THE INFLUENCE OF THE NAO ON WATER RESOURCES IN CENTRAL IBERIA: PRECIPITATION, STREAMFLOW ANOMALIES AND RESERVOIR MANAGEMENT STRATEGIES

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Abstract. This paper analyses the influence of the extreme phases of the winter North Atlantic Oscillation (NAO) on water resources in the Spanish region of the Tagus River basin. By analysing a winter NAO index based on station sea level pressure, the years between 1957 and 2003 were classified as normal, positive, and negative NAO years. A statistical test was then applied to monthly data series of precipitation, river discharge, reservoir storage, and reservoir release to analyse the variations in these variables. For all four variables, significant differences were found between positive and negative NAO years, the former resulting in reduced water availability (negative anomalies), and the latter in increased water availability (positive anomalies). The influence of extreme NAO winters was found to act with different time lags on different variables: the effect of extreme NAO winters on precipitation was found to be quite immediate (and significant for December to March), but this effect was observed later in the year and lasted longer for river discharge, reservoir storage, and water release. Positive and negative NAO years were also found to have different effects on these variables, in that the effects of positive years were more sustained and those of negative years were more rapid and less prolonged. In spite of the high variability of the availability of water resources, the strategies for management of the reservoir system of the basin were found in most cases to provide a regular supply that meets water demands. However, our results also indicate that these water management practises are not adequate for the expected scenarios of climate change and increasing water demand.

Key-words: North Atlantic Oscillation, extreme phases, river discharge, reservoir storage, reservoir management, floods, droughts, Tagus river, Spain

32 **1. Introduction**

33 Management of water resources in the Iberian Peninsula is at present a high priority due to increases
34 in water consumption by agriculture, tourism, and industry. Most Iberian rivers have a marked
35 seasonal and interannual variability, with wet periods characterised by high flows and even
36 catastrophic floods alternating with severe and long droughts (Hisdal et al., 2001) as a consequence
37 of the high precipitation variability in this region (Katz and Acero, 1994; Esteban-Para *et al.*, 1998).
38 During droughts, the Mediterranean areas of the Iberian Peninsula experience low precipitation and
39 water storage levels, as well as strong pressures on water resources (Olcina, 2004). The near
40 continuous water deficit on the Mediterranean coast is partially solved by the Tagus-Segura water
41 transfer, but the donor basin is also prone to water scarcity. Thus, the Tagus-Segura water transfer
42 has only been able to supply about 40% of the projected flows since the beginning of its operation
43 in 1979 (Morales et al., 2005). The determination of the amount of water available for transfer
44 during the dry years causes severe social and political conflicts. Moreover, the transboundary
45 character of the Tagus basin (Spain and Portugal) results in some difficulties in the management of
46 the flows, mainly during the extremes of large flood events and drought periods.

47 These considerations show that it is important to improve the understanding of all factors involved
48 in the climatic and hydrological variability of this region, and to use this knowledge for more
49 precise and reliable management of its water resources. In this respect, it has been shown that
50 several large-scale atmospheric patterns (e.g., the North Atlantic Oscillation, the El Niño-Southern
51 Oscillation, the Scandinavian pattern, and the Mediterranean Oscillation) determine most of the
52 variability of precipitation over the Iberian Peninsula (Pozo-Vázquez et al., 2004; Muñoz-Díaz and
53 Rodrigo, 2004; Rodríguez-Puebla et al., 1998; Vicente-Serrano, 2005; Martín-Vide and López-
54 Bustins, 2006). The North Atlantic Oscillation (NAO) is widely recognised as the most important
55 pattern for explaining the climatic and hydrological variability of the Iberian Peninsula (Zorita et
56 al., 1992; Rodó et al., 1997; Rodríguez-Puebla et al., 1998; Martín-Vide and Fernández, 2001;

57 González-Rouco et al., 2000; Trigo et al., 2004; Xoplaki et al., 2004; Trigo and Palutikof, 2001)
 58 and, in particular, of the Tagus basin (Trigo *et al.* 2004).
 59 The NAO is primarily a North-South dipole characterised by simultaneous out-of-phase
 60 geopotential height anomalies between temperate and high latitudes over the Atlantic sector
 61 (Hurrell et al., 2003). The largest amplitude anomalies are recorded over Iceland and the Iberian
 62 Peninsula. Most studies of the NAO have focused on the northern hemisphere winter months, when
 63 the atmosphere is most active and its influence on climate is greatest (Hurrell and Van Loon, 1997).
 64 The NAO controls the direction and intensity of the wind fields and the interaction between air
 65 masses in the North Atlantic region, and so influences the weather (precipitation, temperature, etc.)
 66 and hydrology over a large part of Europe (Hurrell et al., 2003; Drinkwater et al., 2003; Mysterud et
 67 al., 2003; Kingston et al., 2006 and references therein).
 68 Generally, positive NAO index winters are associated with a northeastward shift in the Atlantic
 69 storm activity and modest activity in the South (Serreze et al., 1997; Trigo et al., 2002; Hurrell and
 70 van Loon, 1997). This shift usually causes severe and persistent droughts in the Iberian Peninsula
 71 although with important spatial variation (Rodríguez-Puebla et al., 1998; Vicente-Serrano and
 72 López-Moreno, 2006).
 73 The impact of the NAO on the hydrological system of the region, especially in its northern section
 74 (Kingston et al. 2006 and references therein), has been addressed by several authors. Kiely (1999)
 75 reported that there has been a sharp increase in the streamflow in Ireland since 1975, and that this
 76 increase is possibly related to the recent positive trend in the NAO. Phillips et al. (2003) described
 77 significant NAO-streamflow relationships in the northwest of Scotland. Shorthouse and Arnell
 78 (1997) demonstrated a positive winter NAO-streamflow correlation for most of northwestern
 79 Europe. There are few studies devoted to southern Europe, although significant relationships
 80 between the NAO and the hydrological cycle have been found in Turkey (Kalayci and Kahya,
 81 2006), Romania (Stefan et al., 2004), the middle-east rivers (Cullen et al., 2002), and the Danube
 82 basin (Rîmbu et al., 2002). Although the effect of the NAO on precipitation in the Iberian Peninsula

