (1959-1977 and 1978-1995, respectively).

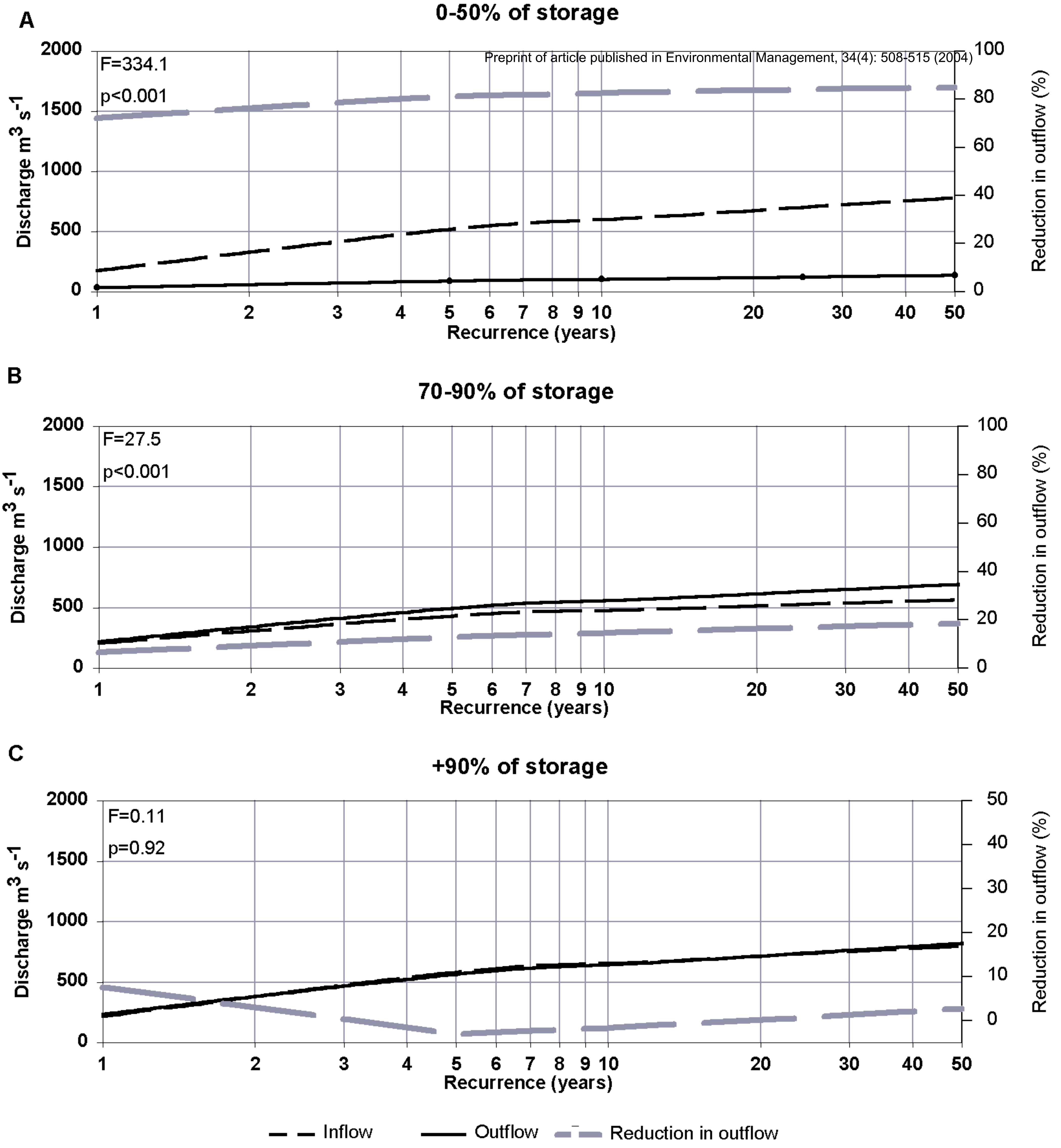
Fig. 11. Correlation between monthly discharge and time (1959-60 / 1995-96) in the Aragón River downstream the Yesa Reservoir.

