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# Drought and Ecological Flows in the Lower Guadiana River Basin (Southwest Iberian Peninsula)

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**Abstract:** Drought temporal characterization is a fundamental instrument in water resource management and planning of basins with dry-summer Mediterranean climate and with a significant seasonal and interannual variability of precipitation regime. This is the case for the Lower Guadiana Basin, where the river is the border between Spain and Portugal (Algarve-Baixo Alentejo-Andalucía Euroregion). For this transboundary basin, a description and evaluation of hydrological drought events was made using the Standardized Precipitation Index (SPI) with monthly precipitation time series of Spanish and Portuguese climatic stations in the study area. The results showed the occurrence of global cycles of about 25–30 years with predominance of moderate and severe drought events. It was observed that the current requirements of ecological flows in strategic water bodies were not satisfied in some months of October to April of years characterized by severe drought events occurring in the period from 1946 to 2015. Therefore, the characterization of the ecological status of the temporary streams that were predominant in this basin should be a priority in the next hydrologic plans in order to identify the relationships between actual flow regimes and habitat attributes, thereby improving environmental flows assessments, which will enable integrated water resource management.

**Keywords:** Standardized Precipitation Index; water management; water quantity; streamflow; frequency analysis; Spain; Portugal; Natura 2000 Network

## 1. Introduction

The hydrographic basins located in regions with typical hot-summer Mediterranean climate conditions [1] have very hot and dry summers that are similar to summers of semi-arid climates along with mild and humid winters. In addition, these basins are usually characterized by a high seasonal and interannual variability of the precipitation regime that sometimes leads to moderate and severe drought events. This influences the availability and allocation of water resources for the different consumptive and non-consumptive uses as well as to the environmental flows required to sustain the aquatic ecosystems and the human well-being that depend on them [2]. Therefore, adaptive and integrative flow regulation management and strategic water resource management plans are required to allow for economic and social development without putting ecosystems at risk [3,4].

A management strategy in the hydrological plans is the characterization and modelization of the seasonal and interannual variability of droughts that have occurred in past periods in these basins with Mediterranean climate conditions. This knowledge will be fundamental for the establishment of medium-term and long-term governance guidelines that guarantee the availability of water resources and the compatibility of the different uses and the environmental flows in the case of future drought events [5,6]. Several indicators can be used for the description of drought events [7] and, among them, one of the most widely used worldwide is the Standardized Precipitation Index (SPI) developed by McKee et al. [8].

The SPI evaluates the precipitation deficit for a given timescale (for example, for 1 month—SPI(1)—or for 6 months—SPI(6)—or for 12 months—SPI(12)), which allows it to describe different drought types (meteorological, agricultural, or hydrological) [9]. SPI calculation is based on precipitation data and is a common tool for identifying drought episodes [10–13].

The hydrographic region of the International Lower Guadiana River (in the province of Huelva in Spain and the regions of the Baixo Alentejo and Algarve in Portugal; The Lower Guadiana Transboundary Basin) has typical conditions of a hot-summer Mediterranean climate with mean ± SD temperatures ranging from 11.35 ± 4.58 °C to 25.3 ± 7.19 °C with a maximal mean temperature of 39.3 °C between May and September. This extreme climatic condition results in Natura 2000 sites with specific species and habitats that are protected under the EU Birds and Habitats Directives [14].

The hydric stress is very high in this basin and it is due to the concurrence of moderate and severe drought events and a growing demand for water use. The highest water use is for irrigated agriculture, having an important increase in the last decade [15–17]. The urban water demand is remarkable mostly in the coastal areas with a high tourist activity [18,19]. The industrial water demand is highlighted in the Spanish part by the important industrial plant located in the Huelva city and nearby areas (Andalucía, Spain). This water diversion for human use can have dramatic consequences for aquatic species [4]. Therefore, in this Algarve-Baixo Alentejo-Andalucía Euroregion there is a clear need for all the water uses and environmental requirements to be made compatible and, for this reason, the European Union is promoting, through cross-border cooperation projects, actions aimed at achieving three dimensions of sustainable development: social, economic, and environmental [20].

In this context, the modelling and assessment of the past drought periods in this international basin is a fundamental factor for the balanced allocation of all water uses and their compatibility with the environmental flows. This is the goal of this work, which is broken up into three phases: (a) calculation of the Standardized Precipitation Index (SPI) for the Lower Guadiana Transboundary Basin using monthly precipitation data from Spanish and Portuguese climatic stations, (b) data collection of monthly and annual streamflows registered in gauging stations of strategic water bodies (those in which there are significant conflicts with water uses), and (c) evaluation of the current requirements of environmental flows considered in the Spanish and Portuguese Hydrological Plans [21,22]. This contribution presents a comparison and analysis of the observed minimal flows applied and the identified minimal flow requirements mentioned in the Spanish and Portuguese Hydrological Plans [21,22].

## 2. The Lower Guadiana River Basin

The Lower Guadiana River Basin drains approximately 67,085 km$^2$ in the Algarve and Baixo-Alentejo regions in Portugal and in the province of Huelva (Andalucía) in Spain (Figure 1). The mean annual precipitation is 521 mm with significant spatial and temporal variability. Minimum annual precipitation values of 264 mm in the low estuary and maximum values of 1397 mm in the high zones of the basin are presented. Most precipitation is concentrated from October to April. The mean annual temperature is 18.24 °C. The minimum and maximum temperatures can reach values of −4 °C in winter and 44 °C in summer [17]. The precipitation and temperature data were recorded by the Spanish State Meteorological Agency (Agencia Estatal de Meteorología de España AEMET, http://www.aemet.es) and the Water Resources National Information System of Portugal (Sistema Nacional de Informação de Recursos Hídricos de Portugal SNIRH, https://snirh.apambiente.pt/). Data from climatic stations distributed in this basin were used in this study (Figure 2).