83 is well known, there are few studies that analyse its effects on precipitation and the different
84 hydrological subsystems throughout the hydrological cycle. Trigo et al. (2004) found decreases in
85 the river discharges of the three Atlantic basins of Spain and Portugal during positive NAO winters.
86 Most of the studies cited above do not take into account the response times of the components of
87 the hydrological cycle to variation of climate conditions. However, this is an important issue
88 because it is known that different usable water sources have different times of response to decreases
89 and increases in precipitation (McKee et al., 1993; Elfatih et al. 1999; Pandey and Ramasastri,
90 1999; Peters et al., 2005). For instance, Trigo et al. (2004) found that correlations between the
91 winter NAO and discharges were significantly higher if a lag of 1 month was taken into account.
92 However, the lag-times between climatic anomalies and the responses of the hydrological
93 subsystems can be highly variable (Vicente-Serrano and López-Moreno, 2005). The lag-time
94 depends on the hydrological functioning of the basin (such as its physiographic characteristics and
95 groundwater circulation) and on the water management strategies used in a given sector, which are
96 dependent on the relation between water availability and demand (Vicente-Serrano and López-
97 Moreno, 2005).

98 In this paper we analyse the effects of the extreme positive and negative phases of the NAO on the
99 various hydrological subsystems in the Spanish region of the Tagus River basin. The objectives of
100 our study were: i) to assess the magnitude and duration of the effects of the extreme phases of the
101 winter NAO on precipitation and surface water resources in the Tagus basin; ii) to determine if
102 there are differences in the impact of the NAO on various hydrological sub-systems: precipitation,
103 river discharge, reservoir storage, and reservoir release; and iii) to determine to what extent the
104 management strategies of the reservoirs can reduce the impacts of the extreme phases of the NAO
105 on the availability of water resources.

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109 2. Study area

110 This study investigated the Spanish region of the Tagus River basin (Figure 1). The Tagus River is
111 located in the centre of the Iberian Peninsula and flows from East to West for 1009 km (73% of its
112 length is in Spain; 27% in Portugal), draining a total area of 80,100 km² (69% of the total area is in
113 Spain; 31% in Portugal). Close to the border between the two countries is the Alcántara Dam (135
114 m high), which was built in 1969 for hydro power production. With a storage capacity of 3,162
115 hm³, the Alcántara reservoir is the second largest reservoir in Europe and significantly modifies the
116 downstream river regime. For this reason, the hydrological records for the Portuguese section of the
117 river were not included in the analysis, and we only analysed the records for the Spanish section, for
118 which the climatic influence is clearer.

119 The total capacity of the reservoirs in the Tagus basin is 14,500 hm³, of which 12,500 hm³ belong to
120 Spain. The discharge of the Tagus River in its outlet to the Atlantic Ocean (in Lisbon) is about
121 17,730 hm³ yr⁻¹, of which 12,230 hm³ yr⁻¹ are generated in Spanish territory (CHT, 2000). This
122 means that the Tagus is among the most important rivers in Spain, and is the most affected by the
123 construction of large reservoirs. In the headwaters, the Entrepeñas (802 hm³) and Buendía (1638
124 hm³) reservoirs are the largest, and provide water for the Tagus-Segura transfer (Gómez-Mendoza
125 and Mata, 1999; Morales *et al.*, 2005). There are a total of 40 reservoirs with more than 15 hm³ of
126 capacity in the Tagus Basin, which affect most of the main tributaries (Flores, 2004).

127 The Tagus River is one of the main water sources in Spain, and is used for both urban (i.e., the
128 cities of Madrid and Lisbon) and agricultural purposes (García and Alcolea, 2006). About 15.5% of
129 the Spanish population lives within its basin. The headwaters of the Tagus River are located in the
130 Albarracín Range, up to 1500 m a.s.l., which is a massif belonging to the Iberian Range. The middle
131 reach runs through the Tagus sedimentary basin. This basin is delimited to the north by the Central
132 Range, with granite peaks that reach 2592 m above sea level (Almanzor peak) in the Gredos massif,
133 and to the south by the Toledo Mountains, a Paleozoic range of moderate altitude (1600 m).