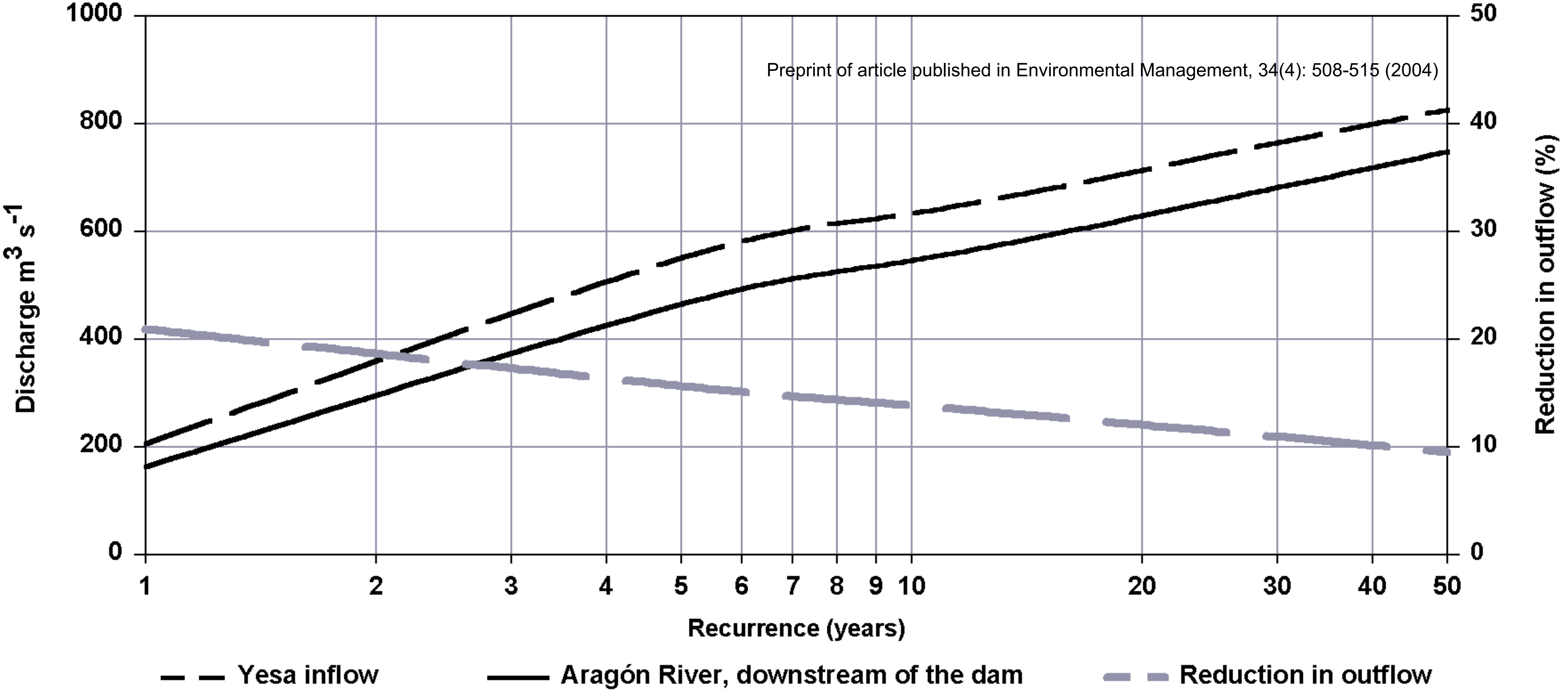

Autumn
Spring
Discharge (m^3s^{-1})
0
200
400
600
800
1000
1200
1400
1
10
100
1000
Recurrence interval (years)
■ Yesa Inflow
○ Aragon river, Yesa


RESERVOIR INFLOW
Number of floods (year)
0
1
2
3
4
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
ARAGÓN RIVER, YESA
Number of floods (year)
0
1
2
3
4
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Average discharge x3 (126 m3s-1)
Average discharge x5 (210 m3s-1)


20
15
10
5
0
Frequency (% of days)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
%water stored in autumn


50
40
30
20
10
0
Frequency (% of days)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
%water stored in spring


A
0-50% of storage
F=334.1
p<0.001
Discharge $m^3 s^{-1}$
0
500
1000
1500
2000
Reduction in outflow (%)
0
20
40
60
80
100
Recurrence (years)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
B
70-90% of storage
F=27.5
p<0.001
C
+90% of storage
F=0.11
p=0.92
0
10
20
30
40
50
Inflow
Outflow
Reduction in outflow


1000
800
600
400
200
0
Discharge m^3 s^{-1}
50
40
30
20
10
0
Reduction in outflow (%)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
Recurrence (years)
Yesa inflow
Aragón River, downstream of the dam
Reduction in outflow

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