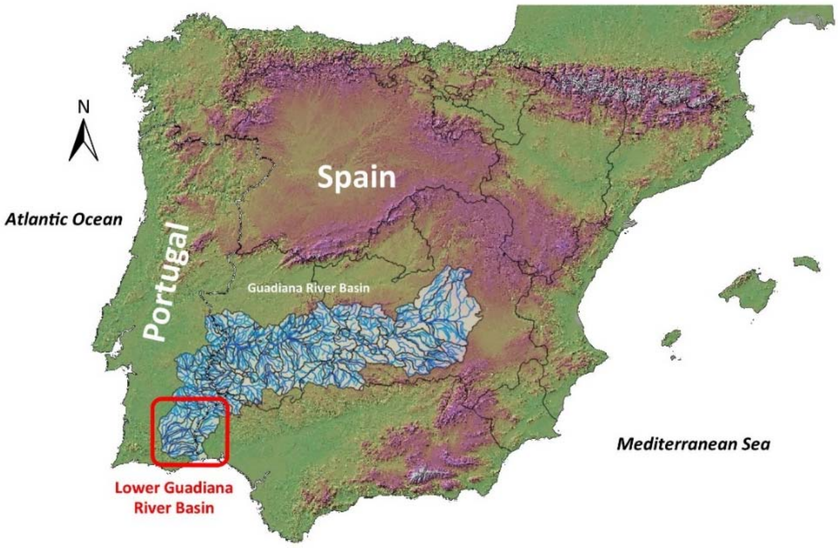


**Figure 1.** The Guadiana River Basin in the Iberian Peninsula: Localization of the study area (the hydrographic region of the International Lower Guadiana River; http://ide.unex.es/conocimiento/ and [17]).

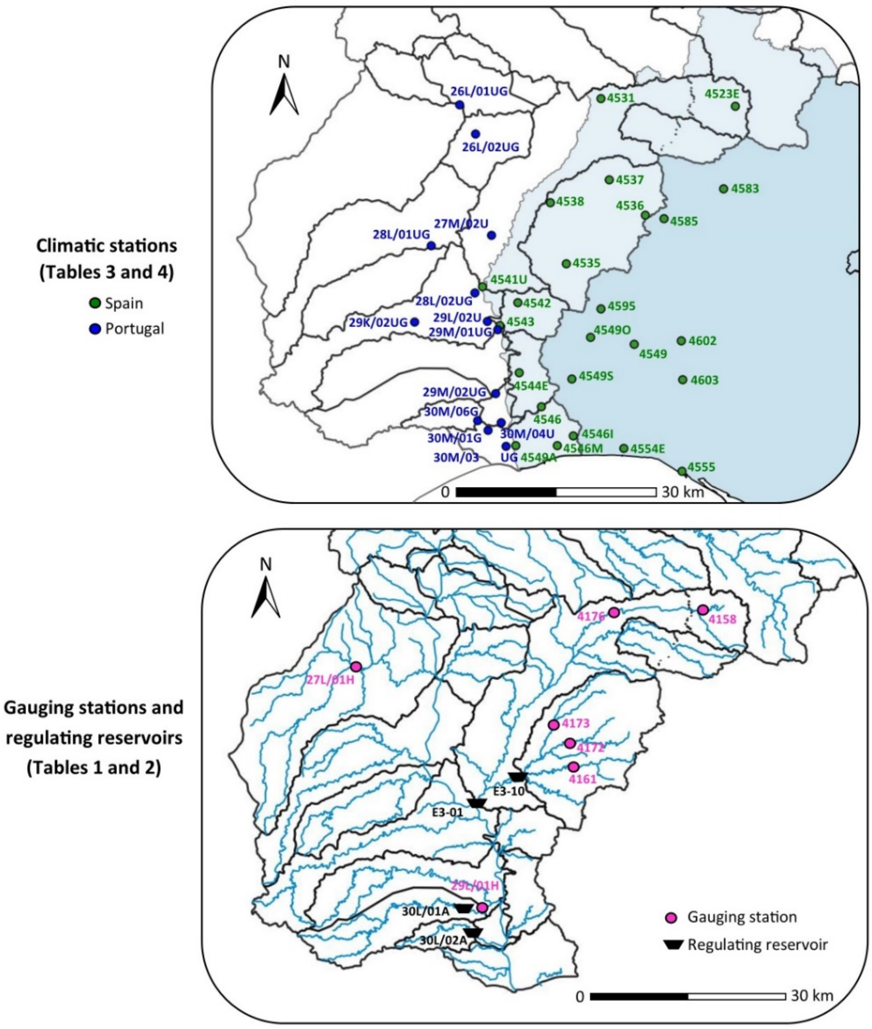


**Figure 2.** Climatic stations, gauging stations, and regulating reservoirs distributed along all the Lower Guadiana River Basin [17].

The water resource system is composed of four regulating reservoirs: (a) the Chanza (E3-01) and the Andévalo (E3-10) reservoirs on the Spanish side; and (b) the Beliche (30L/02A) and the Odeleite (30L/01A) reservoirs on the Portuguese side (Figure 2). The Chanza and Andévalo reservoirs are connected and constitute the main source of water resource supply for the Huelva province (Andalucía, Spain) for the city of Huelva (including its important industrial plant) and for the urban and irrigation supply of the western area of the Huelva province. The Odeleite and Beliche reservoirs are also connected and used to urban and irrigation supply of the Sotavento Algarvio region (eastern Algarve, Portugal). Table 1 shows the main characteristics of these four reservoirs [17].

**Table 1.** Regulating reservoirs of the water resources system of the Lower Guadiana Transboundary Basin [17].

| Parameter | Chanza | Andévalo | Beliche | Odeleite |
|---|---|---|---|---|
| Capacity ($hm^3$) | 341 | 634 | 48 | 130 |
| Municipal district | El Granado (Huelva, Spain) | Puebla de Guzmán (Huelva, Spain) | Castro Marim (Faro, Portugal) | Castro Marim (Faro, Portugal) |
| Latitude | 37°33′ N | 37°37′ N | 37°16′ N | 37°19′ N |
| Longitude | 7°31′ W | 7°24′ W | 7°30′ W | 7°31′ W |
| Denomination (control network) | E3-01 (SAIH Guadiana *) | E3-10 (SAIH Guadiana *) | 30L/02A (SNIRH **) | 30L/01A (SNIRH **) |
| Full operation year | 1985 | 2002 | 1986 | 1996 |
| Water consumptive uses | Irrigation<br>Urban uses<br>Industrial uses<br>Hydropower | Irrigation<br>Urban uses<br>Industrial uses | Irrigation<br>Urban uses<br>Industrial uses | Irrigation<br>Urban uses<br>Industrial uses |

* SAIH Guadiana = Automatic Hydrological Information System of the Guadiana river (Sistema Automático de Información Hidrológica del Guadiana, http://www.saihguadiana.com/). ** SNIRH = Water Resources National Information System of Portugal (Sistema Nacional de Informação de Recursos Hídricos de Portugal, https://snirh.apambiente.pt/).