134 The climate varies from Mediterranean with strong continental influences eastwards to an
135 increasing influence of Atlantic conditions westwards. The average annual precipitation varies
136 significantly along the length of the river. The headwaters receive about 1100 mm per year on
137 average, but a very important section of the middle reach (south of Madrid) receives less than 450
138 mm per year. The headwaters of the tributaries coming from the north (that is, from the central
139 ranges: the Gredos, Peña de Francia, and Estela sierras) receive more than 1500 mm per year.
140 Potential evapotranspiration is estimated at more than 800 mm per year in the central and lower
141 parts of the basin (CHT, 2000). The mean annual temperature is about 11°C, is even lower in the
142 mountain areas (5-7° C), and is 14–15°C in the central part of the basin (i.e., Madrid, 14.1°C;
143 Toledo, 15.4°C).

144

145 3. Methods

146 3.1. Data

147 There is a dense network of gauging stations in the Spanish region of the Tagus River basin,
148 including 104 standard stations
149 (http://www.chtajo.es/redes/aforos/estaciones/informes_aforos.html) and 56 stations at the
150 entrances to the main reservoirs
151 (http://www.chtajo.es/redes/aforos/embalses/informes_embalses.html). The temporal coverage and
152 the amount of missing data for each station vary significantly. With the objective of obtaining a
153 robust database covering the longest time period possible that includes a representative sample of
154 good quality data series (with less than 5% missing values), a careful review of the original data
155 was carried out. The filling in of missing data was carried out by means of a linear regression
156 analysis that considered the most correlated series. Finally, a database with observations from 18
157 gauging stations, seven reservoirs and five precipitation observatories was constructed, covering the
158 period between 1958 and 2003 (Figure 1). Table 1 and 2 show the statistics for the rivers monitored
159 by each gauging station and also for the reservoirs we analysed. Also listed in the table are the

160 general lithological characteristics of the basin recorded at each gauging station and the use of each
161 reservoir.

162 Regional data series for river discharge, reservoir storage, and reservoir release for the whole basin
163 were created from the monthly records for the stations and reservoirs. The purpose was to obtain a
164 regional overview of the main effects of the NAO extreme phases on the water resources of the
165 basin.

166

167 *3.2. Determination of the extreme phases of the North Atlantic Oscillation*

168 Of the several procedures available for characterizing the NAO, we selected the NAO index, which
169 is created from the differences between the standardized pressure anomalies of Gibraltar (south of
170 Spain) and Reykjavik (Iceland). The advantage of using these stations is discussed in depth by
171 Jones *et al.* (1997): the records of Gibraltar appear to better represent the southern part of the NAO
172 dipole than those of other commonly used stations, such as Lisbon or Ponta Delgada in the Azores.
173 A temporal series of the NAO index for the period 1957–2003 was obtained from the Climate
174 Research Unit of the University of East Anglia (<http://www.cru.uea.ac.uk/cru/data/nao.htm>). We
175 calculated the average winter NAO index, which includes the months of December, January,
176 February and March; this period was selected because the NAO has its highest activity in these
177 months (Hurrell *et al.*, 2003), and the impact of the NAO on climate over the North Atlantic region
178 is better characterised for this period than for other periods (Cook *et al.*, 2002).

179 Following Muñoz-Díaz and Rodrigo (2004), we calculated the average and standard deviation of
180 the winter NAO index throughout the whole study period (0.40 and 1.16, respectively), and set a
181 threshold of one standard deviation to define the extreme NAO phases. Years with a winter NAO
182 higher than 1.56 were characterised as positive phases, and years with a winter NAO below -0.76
183 were characterised as negative phases. The positive years were 1961, 1967, 1983, 1989, 1990, 1992,
184 1994, 1995, and 2000 and the negative years were 1963, 1964, 1965, 1969, 1977, 1979, and 1996.
185 The rest of the years were characterised as ‘standard’ and were not included in our study. Although

186 the NAO is mainly active in winter we also considered the spring and autumn NAO phases to know
187 if autumn and spring precipitation could influence the water resources. We also obtained positive
188 and negative years for the autumn and spring NAO following the same threshold of one standard
189 deviation regarding the average.

190

191 *3.3. Analysis*

192 The monthly data series for precipitation, river discharge, reservoir storage, and reservoir release
193 were standardised (standard deviation units from the average) to allow comparison of records with
194 different magnitudes, and the Wilcoxon Mann-Whitney rank test was used (Siegel and Castelan,
195 1988) to determine whether significant humid or dry conditions dominate during positive or
196 negative winter NAO phases. Although the Wilcoxon Mann-Whitney test is slightly less powerful
197 than parametric tests such as the t-test, it was preferred here because of its robustness against non-
198 normality of the variables (Helsel and Hirsch, 1992). The normalised monthly values of the
199 hydrological variables during positive and negative NAO years were compared with the monthly
200 values during i) normal NAO years and ii) years of opposite NAO sign. The significance level for
201 this test was established at $\alpha < 0.05$.