Water uses in this basin are mostly for irrigation, with approximately 78% of the total demand (about 12,000 ha of irrigation districts). Urban and industrial uses are 17% and 5%, respectively. In the Portuguese area, approximately 123 $hm^3$/year is used for agricultural purposes (84.5%), for urban use (13.6%; residential sector, commerce, and tourism), and for industrial use (1.9%). In the Spanish area, approximately 211 $hm^3$/year is used for agricultural purposes (71.4%), for urban use (20%), for industrial use (7.8%), and for livestock use (0.8%) [21,22].

The water resources system of the Lower Guadiana River Basin comprises eight contiguous and bordering natural spaces classified by the Natura 2000 Network by having sites of ecological importance in Spain and Portugal [14], which are "Guadiana" (PTCON0036), "Vale do Guadiana" (PTZPE0047), and "Sapais de Castro Marim" (PTZPE0018) (in Portugal), and "Rivera del Chanza" (ES6150022), "Río Guadiana y Ribera del Chanza" (ES6150018), "Andévalo Occidental" (ES6150010), "Marismas de Isla Cristina" (ES6150005), and "Isla San Bruno" (ES6150015) (in Spain), in an approximate total area of 1750 $km^2$.

The surface water bodies included in the Lower Guadiana Basin River are generally characterized by intermittent fluvial courses that present a high seasonality with periods without flows rates ranging from 1 to 5 months (from May to September) depending on the precipitation regime. During these periods of flows interruption, there are disconnected pools with the presence of fish species in some sections or localized areas.

There are five groundwater bodies in the Lower Guadiana Basin River: three in the north and two in the south at the Guadiana mouth to the Atlantic Ocean. These water bodies have an approximate extension of 580 $km^2$, which means a very small area (0.86%) of this basin under study. According to the Spanish and Portuguese Hydrological Plans, all these groundwater bodies have a good quantitative status [23].

## 3. Data Collection and Synthesis

In order to evaluate if the streamflows of the basin meet the current requirements of environmental flows considered in the Spanish and Portuguese Hydrological Plans [21,22], flow time series were needed. For this reason, the variables used in this study included monthly and annual streamflows registered in gauging stations of strategic water bodies at the study area (Figure 2). These data were obtained from the Gauging Stations Official Network (Red Oficial de Estaciones de Aforo ROEA, https://sig.mapama.gob.es/redes-seguimiento/) of the Spanish Government and the Water Resources National Information System of Portugal (Sistema Nacional de Informação de Recursos Hídricos de Portugal SNIRH, https://snirh.apambiente.pt/). The characteristics of these gauging stations are shown in Table 2.

**Table 2.** Characteristics of gauging stations in strategic water bodies at the Lower Guadiana River Basin (Figure 2) ($\bar{x}$ = daily mean flow in m$^3$/s; VC = variation coefficient; max = daily maximum flow in m$^3$/s; min = daily minimum flow in m$^3$/s) [17].

| Station | Denomination (Control Network) | Latitude/Longitude | Daily Mean Flow ($\bar{x}$; VC) (Max; Min) | Years |
|---|---|---|---|---|
| Albahacar | 4173 (ROEA) | 37°43′ N 7°19′ W | (0.46 m$^3$/s; 7.35)<br>(246.26 m$^3$/s; 0 m$^3$/s) | 1969–2004 |
| Chanza in Aroche | 4158 (ROEA) | 37°58′ N 6°57′ W | (0.50 m$^3$/s; 3.16)<br>(47.00 m$^3$/s; 0 m$^3$/s) | 1960–2006 |
| Chanza in Rosal Frontera | 4176 (ROEA) | 37°57′ N 7°12′ W | (1.26 m$^3$/s; 4.12)<br>(138.50 m$^3$/s; 0 m$^3$/s) | 1969–2002 |
| Cóbica | 4161 (ROEA) | 37°38′ N 7°15′ W | (0.40 m$^3$/s; 12.60)<br>(285.00 m$^3$/s; 0 m$^3$/s) | 1969–2004<br>2008–2010 |
| Malagón | 4172 (ROEA) | 37°41′ N 7°16′ W | (1.65 m$^3$/s; 7.79)<br>(778.08 m$^3$/s; 0 m$^3$/s) | 1969–2004<br>2007–2010 |
| Pulo do Lobo | 27L/01H (SNIRH) | 37°48′ N 7°37′ W | (140.34 m$^3$/s; 2.86)<br>(7752.53 m$^3$/s; 0 m$^3$/s) | 1946–2000<br>1990–2018 |
| Monte dos Fortes (Ribeira de Odeleite) | 29L/01H (SNIRH) | 37°20′ N 7°37′ W | (2.40 m$^3$/s; 4.07)<br>(350.43 m$^3$/s; 0 m$^3$/s) | 1960–2001<br>1990–2018 |

In order to calculate the SPI index for the Lower Guadiana River Basin, long historical continuous observations of monthly precipitation were needed. These precipitation data were provided of climatic stations of the Spanish State Meteorological Agency (Agencia Estatal de Meteorología de España AEMET, http://www.aemet.es) and the Water Resources National Information System of Portugal (SNIRH) distributed over the study area (Tables 3 and 4, Figure 2).

Some of the monthly streamflows and precipitation series had missing values that were filled by applying an approach based on autoregressive integrated moving average (ARIMA) modeling. For filling a monthly gap, the ARIMA model used the previous observations for each gap in a given climatic or gauging station. The implementation of these ARIMA models was performed in RStudio v3.3.2 [24]. For this purpose, the auto.arima function proposed by Hyndman and Khandakar [25] was used, which returns the best ARIMA model according to the value of the Akaike information criterion (AIC, AICc), or the Bayesian information criterion (BIC) [26]. Additional packages included in the script development were "forecast" [26], "lmtest" [27], "stats" [24], and "tseries" [28].