202 The consistency of the responses of the monthly series to positive and negative NAO phases was
203 also checked by examination of the standard error of the monthly averages. A low standard error
204 was considered to be an indication of strong coherence between events, i.e., a guarantee that the
205 influence of NAO extreme phases is not the result of a few major events, but rather the reflection of
206 fairly stable and quantitatively similar results for all of the positive/negative years.

207

208 **4. Results**

209 *4.1. Influence of the extreme NAO phases on precipitation*

210 Figure 2 shows the average and standard deviation of the monthly normalised precipitation
211 corresponding to extreme positive and negative winter NAO phases. The significant differences

212 between the positive and negative extreme NAO years and the other years (black columns) are
213 clear. Averages for periods of more than 12 months after the NAO phases were not shown to avoid
214 likely misinterpretation due to difficulties in isolating the effects of the current year from the effects
215 of the previous year.

216 The effects of extreme phases of the winter NAO are statistically significant for the majority of
217 weather stations from December to March.

218 Positive phases of the winter NAO cause negative precipitation anomalies, and negative phases
219 produce the opposite pattern, i.e., positive average anomalies of precipitation. The magnitudes of
220 the anomalies are usually lower during negative phases, which suggest that the response of
221 precipitation to the winter NAO is non-linear. Some spatial differences were also identified, with a
222 trend to more significant anomalies in the eastern observatories (see the results for Madrid, Toledo,
223 and Cuenca). In Segovia (North) and in Cáceres (West) the numbers of significant anomalies were
224 found to be lower.

225

226 *4.2. Influence of extreme NAO phases on river discharge*

227 Figure 3 shows the average and standard deviation of the monthly normalised river discharge. As
228 was found in the case of precipitation, during positive NAO phases negative anomalies in river
229 discharge arise, whereas positive anomalies were recorded during negative NAO phases. However,
230 there are several differences between the effects of extreme phases on river discharge and those on
231 precipitation. For example, river discharge anomalies in December did not show significant
232 differences as a function of the NAO phase, whereas significant differences were observed in the
233 precipitation data. This suggests there is a lag of at least one month in the hydrological response to
234 climate conditions, as already suggested for the Tagus River by Trigo et al. (2004) and for the north
235 of Spain by Vicente-Serrano and López-Moreno (2005). Secondly, it was found that the NAO-
236 induced anomalies in river discharge extended beyond the winter months, indicating a more
237 persistent influence of the winter NAO on river discharge than on precipitation. The influences of

238 the positive and negative NAO phases were found to be significantly different. Thus, the response
239 of river discharge to negative phases was very quick and intense but relatively short, in that it was
240 significant only from January to April. In contrast, the intensities of the anomalies arising due to
241 positive NAO phases were more moderate, but were significant even during summer and autumn
242 months.

243 Figures 4a, b, and c show the average anomalies in river discharge at each gauging station during
244 positive and negative NAO phases. The records of the majority of the stations follow the general
245 pattern observed for the regional series: negative anomalies in positive years and positive anomalies
246 in negative years. Nevertheless, the timing and magnitude of the significant anomalies vary, even
247 between neighbouring stations.

248 The lag in the hydrological response found in the regional series (Figure 3) was detected at all
249 gauging stations, but varied from 1 month (e.g. Peralejos) to 3–4 months (e.g. Trillo). Moreover, the
250 lag-times tended to be lower for negative NAO phases than for positive phases.

251 Generally, stations located in the headwaters of the Tagus River recorded a lower number of months
252 with significant anomalies. At Peralejos (the first gauging station on the Tagus River), significant
253 anomalies were only recorded in January, February, and March. In lower parts of the basin, at
254 stations with larger drainage areas (e.g. Trillo, Entrepeñas, and Buendía), the response to extreme
255 NAO phases is slightly more complex, with a larger number of months with significant anomalies
256 during positive NAO phases. During negative NAO phases, on the contrary, significant anomalies
257 were only found between January and April. The variability between events for negative phases,
258 represented by the standard error of the average, is also higher than for positive phases. Moreover,
259 the response to the NAO was clearly non-linear, as indicated by the higher magnitude of the
260 anomalies due to positive NAO phases.

261 The records of the stations located on the Tajuña River (Maseoso and Orusco) adhered to the
262 general pattern observed at other stations during positive NAO phases, but the response at Maseoso
263 (in the headwaters) was found to be quicker and more intense during negative NAO phases than at

264 Orusco (on the final section of the river), where positive anomalies between the negative years and
265 the other years were identified between May and December.

266 With the exception of Bujalaro station, for which the most important anomalies were identified
267 during positive NAO phases, the stations located on the Jarama and Henares rivers (Humanes,
268 Belena, Espinillos, Parque Sindical, and Mejorada) only recorded significant negative anomalies in
269 the winter and spring months during positive NAO phases, and between January and April during
270 negative NAO phases.

271 For the Guadarrama (Villalba station) and Alberche (San Juan station) rivers, similar behaviour was
272 found to that observed in the basin of the Henares-Jarama. Again, the responses to positive and
273 negative NAO phases were found to be different, with the anomalies during negative phases found
274 to be variable but more intense.

275 Finally, at the station located in the lowest section of the Tagus River (Valdecañas) and at the two
276 located in the basin of the Alagón River (Gabriel y Galán and Eljerte), very small anomalies were
277 found, although general responses to the positive and negative NAO phases were also detected.