**Table 3.** Characteristics of Portuguese climatic stations distributed over the Lower Guadiana River Basin (control network SNIRH, Figure 2) ($\bar{x}$ = monthly mean precipitation in mm/month; VC = variation coefficient; max = monthly maximum precipitation in mm/month; min = monthly minimum precipitation in mm/month) [17].

| Station | Denomination | Latitude/Longitude | Precipitation [$\bar{x}$; VC] (Max; Min) | Years |
|---|---|---|---|---|
| Alcoutim | 29M/01UG | 37°27′ N 7°28′ W | (42.18 mm/month; 1.31) (411.6 mm/month; 0) | 1976–2017 |
| Azinhal | 30M/04U | 37°15′ N 7°27′ W | (35.54 mm/month; 1.60) (324.4 mm/month; 0) | 1981–1985 |
| Barragem do Beliche | 30M/06G | 37°16′ N 7°30′ W | (45.89 mm/month; 1.09) (300.4 mm/month; 0) | 2001–2016 |
| Castro Marim | 30M/03UG | 37°12′ N 7°26′ W | (40.81 mm/month; 1.37) (398.2 mm/month; 0) | 1981–2016 |
| Cortes Pereiras | 29L/02U | 37°28′ N 7°30′ W | (40.84 mm/month; 1.39) (380.7 mm/month; 0) | 1980–2001 |
| Figueirais | 30M/01G | 37°14′ N 7°29′ W | (45.27 mm/month; 1.26) (322.7 mm/month; 0) | 1936–1984 |
| Mértola | 28L/01UG | 37°38′ N 7°39′ W | (35.23 mm/month; 1.23) (301.6 mm/month; 0) | 1932–2017 |
| Mesquita | 28L/02UG | 37°32′ N 7°32′ W | (34.97 mm/month; 1.34) (351.0 mm/month; 0) | 1981–2016 |
| Minas de São Domingos | 27M/02U | 37°39′ N 7°30′ W | (43.55 mm/month; 1.10) (313.4 mm/month; 0) | 1900–1968 |
| Santa Iria | 26L/02UG | 37°52′ N 7°33′ W | (37.04 mm/month; 1.26) (278.3 mm/month; 0) | 1981–2017 |
| Sapal de Odeleitte (Ex. Fonte do Penedo) | 29M/02UG | 37°19′ N 7°28′ W | (38.28 mm/month; 1.02) (162.8 mm/month; 0) | 2002–2016 |
| Serpa | 26L/01UG | 37°56′ N 7°36′ W | (43.98 mm/month; 1.16) (388.7 mm/month; 0) | 1932–2011 |

**Table 4.** Characteristics of Spanish climatic stations distributed over the Lower Guadiana River Basin (control network Agencia Estatal de Meteorología de España (AEMET), Figure 2) ($\bar{x}$ = monthly mean precipitation in mm/month; VC = variation coefficient; max = monthly maximum precipitation in mm/month; min = monthly minimum precipitation in mm/month) [17].

| Station | Denomination | Latitude/Longitude | Precipitation ($\bar{x}$; VC) (Max; Min) | Years |
| --- | --- | --- | --- | --- |
| Aroche (Las Cefiñas) | 4523E | 37°57′ N 6°51′ W | (66.25 mm/month; 1.11) (439.0 mm/month; 0) | 1968–2017 |
| Ayamonte (Telégrafos) | 4549A | 37°13′ N 7°24′ W | (40.50 mm/month; 1.35) (378.0 mm/month; 0) | 1949–1985 |
| Cabezas Rubias | 4536 | 37°43′ N 7°05′ W | (55.21 mm/month; 1.21) (441.6 mm/month; 0) | 1964–2017 |
| Cartaya (Pemares) | 4554E | 37°13′ N 7°07′ W | (50.56 mm/month; 1.39) (459.5 mm/month; 0) | 1987–2014 |
| Cerro Andeválo (El Cóbico) | 4585 | 37°43′ N 7°02′ W | (54.59 mm/month; 1.21) (468.5 mm/month; 0) | 1964–2017 |
| El Almendro (La Burrilla) | 4595 | 37°31′ N 7°11′ W | (56.00 mm/month; 1.27) (470.0 mm/month; 0) | 1962–1984 |
| El Granado | 4542 | 37°31′ N 7°25′ W | (46.25 mm/month; 1.23) (409.5 mm/month; 0) | 1964–2017 |
| El Granado (Bocachanza) | 4541U | 37°33′ N 7°31′ W | (42.25 mm/month; 1.22) (380.1 mm/month; 0) | 1976–2017 |
| Gibraleón | 4603 | 37°22′ N 6°58′ W | (47.96 mm/month; 1.29) (394.7 mm/month; 0) | 1965–2012 |
| Isla Cristina (Cañada Corcho) | 4546M | 37°13′ N 7°17′ W | (47.38 mm/month; 1.34) (391.2 mm/month; 0) | 1989–2013 |
| Lepe (Valdeluz) | 4546I | 37°14′ N 7°15′ W | (49.33 mm/month; 1.40) (470.5 mm/month; 0) | 1989–2006 |
| Paymogo | 4538 | 37°44′ N 7°20′ W | (53.37 mm/month; 1.27) (381.6 mm/month; 0) | 1952–1984 |
| Presa de Sancho | 4602 | 37°44′ N 7°20′ W | (51.46 mm/month; 1.26) (377.5 mm/month; 0) | 1961–1992 |
| Presa del Piedras | 4549S | 37°21′ N 7°15′ W | (43.98 mm/month; 1.31) (407.5 mm/month; 0) | 1972–1992 |
| Puebla de Guzmán (Herrerias) | 4535 | 37°36′ N 7°17′ W | (42.75 mm/month; 1.20) (318.0 mm/month; 0) | 1966–2017 |
| Punta Umbría | 4555 | 37°10′ N 6°57′ W | (39.25 mm/month; 1.38) (380.0 mm/month; 0) | 1988–2017 |
| Rosal de la Frontera | 4531 | 37°58′ N 7°13′ W | (50.28 mm/month; 1.11) (312.0 mm/month; 0) | 1966–1982 |
| San Bartolomé de la Torre | 4599 | 37°26′ N 7°06′ W | (49.19 mm/month; 1.27) (373.4 mm/month; 0) | 1963–1989 |
| San Silvestre de Guzmán (Labrados) | 4544E | 37°22′ N 7°24′ W | (45.72 mm/month; 1.30) (465.6 mm/month; 0) | 1980–2016 |
| Sanlúcar de Guadiana | 4543 | 37°28′ N 7°28′ W | (40.58 mm/month; 1.28) (334.4 mm/month; 0) | 1961–1986 |
| Santa Bárbara de Casa | 4537 | 37°47′ N 7°11′ W | (62.31 mm/month; 1.10) (399.0 mm/month; 0) | 1952–1981 |
| Valdelamusa (Minas) | 4583 | 37°47′ N 6°52′ W | (66.66 mm/month; 1.17) (477.0 mm/month; 0) | 1972–1992 |
| Villablanca | 4546 | 37°18′ N 7°20′ W | (52.08 mm/month; 1.26) (422.7 mm/month; 0) | 1964–2012 |
| Villanueva de los Castillejos (Toril Nuevo) | 4549O | 37°27′ N 7°13′ W | (50.71 mm/month; 1.25) (417.0 mm/month; 0) | 1972–1992 |

## 4. Drought Events Evaluation: Standardized Precipitation Index SPI

The characterization of the drought temporal variability can be very useful for an optimal planning and management of water resources. Several indicators are usually used to identify these drought events [7] and, among them, one of the most widely used is the Standardized Precipitation Index (SPI) developed by McKee et al. [8].

SPI is calculated with the probability distribution function that best fits the historical records of monthly precipitation at the study area. This probability is transformed to a normal distribution and SPI is the normalized variable obtained [7]. Thus, SPI positive values indicate an above mean precipitation and SPI negative values indicate a below mean precipitation. Mckee et al. [8] established a reference system to identify the drought intensity as a function of the values obtained from the SPI. Thus drought episodes occur when the SPI is continuously negative and with a value of −1.0 or lower [29].

SPI can be calculated at different time scales in order to study different types of drought. Normally SPI of 1 or 2 months is determined for meteorological drought, SPI of 1 to 6 months for agricultural drought, and of 6 to 24 months for hydrological drought [29].

In this study, the SPI calculation was performed in Rstudio v3.3.2 [24]. For this, the Standardized Precipitation Evapotranspiration Index (SPEI) library was used—a statistical package developed in environment R that has implemented a function set from which SPI can be obtained [30–32]. The spi function that returns SPI time series was used. This function has two basic arguments: (a) the determination of the SPI time scale; in our case SPIs of 6, 12, and 24 months were obtained to study the hydrological drought, and (b) the calculation of the probability distribution where one can choose between adjusting to a Gamma type distribution or Pearson type III. In our case, the Pearson III function was chosen because, according to the specialized literature, this has better fits than the Gamma type function [12,13,33].

An SPI was calculated for the Lower Guadiana River Basin. For this purpose, two mean monthly precipitation series were simulated for the Spanish and Portuguese zones. The mean precipitation series of the Spanish zone has a temporal extension of 68 years (1949–2017) and was obtained using the monthly precipitation series of the climatic stations showed in Table 4. The mean precipitation series for the Portuguese zone was calculated in the same way as for the Spanish zone, but with a longer temporal length, in this case for 117 years (1900–2017). The Portuguese climatic stations shown in Table 3 were used. Correlation analysis between monthly precipitations of Spanish and Portuguese climatic stations showed high significant correlation values ($R > 0.76$; $p < 0.05$). Therefore, with the Spanish and Portuguese precipitation series, the arithmetic mean precipitation series for the entire Lower Guadiana Transboundary Basin from 1900 to 2017 was obtained and used to calculate the SPI series.

## 5. Seasonal and Interannual Analysis of Ecological Flows

The ecological flow is defined as the streamflows regime that provides adequate environmental conditions in the water bodies to sustain the aquatic ecosystems and the human well-being that depend on them [2]. In this work, an evaluation was made to see if the monthly and annual streamflows registered at gauging stations of strategic water bodies (those in which there are significant conflicts with water uses; Table 2) are in accordance with the ecological flow requirements identified in the Spanish and Portuguese Hydrological Plans [21,22].

The comparison of the available historical records of the monthly streamflows at selected gauging stations (Table 2) with the environmental flow requirements identified in the Spanish and Portuguese Hydrological Plans [21,22] was carried out by means of a frequency analysis of months in which the ecological flows were not reached.

In the Spanish and Portuguese Hydrological Plans of the Guadiana Hydrographic Demarcation [21,22], the current requirements of environmental flows were calculated through considering a combination of methods corresponding to the categories of hydrological, hydraulic rating, and habitat simulation [34]. It is a main priority for future hydrological plans to consider holistic approaches that incorporate ecologically relevant features of the natural hydrologic regime to protect the entire riverine ecosystem. These holistic assessments must include as ecosystem components: geomorphology and channel morphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates and fish, and other vertebrates with some dependency on the river/riparian ecosystem [2].

The regimes of temporary streams of the fluvial courses distributed over the Lower Guadiana Basin River implies current requirements of environmental flows zero from May to September as shown in Table 5.

**Table 5.** Gauging station "Chanza in Rosal de la Frontera" (4176 Red Oficial de Estaciones de Aforo (ROEA); Guadiana tributary): months with streamflows lower than the current requirements of ecological flows by the Spanish and Portuguese Hydrological Plans of the Guadiana Hydrographic Demarcation [21,22]. Data period from October 1969 to September 2002.

| Month | Current Ecological Flows ($hm^3$/month) | Years of Non-Compliance |
|---|---|---|
| October | 0.018 | 1970, 1973, 1974, 1975, 1976, 1977, 1983, 1992, 1997, 2000 |
| November | 0.064 | 1971, 1974, 1975, 1976, 1977, 1981, 1992 |
| December | 0.054 | 1976 |
| January | 0.049 | 1976, 1977 |
| February | 0.119 | 2000 |
| March | 0.103 | - |
| April | 0.112 | 1993, 1995, 1999 |

## 6. Results and Discussion

### *6.1. Characterization of Hydrological Drought Rvents*

Figure 3 shows SPI(12) (12-month time scale) and SPI(24) (24-month time scale) calculated for the Lower Guadiana River Basin. The SPI at these time scales reflects long-term precipitation patterns and are usually tied to streamflows. A 24-month SPI is a comparison of the precipitation for 24 consecutive months with that recorded in the same 24 consecutive months in all previous years of available data [29].