278 Therefore, although the records of the majority of the stations were found to adhere to a general
279 pattern consisting of negative, less intense, less variable and more persistent anomalies during
280 positive phases than during negative phases, substantial differences were found between different
281 parts of the catchments. The responses to extreme NAO phases of the headwaters of the Tagus
282 River and of the small rivers were quicker, with some exceptions, becoming more and more
283 moderate towards the middle sections. The records of the stations at Trillo, Entrepeñas, and
284 Buendía on the Tagus River provide the best examples of this retarded response to extreme NAO
285 phases. This is clearest during positive NAO phases, in which this effect was found even in the last
286 months of the year. In the lowest section of the river system, the effect of extreme NAO phases was
287 found to be much more attenuated.

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289

290 *4.3. The influence of extreme NAO phases on reservoir storage and water release*

291 The influence of extreme NAO phases on reservoir storage was noticeably different to the influence
292 on precipitation and river discharge (Figure 5). No significant anomalies were found during the
293 winter months for either positive or negative phases. In contrast, significant anomalies were found
294 during the rest of the year (from February to November), with stronger effects during the summer
295 and autumn months. During positive NAO phases, negative anomalies were identified during 10
296 months compared to both negative phases and normal years. During negative NAO phases,
297 significant positive anomalies were found from April to December. In general, it can be said that
298 there is a longer lag in the effect of extreme NAO phases on reservoir storage than that found for
299 river discharge, but that these effects were more sustained, affecting almost all the rest of the year.

300 As for the amount of water released from the reservoirs, the behaviour follows the general pattern
301 observed for other variables: negative anomalies during positive NAO phases and positive
302 anomalies during negative phases. As was observed in the case of river discharge, the influence of
303 the NAO on water release was not linear. The magnitudes of the anomalies were lower during
304 positive NAO phases than during negative phases, although the former anomalies lasted longer.
305 However, the magnitude of the anomalies and the number of months with significant differences
306 between positive and negative phases were lower for reservoir release than for river discharge. This
307 was especially true during positive phases, in which less dry conditions were recorded for reservoir
308 release than for river discharge. Figure 6 shows the anomalies in the storages of the different
309 reservoirs arising in the positive and negative NAO phases. There are some differences between the
310 results for the reservoirs. The largest influence of the extreme NAO phases was seen for the two
311 reservoirs located in the upper section of the Tagus River (Entrepeñas and Buendía). These
312 reservoirs have the largest storage capacity of the analysed reservoirs. The effect of the NAO is
313 lower in the reservoirs that have less storage capacity (see Table 1 for details).

314 Figure 7 shows the average anomalies in water release for the seven reservoirs. The differences
315 between the results for the reservoirs can be explained by their contrasting characteristics and

316 operation. The impact of extreme NAO phases on the Entrepeñas and Buendía reservoirs, which are
317 the largest in the basin, is the lowest. The influence of extreme NAO phases on the other smaller
318 reservoirs is larger, and similar to that observed in the case of river discharge. The non-symmetrical
319 character of the influence of the positive and negative NAO phases is also much clearer for these
320 smaller reservoirs.

321

322 *4.4. The influence of spring and autumn NAO phases on water resources*

323 Figure 8 shows the average values of reservoir storages, river discharges and reservoir releases
324 considering the winter, spring and autumn NAO phases. The role of the winter NAO is clearly
325 identified during the winter months, but also during several months later. The role of the autumn
326 NAO on water resources is very little and the spring NAO, although shows some effects during
327 positive phases, the magnitude of the anomalies is not significant regarding the rest of the years in
328 the majority of the months. Although some strength of the NAO effects could be inferred if
329 negative or positive NAO phases coincide the same year in winter and spring this pattern is not
330 usual. Therefore, the role of NAO on water resources can be considered mainly as a winter
331 phenomenon that affects water resources several months after whereas autumn and spring NAO
332 conditions have a minimum role.

333 Moreover, the pattern observed so far is strengthened during periods of several years of
334 persistence of the NAO in one of the extreme phases. We calculated the anomalies during the two
335 most extreme periods (1964-1965— negative phase—, and 1994-1995—positive phase) and found
336 that the pattern is very similar to the single-year extreme phases obtained for the 1958-2003 period
337 (results are not shown). Nevertheless, we found a more pronounced effect as a natural consequence
338 of these periods being the two most extreme events of the NAO identified during the twentieth
339 century.