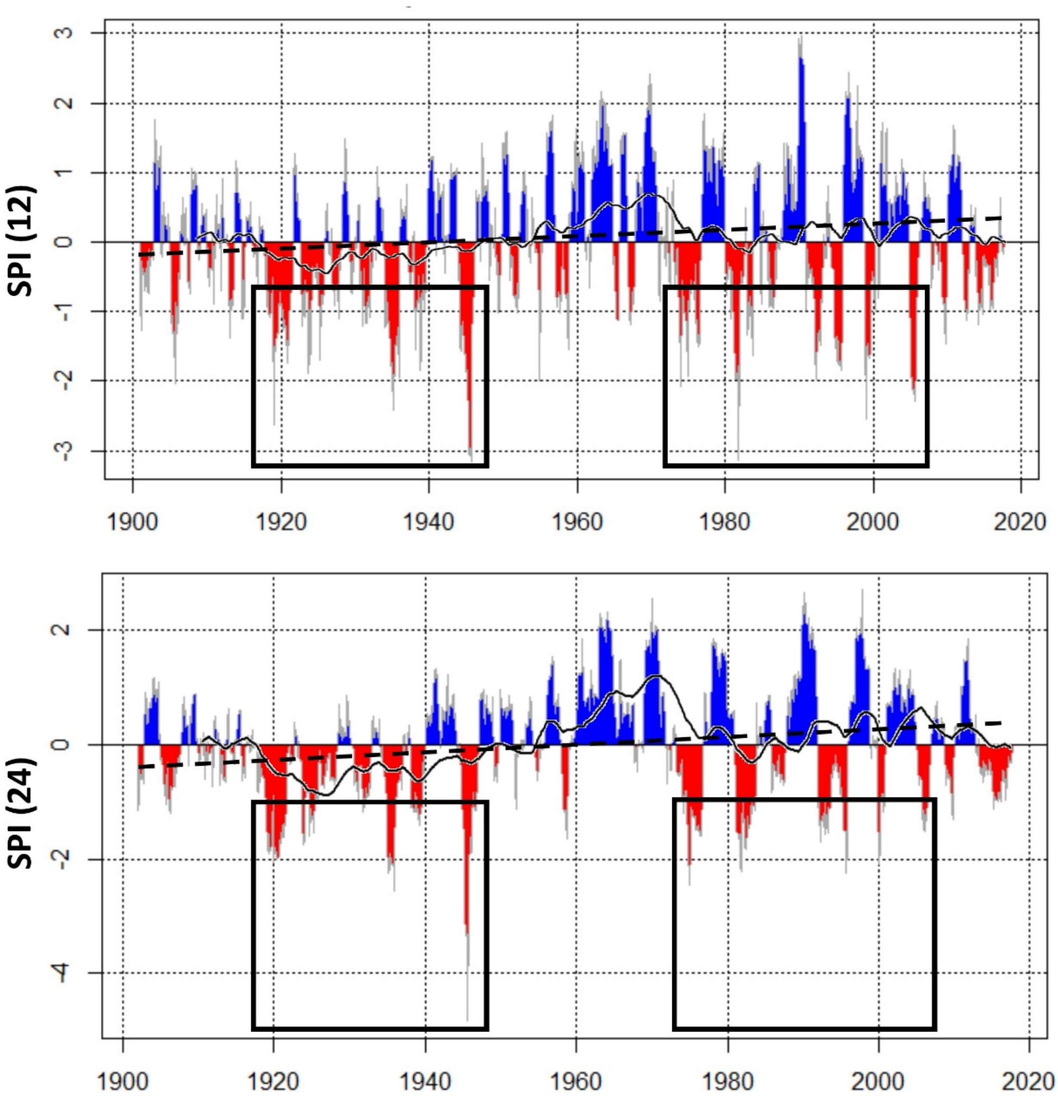


**Figure 3.** Standardized Precipitation Index for 12-month (SPI 12) and 24-month (SPI 24) time scales in the Lower Guadiana River Basin. Cycles of about 25–30 years with predominance of moderate and severe drought events occurred (these global drier cycles are marked in this figure by rectangles). Dashed lines indicate linear trend of fit and solid lines indicate the 10-year moving average of the SPI(12) and SPI(24) series.

Qualitative analysis of SPI(12) and SPI(24) time series suggests global cycles of about 25–30 years of predominance of moderate and severe drought events between approximately 1920–1950 and 1975–2005 (SPI from −1.0 to −1.49 indicates moderately dry, from −1.5 to −1.99 severely dry, from −2 and less extremely dry). In the periods from 1900 to 1920 and from 1950 to 1970, the SPI intensity was rarely less than −1, and therefore can be considered a normal or approximately normal situation without episodes of hydrological drought [29].

These two global cycles with moderate and severe droughts identified in the study area included specific drier periods that affected most of Europe that took place in 1920–1921, 1933–1934, 1975–1976, 1990–1992, and 1995–1997. These drier events in oceanic climate areas were of shorter duration than in Mediterranean climate areas (one to two years versus two to three years), but the intensity in some cases crossed over the extreme drought level [35,36]. The remaining drier years that compose the two observed global cycles could be considered regional drought episodes in the Lower Guadiana River Basin.

A spectral analysis of the SPI(12) and SPI(24) series provided high spectral densities for periods of 40 and 82 months (3.3 and 6.8 years) and of 351 and 347 months (29.2 and 28.9 years), respectively. This analysis supports the two global drier cycles cited previously as well as the drier yearly periods included in these global cycles.

The linear trends of the SPI series revealed a slight non-significant increase of wetter conditions but a clear change in drought conditions at the annual scale did not show (Figure 3). These results are consistent with those obtained by Coll et al. in the western Iberia Peninsula [37], by García-Valdecasas et al. in the Guadiana River Basin [38], and by Sánchez-Carrillo and Álvarez-Cobelas in the Upper Guadiana River Basin [39]. The decadal moving average of the SPI series identified the drier and wetter global cycles cited previously (Figure 3).

This alternating pattern of long cycles with predominance of moderate and severe drought events with precipitation normal regime cycles hindered the hydrological planning of the basin under study and suggests the need to establish medium-term to long-term governance guidelines that guarantee the water resources availability, the compatibility of the different uses, and the environmental flows in the case of future drought events.

### *6.2. About the Ecological Flows Regime*

The comparison of the available historical records of monthly streamflows of the gauging stations (from strategic water bodies; Table 2) with the current requirements of the environmental flows identified in the Spanish and Portuguese Hydrological Plans [21,22] was carried out by means of a frequency analysis of months in which the ecological flows were not reached.

The results of these frequency analyses showed that the current requirements for ecological flows were not met in months of years characterized by severe drought events (SPI $< -1.5$; [29]) even in time periods in which there were no regulation elements (reservoirs) of surface waters (full operation year of reservoirs: Chanza in 1985, Andévalo in 2002, Beliche in 1986, Odeleite in 1996). This occurred in the periods 1946–1948, 1975–1977, 1981–1985, 1992–1995, 1999–2000, and 2005–2008, with severe periods of hydrological drought (Figure 3).