340

341 *4.5. The role of reservoirs in mitigating the hydrological anomalies associated with extreme NAO*
342 *phases*
343

344 The results discussed above show that reservoirs have important roles in the management of the
345 hydrological extremes associated with extreme NAO phases. Figure 9 shows the average values of
346 river discharge for the reservoirs, and the real magnitudes (hm^3) of the total water stored and total
347 water released in the whole reservoir system. During positive NAO years, the inflows and the water
348 released have completely different behaviours than are observed during the negative years. These
349 differences are especially evident during the winter months, which are responsible for the annual
350 peak discharge during negative NAO phases but represent a secondary minimum during positive
351 phases. The abundant inflow during negative years has two effects on water resources management
352 during winter and spring: i) the possibility of noticeably increasing the volume of water stored in
353 the reservoir system; and ii) the release of high flows downstream of the dams. During the positive
354 phases, the managers equalize the inflows and the outflows, with the latter noticeably lower than
355 during the negative NAO years. From May to December, the inflows to the reservoirs vary between
356 the different NAO phases, with average inflows of $172.2 \text{ m}^3\text{s}^{-1}$ during negative winter NAO phases
357 and $113.4 \text{ m}^3\text{s}^{-1}$ during positive winter NAO phases. Outflows are also similar for both types of
358 NAO phases and so the decreases in the water stored in reservoirs have similar magnitudes (427
359 hm^3 and 418 hm^3 for negative and positive phases respectively), which were achieved by means of
360 adjustments of the reservoir releases; on average the reservoir releases were $227 \text{ m}^3\text{s}^{-1}$ during
361 negative winter NAO phases and $164 \text{ m}^3\text{s}^{-1}$ during positive winter NAO phases. The differences
362 between the water stored in winter and spring during the different NAO extreme phases explain the
363 persistence of the significant anomalies in water stored, as shown in Figure 5.

364 Figure 10 shows the average values of the river discharge, reservoir storage, and water release for
365 the reservoirs of the basin. As Figure 6 shows, there are large differences in the effects of extreme
366 NAO phases on reservoir management. The global pattern described above is clearly appropriate for
367 the Entrepeñas and Buendía reservoirs. This is due to the importance of these two reservoirs in the

whole system, since they make up the largest fraction of the total storage capacity of the system. The results for the other reservoirs exhibit various levels of discrepancy with respect to the global behaviour. Although for most reservoirs the inflows are clearly higher during negative NAO phases, these inflows are not always used for increasing the reservoir storage (e.g., in Barballón, El Vado, San Juan, and El Burgillo). This is because these reservoirs are smaller, and because water release is used for hydropower production and for the infilling of downstream reservoirs. Thus no clear trends in water storage are found during variation of the NAO phases. Differences in water release according to NAO phase are less distinct during summer and autumn, although they can be important for the Buendía, Entrepeñas, and El Burgillo reservoirs.

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378 **5. Discussion and conclusions**

This study focused on the impact of extreme winter NAO phases on three different subsystems of the water cycle: precipitation, river discharge, and reservoir storage. The results highlight the importance of the NAO extreme phases, with variation of their influence depending on i) the hydrological subsystem, ii) the occurrence of a positive or a negative phase, and iii) the geographical location within the basin.

Precipitation tends to decrease during positive extreme NAO phases, and tends to increase during negative phases. These results are in general agreement with the pattern of precipitation anomalies in the Iberian Peninsula, which are mainly associated with the winter NAO (Martín-Vide and Fernández, 2001).

López-Moreno and Vicente-Serrano (2007) demonstrated that extreme NAO phases noticeably affect the field pressures over Europe, which explains the regional differences in drought conditions. However, the extreme NAO phases only affect precipitation from December to March, i.e., their impact on precipitation does not continue into spring. Nevertheless, these authors also indicated that although precipitation is not affected, drought conditions last longer in southern

Europe during positive phases of the NAO, which is made clear by their analysis of river discharge and reservoir storage in the Tagus basin.

Another important result of this study is the non-linearity of the responses of precipitation and river discharge to extreme NAO phases. In general, higher anomalies are recorded during negative years. This result might be explained by the influence of extreme NAO phases on rainfall characteristics. Muñoz-Díaz and Rodrigo (2003, 2004) documented significant changes in the frequency distribution of precipitation and the extreme events as a function of the positive and negative phases of the NAO. Gallego et al. (2005) demonstrated that the strong influence of the NAO on southern Europe is mainly due to the effect of the winter NAO on intense rainfall events, which occur more frequently during negative extreme phases. The asymmetrical response of precipitation to various atmospheric circulation patterns has been observed in several regions (Katz and Parlange, 1994; Kiely et al., 1998; Smith and Roppelwesi, 1997; Vicente-Serrano, 2005). Recently, Pires and Perdigao (2007) have assessed asymmetry within the statistical response of the winter precipitation to the NAO over the North Atlantic-European region. They found that near the central North Atlantic, around 40N-20W, and southeast of Iceland, the correlation is much stronger in the wet-favorable regime: negative phases of the NAO in the first location and positive phases in the second location. On the contrary, around 42 N, 48 W in the west North Atlantic and in the west Mediterranean near 36 N, the correlation is only relevant for the dry-favorable positive phases. These authors have shown that there are some coherent regions where the nonlinear component of the response of winter precipitation to the NAO is more important.

A possible uncertainty of the results obtained arises from the small size of the sample due to the restrictive threshold used to define the extreme phases of the NAO— ± 1 NAO sigma. Therefore, only 7 negative and 9 positive cases were identified, and 30 years fell into the neutral class. Nevertheless, if a less restrictive threshold is chosen (e.g., ± 0.5 sigma, which results in 12 positive and 11 negative phases), the reservoir storages and reservoir releases anomalies during positive and negative phases is very similar to the ones found for ± 1 sigma (results not shown). Therefore, the

419 criterion used to select the NAO phases does not affect noticeably the results, which show a high
420 degree of robustness against changes in the threshold used to select the NAO phases.