The months (without considering the summer season) with the highest frequency of non-compliance of environmental requirements were October and November due to seasonal variability of precipitation in this basin. Tables 5 and 6 and Figures 4 and 5 show, by way of example, the results of these frequency analyses and the streamflow time series at the gauging stations "Chanza in Rosal de la Frontera" (4176 ROEA; Guadiana tributary) and "Pulo do Lobo" (27L/01H SNIRH; main course of the Guadiana River). The regime of temporary streams of the tributaries of the Lower Guadiana River implies current requirements of environmental flows zero from May to September.

**Table 6.** Gauging station "Pulo do Lobo" (27L/01H SNIRH; main course of the Lower Guadiana River): months with streamflows lower than the current requirements of ecological flows by the Spanish and Portuguese Hydrological Plans of the Guadiana Hydrographic Demarcation [21,22]. Data period from October 1946 to November 2000, from October 2001 to September 2009 and October 2014 to September 2015.

| Month | Current Ecological Flows ($hm^3$/month) | Years of Non-Compliance |
|---|---|---|
| October | 24 | 1946, 1948, 1950, 1951, 1954, 1983, 1994, 2002 |
| November | 49 | 1946, 1947, 1948, 1950, 1952, 1953, 1954, 1956, 1957, 1958, 1973, 1974, 1975, 1980, 1981, 1985, 1986, 1991, 1992, 1995, 2000, 2002, 2005 |
| December | 51 | 1946, 1954, 1956, 1957, 1974, 1975, 1980, 1985, 1986, 1991, 1993, 1999, 2005, 2008 |
| January | 51 | 1954, 1976, 1977, 1981, 1992, 1993, 1995, 1999, 2000, 2009 |
| February | 47 | 1949, 1981, 1983, 1989, 1992, 1993, 1995, 1999, 2000, 2002, 2008 |

**Table 6.** *Cont.*

| Month | Current Ecological Flows ($hm^3$/month) | Years of Non-Compliance |
|---|---|---|
| March | 51 | 1949, 1976, 1981, 1982, 1983, 1989, 1992, 1993, 1997, 1999, 2000, 2005, 2008 |
| April | 34 | 1981, 1982, 1983, 1992, 1993, 1994, 1995, 1999 |
| May | 35 | 1949, 1950, 1954, 1955, 1958, 1981, 1982, 1983, 1991, 1992, 1993, 1994, 1995, 2002, 2003, 2009 |
| June | 24 | 1949, 1950, 1953, 1954, 1955, 1958, 1959, 1976, 1981, 1982, 1983, 1986, 1987, 1993, 1994, 1995, 1996, 1999, 2000, 2002, 2003, 2009 |
| July | 16 | 1947, 1949, 1950, 1951, 1953, 1954, 1955, 1957, 1959, 1981, 1982, 1983, 1993, 1994, 1995, 1996, 1999, 2003, 2009 |
| August | 16 | 1947, 1948, 1949, 1950, 1951, 1952, 1953, 1954, 1982, 1983, 1993, 1994, 1995, 2003 |
| September | 16 | 1947, 1948, 1950, 1951, 1953, 1954, 1983, 1993, 1994, 1995, 2002, 2003 |

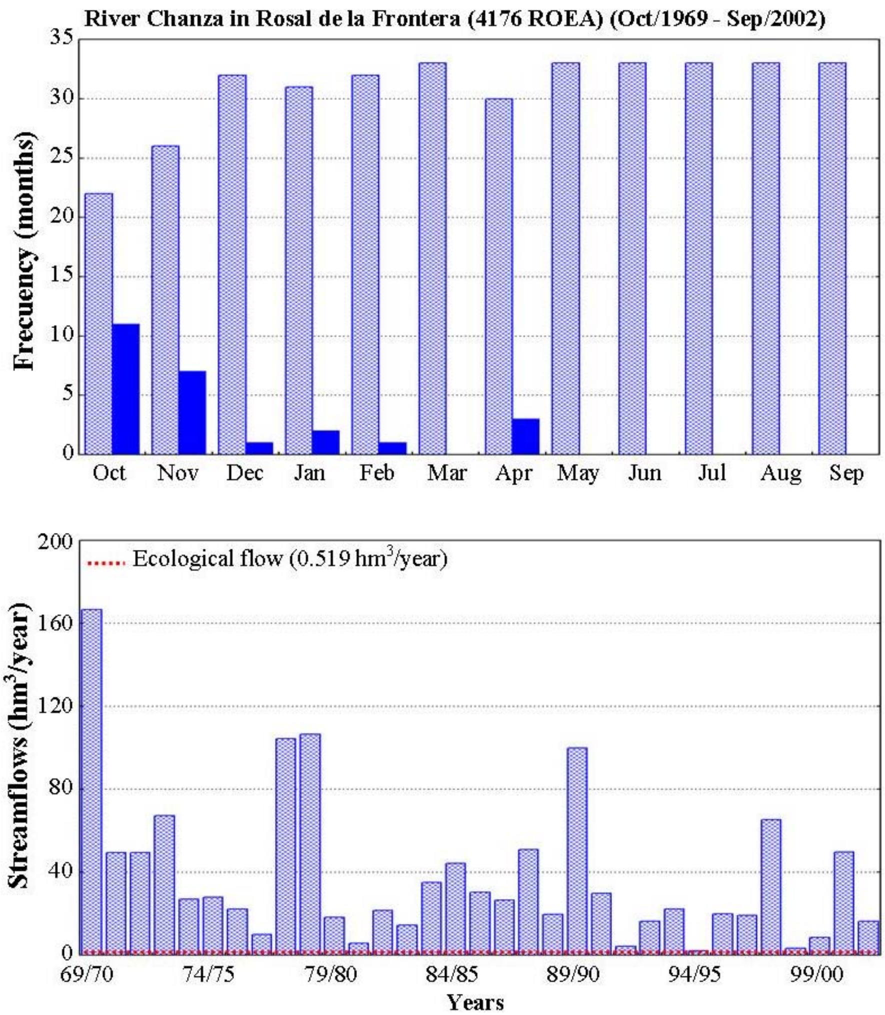


**Figure 4.** Frequency analysis of the months in which the streamflows were higher (light blue) or lower (dark blue) than the ecological flow requirements identified by the Hydrological Plan of the Guadiana Hydrographic Demarcation (Table 5) and time series of annual streamflows at the gauging station "River Chanza in Rosal de la Frontera" (4176 ROEA; Guadiana tributary) [17].