421 Precipitation is the main variable affecting the interannual variability of river flows (e.g., Dooge et
422 al. 1999; Jones 1999; Beguería et al. 2003). However, there is usually a time lag in the conversion
423 of rainfall to runoff, which attenuates the effect of climatic anomalies; this result can be explained
424 by the complexity of the processes involved in runoff generation in a large basin. Thus anomalies in
425 river discharge can be found several months after winter, even if the influence of the NAO on
426 precipitation acts on a much more immediate time scale. This is not the only difference between
427 precipitation and river discharge with respect to the influence of the NAO: the non-linear character
428 of the response of river discharge to the NAO is higher than that found for precipitation, resulting in
429 very intense but short discharge anomalies during negative NAO phases and significantly prolonged
430 but less marked discharge anomalies during positive NAO phases. This behaviour can also be
431 explained in terms of the hydrological processes of the basin. Thus, in negative NAO years the
432 basin receives more rainfall than usual, the soils become saturated more easily and a rapid transfer
433 of rainfall to runoff occurs due to this saturation, and this is the cause for high positive anomalies in
434 river discharge. Since this is a rapid process, the effects of increased precipitation do not last very
435 long. During positive NAO years the basin receives less water, and the average surface runoff is
436 drastically reduced, but recharging of the water reserves in soils and aquifers is also diminished.

437 Although the response of river discharge to the NAO that we have described is a general trend for
438 the basin, there are significant differences in the results for the stations in the magnitude and timing
439 of the anomalies. In general, deviations from the global behaviour can be explained in terms of the
440 specific characteristics of each sub-catchment. For example, Vicente-Serrano and López-Moreno
441 (2005) showed that the time of response of Pyrenean rivers depends mainly on the characteristics of
442 the basin, the climatic regime, and the water management carried out upstream of the observation
443 sites. Our results show that similar factors seem to have an important influence on the hydrological
444 responses of the sub-catchments. For example, a more rapid response was found in small, non-

445 regulated catchments, especially in combination with more impervious substrates such as granite
446 (e.g. Belena); in contrast, a more moderate response was found in large and highly regulated
447 catchments, in particular in those with permeable substrates (e.g. Trillo). However, the different
448 combinations of all these factors in the sub-catchments hampers their classification.

449 The extreme NAO phases not only affect river discharge, but also the water management practices
450 applied to the basin's reservoir system. In general, the reservoirs are managed with the objective of
451 synchronizing water availability with water demand, and this is achieved by adjusting the
452 downstream water release as a function of the river inflow to the reservoir and the desired storage
453 volume. The capacity of reservoir management strategies to adapt to the climatic variability is very
454 high, and usually provides an adequate supply of water even during dry years, as has been
455 highlighted by previous studies (Petts, 1984; McCully, 2001; Bonacci and Roje-Bonacci, 2003).

456 The flexibility of these reservoir management strategies is particularly important when long term
457 hydrological trends are present. For example, López-Moreno et al. (2004) analysed the case of a
458 large reservoir in the Pyrenees (north of the Iberian Peninsula), where the strategies were adjusted
459 to manage the decreases in water availability that resulted from a generalised revegetation process
460 after farmland abandonment during the second half of the 20th century (Beguería et al. 2003 and
461 2006). In the case of the Tagus basin, the number and magnitude of the significant differences in
462 monthly reservoir releases are lower than those observed for the river discharge, thus demonstrating
463 the capacity of reservoir management strategies to manage hydro-climatic variability. However, it
464 was also found that very different management strategies need to be applied during positive and
465 negative NAO years in order to comply with water demands. During negative NAO phases, there is
466 a significant winter peak in the inflows to the reservoirs, which allows for a rapid increase in the
467 water storage level, and consequently a high discharge is released downstream of the dams. In
468 contrast, during positive NAO years there is no winter peak in discharge, so the water released from
469 the dams is reduced to a minimum in order to increase the water storage as much as possible. Since
470 the desired water storage volume is not reached during negative NAO winters, the anomalies

471 continue during the rest of the year, and in the most extreme negative events are probably
472 transferred to the following year.

473 We also found that not only does the average storage volume differ between positive and negative
474 NAO years, but also the availability of water resources in the year following an extreme NAO year
475 is affected. Thus, during extreme positive NAO years the total reservoir storage decreases
476 throughout the year, from an average value of 1254 hm³ in December to 874 hm³ in November. In
477 contrast, the negative NAO years enable an increase in the water reserves, ranging from 1573 hm³
478 in December to 1815 hm³ in November. These results clearly show that water availability will be
479 affected in the year following an extreme NAO year, since the baseline at the beginning of the
480 infilling season will be markedly different.