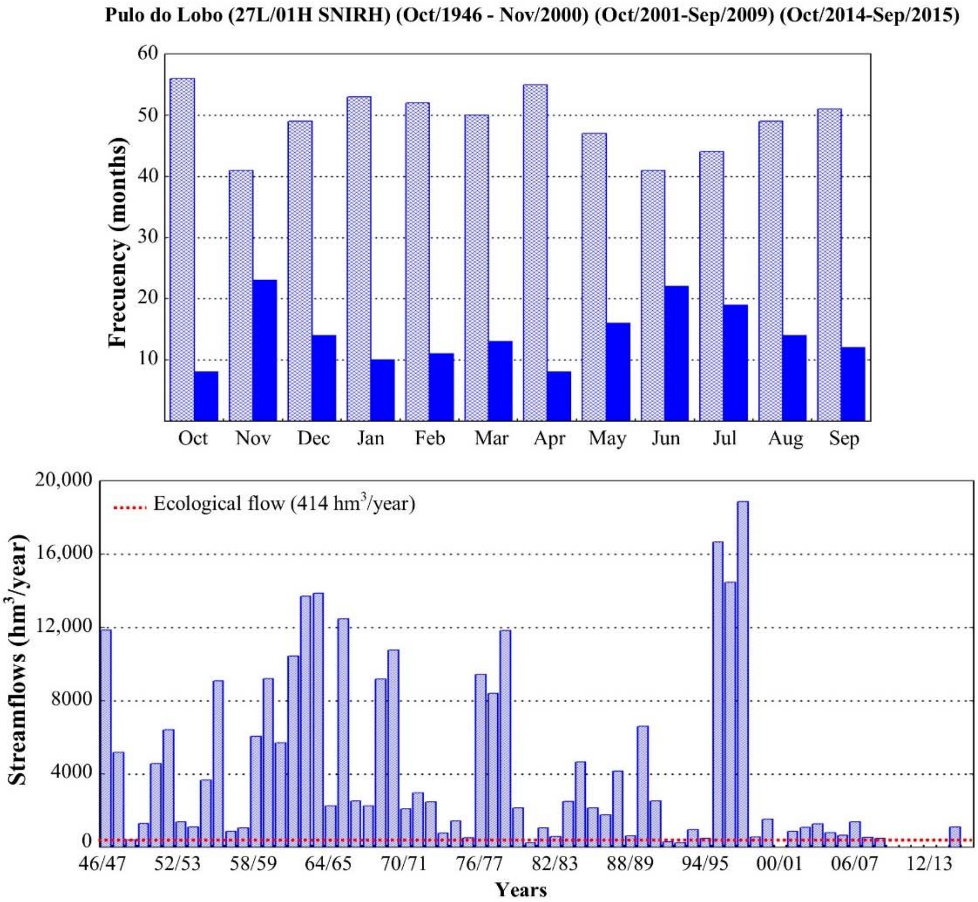


**Figure 5.** Frequency analysis of the months in which the streamflows were higher (light blue) or lower (dark blue) than the ecological flows requirements identified by the Hydrological Plan of the Guadiana Hydrographic Demarcation (Table 6) and time series of annual streamflows at the gauging station 'Pulo do Lobo' (27L/01H SNIRH; main course of the Lower Guadiana River; no available data for hydrological years 2000/01 and from 2009/10 to 2013/14) [17].

In general, the water bodies analyzed did not show significant differences in the non-compliance frequencies of current environmental requirements in time periods with streamflows under the natural and regulated regimes. In the case of the Guadiana tributaries characterized by a high seasonality of flows regime (intermittent courses with flow cessation periods from May to September; Table 5), it may be reasonable to state that the associated aquatic and terrestrial ecosystems must have mechanisms in order to adapt to the events of moderate and severe drought that frequently occur in the area under study.

In the case of the "Pulo do Lobo" station, on the main course of the Lower Guadiana River, the streamflow times series (Figure 5) made evident the influence in the last decade of the Alqueva-Pedrogão regulation system (upstream of the Lower Guadiana River Basin). However, there were no significant differences in the frequency of non-compliance of ecological flows before and after the implementation of this regulation system (Alqueva-Pedrogão regulation system from 2002–2006). Months with a flow regime lower than the current environmental requirements and whose occurrence coincided with moderate and severe droughts were observed. These months were before and after of the full operation of Alqueva-Pedrogão regulation system (2002–2006). This way, the correlation between the streamflows and SPI series with severe dry conditions was clearly significant ($R = 0.74$; $p < 0.05$). In this sense, one of the most severe droughts occurred in the study area during the period of 1946–1948 (Figure 3 and Table 6).

It would be advisable to carry out specific studies on selected water bodies of the basin, in protected areas and in associated areas, which allow for the seasonal and interannual location and characterization of aquatic ecosystems and their relationship with the existing flow regime. In this way, it would be possible in a more approximate way to determine temporary patterns of environmental requirements that allow the conservation of these biological communities [40–43].

Another aspect that would be important to study is the evaluation and quantification of the interrelationship between surface waters and groundwater in the natural habitats of the Natura 2000 Network for the Lower Guadiana hydrographic region [23]. This river–aquifer relationship should be included in future studies to analyze the way in which the water management measures influence the groundwater level and how this could accentuate the drought effects.

## 7. Conclusions

The occurrence of moderate and severe drought events that repeat cyclically were observed in the hydrographic region of the International Lower Guadiana River. These drought periods could cause difficulties in guaranteeing the water resources supply to users of this basin. Thus, in this work, we checked that the current requirements for ecological flows in strategic water bodies were not satisfied in some months of October to April of years characterized by severe drought events even in time periods in which there were no regulation elements (reservoirs) of surface waters. This supports the fact that local and endemic aquatic species are adapted to the drought events that often occur in the study area. However, during the droughts occurrence, it will be necessary to evaluate other factors, such as the variation of water physical-chemical conditions, the introduction of exotic invasive species, and the pollutant concentration, in order to achieve a good aquatic habitat quality.

Therefore, the environmental flow assessment in the hydrological modelling of the Lower Guadiana River Basin must consider novel approaches that incorporate the seasonal and interannual variation of aquatic ecosystems in order to know the relationships between the streamflow regime and the habitat attributes, especially in intermittent fluvial courses predominant in this basin and in the estuarine ecosystem included in the Natura 2000 Network. These approaches will encourage an adaptive flow regulation management, which integrates the environmental component, in order to allow a dynamic and balanced allocation of the different water uses.

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