481 According to these results, how sustainable is the water resources supply in the Tagus River basin?
482 This question is of great strategic interest due to i) the importance of the supply to the urban Madrid
483 and Lisbon regions, ii) water diversion to the Mediterranean coast, and iii) the international
484 character of the basin, which must also meet the water demands of the Portuguese sector of the
485 basin. The most likely medium-term scenarios for the basin indicate an increase in the water
486 demand due to urban growth and development in the Madrid metropolitan area and in the
487 Mediterranean coast (Gil-Olcina, 1993; Vera-Rebollo and Torres-Alfosea, 1999), together with
488 likely alterations in the hydrological cycle induced by climate and land cover change. Our results
489 show that the capacity of reservoir management strategies to adapt to extreme hydro-climatic events
490 is probably reaching its limit, and that large difficulties will probably arise as the new conditions
491 anticipated by global change scenarios (climate and land-use/plant cover change) emerge since
492 more extreme NAO phases are predicted for the future (Osborn, 2004), as well as changes in the
493 stochastic properties of precipitation and the most extreme events (Katz and Brown, 1992).

494 Since the construction of new reservoirs in the basin is technically difficult and has a large social
495 impact, delicate adjustments to water management strategies and technologies will be needed.
496 Management of the new circumstances will need to increasingly consider aspects that are now

497 marginal, such as the adoption of more water-efficient practices and technologies, the prizing of
498 water for different uses, an improved protocol of minimum discharge and water sharing between
499 Spain and Portugal, etc. The main problems are as follows: how can integrated water resources
500 management (IWRM) ensure the sustainability of water resources, improve water quality, reduce
501 flood hazards and ensure the protection of natural landscapes and at the same time maintain the
502 welfare of the population? These are difficult questions that require a holistic perspective and the
503 participation of hydrologists, economists, sociologists, and politicians from both Spain and
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505

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682 Table 1. Statistical characteristics of the gauging stations. Also the lithological characteristics of the
683 basin in each gauging station are shown.
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	Gauging station name	main lithology	Annual discharge (hm ³)	
			Mean	Standard deviation
1	Peralejos de las Truchas	Limestones	162.7	0.41
2	Trillo	Limestones	582.5	0.49
3	Ventosa	Limestones	57.4	0.43
4	Mejorada	Limestones	796.8	0.58
5	Bujalaro	Limestones	109.2	0.62
6	Espinillos	Limestones	410.0	0.58
7	Belena	Limestones	144.6	0.78
8	Parque Sindical	Granites	96.3	0.89
9	Maseoso	Limestones	67.9	0.60
10	Orusco	Limestones	364.1	0.76
11	Humanes	Limestones	308.3	0.64
12	Villalba	Granites	65.6	0.54
13	Eljerte	Granites	458.8	0.34
14	Entrepeñas	Limestones	589.8	0.46
15	Buendía	Limestones	553.1	0.58
16	San Juan	Granites	572.1	0.49
17	Valdecañas	Sedimentary	424.9	0.53
18	Gabriel y Galán	Granites	932.0	0.51

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Table 2. Statistical characteristics of the reservoirs. Also the use of each reservoir is shown.

	Reservoir name	Main purpose	Max. storage capacity (hm ³)	Monthly water storage (hm ³)	
				Mean	Standard deviation
1	Entrepeñas	Irrigation-hydropower	802.56	454.58	0.40
2	Buendía	Irrigation-hydropower	1638.7	764.49	0.51
3	San Juan	Irrigation-water supply-hydropower	148.3	117.14	0.17
4	Puentes Viejas	Urban supply	49.2	37.5	0.25
5	El Vado	Urban supply	55.6	30.6	0.27
6	Borbollón	Irrigation-hydropower	85	47.7	0.26
7	El Burguillo	Irrigation-hydropower	208	123.33	0.23

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Figure 1. Study area and location of the stations used: 1) reservoirs (black squares) and precipitation (white squares); 2) gauging stations. Names and characteristics of reservoirs and gauging stations are indicated in table 1.

Figure 2. Precipitation: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years. Black columns indicate significant differences between positive/negative years and the rest of years. + indicates significant differences between positive and negative years. ⊕ indicates significant differences between positive/negative years and normal years.

Figure 3. River discharge: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years for the whole Tagus basin (regional compound series). Legend is the same as in figure 2.

Figure 4a: River discharge: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years in different gauging stations of the Tagus River basin. Legend is the same as in figure 2.

Figure 4b: River discharge: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years in different gauging stations of the Tagus River basin. Legend is the same as in figure 2.

Figure 4c: River discharge: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years in different gauging stations of the Tagus River basin. Legend is the same as in figure 2.

Figure 5. Total water storage and reservoir release in the Tagus basin reservoir system: average and standard error of the anomalies during positive and negative winter NAO years. Same legend as in figure 2.

Figure 6: Water storage in various reservoirs in the Tagus basin: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years. Legend is the same as in figure 2.

Figure 7: Water release from various reservoirs in the Tagus basin: monthly average anomalies (bars) and standard error (whiskers) during positive and negative winter NAO years. Legend is the same as in figure 2.

Figure 8. Average reservoir storages, reservoir releases and river discharges for the whole Tagus basin during positive (left) and negative (right) winter, spring and autumn years.

Figure 9: Average river discharge, total reservoir storage and total reservoir release for the whole Tagus basin during positive and negative NAO phases.

Figure 10: Spatial distribution in the average values of river discharges, reservoir storages and reservoir releases for the whole Tagus basin corresponding to positive and negative NAO phases