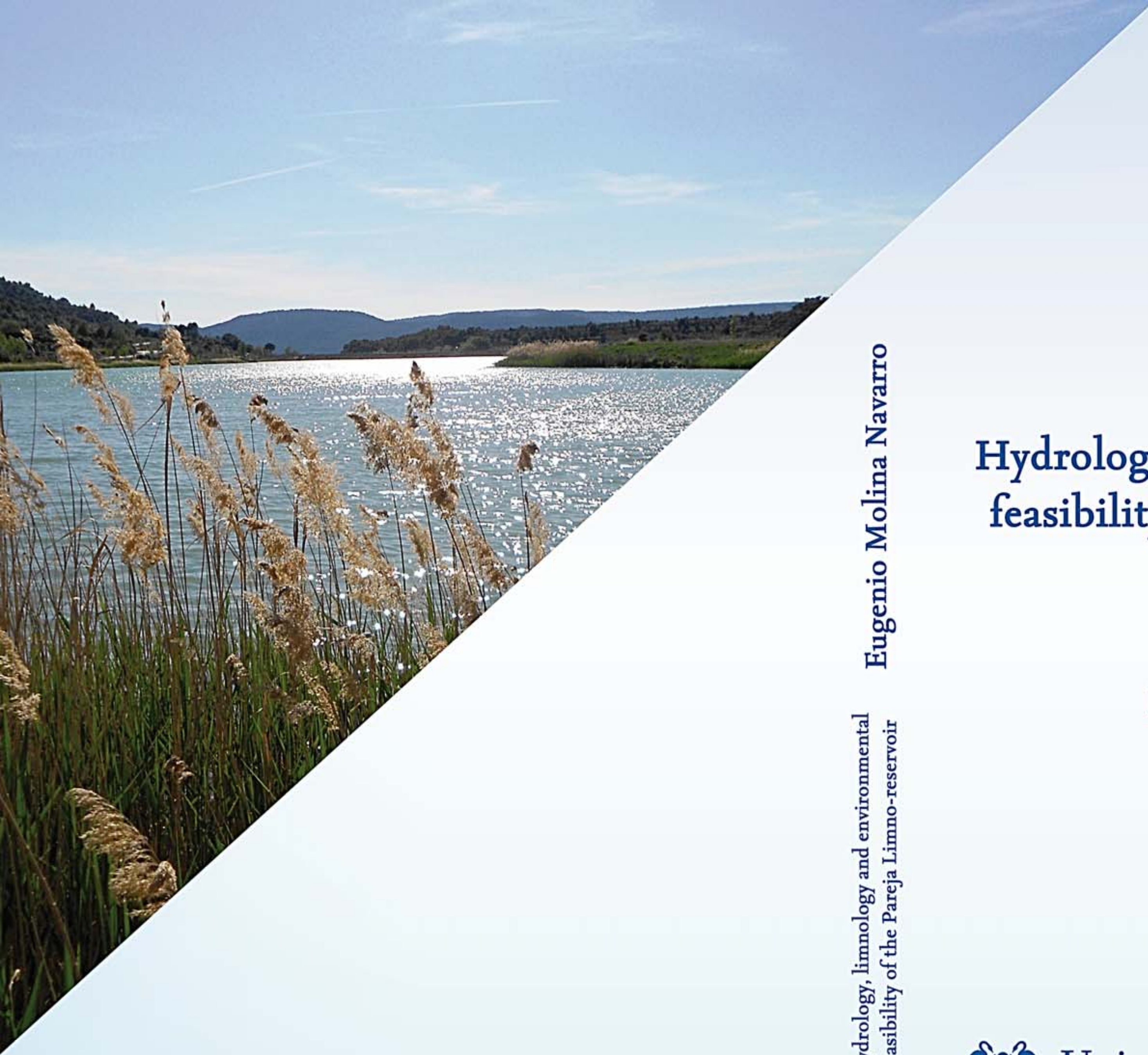

Eugenio Molina Navarro

Hydrology, limnology and environmental feasibility of the Pareja Limno-reservoir

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Hydrology, limnology and environmental feasibility of the Pareja Limno-reservoir

Doctoral Dissertation

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Universidad de Alcalá

DEPARTAMENTO DE GEOGRAFÍA Y GEOLOGÍA

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Silvia Martínez Pérez y Antonio Sastre Merlín, Profesores Titulares del Departamento de Geografía y Geología de la Universidad de Alcalá y directores de esta Tesis Doctoral,

Hacen constar:

Que el trabajo descrito en la presente memoria, titulado "*Hydrology, limnology and environmental feasibility of the Pareja Limno-reservoir*", ha sido realizado bajo su dirección por Eugenio Molina Navarro en la Unidad Docente de Geología del Departamento de Geografía y Geología de la Universidad de Alcalá, dentro del Programa de Doctorado "Ciencias Ambientales: Recursos Hídricos y Ecosistemas Acuáticos" (D279), reuniendo todos los requisitos necesarios para su aprobación como Tesis Doctoral.

Alcalá de Henares, 18 de abril de 2013.

Dra. Silvia Martínez Pérez

Dr. Antonio Sastre Merlín

Universidad de Alcalá
DEPARTAMENTO DE GEOGRAFÍA Y GEOLOGÍA
Unidad Docente de Geología

José Francisco Sancho Comins, director del Departamento de Geografía y Geología de la Universidad de Alcalá,

Hace constar:

Que el trabajo descrito en la presente memoria, titulado "*Hydrology, limnology and environmental feasibility of the Pareja Limno-reservoir*", ha sido realizado dentro del Programa de Doctorado "Ciencias Ambientales: Recursos Hídricos y Ecosistemas Acuáticos" (D279), reuniendo todos los requisitos necesarios para su aprobación como Tesis Doctoral.

Alcalá de Henares, 18 de abril de 2013.

Dr. José Francisco Sancho Comins

Universidad de Alcalá
DEPARTAMENTO DE GEOGRAFÍA Y GEOLOGÍA
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Hydrology, limnology and environmental feasibility of the Pareja Limno-reservoir

Memoria presentada para optar al grado de Doctor por la Universidad de Alcalá

Programa de doctorado:
"Ciencias Ambientales: Recursos Hídricos y Ecosistemas Acuáticos" (D279)

Eugenio Molina Navarro

Directores:
Silvia Martínez Pérez
Antonio Sastre Merlín

Alcalá de Henares, abril de 2013

A mi abuelo Mariano,
que siempre estuvo pendiente de este trabajo.

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Eugenio Molina Navarro

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ABSTRACT

Large reservoirs allow increasing the availability of the natural water resources, especially in areas with Mediterranean climate. There are nearly 1200 large dams in Spain, most of them were built in the second half of the 20th century. However, large reservoirs entail a variety of negative environmental and socioeconomic impacts. Many of them result from the wide water level fluctuations, which develop an arid band in the drawdown zone of the reservoir.

During the last decades, water managers have promoted some innovative actions in Spain to mitigate these impacts. One such attempt is to construct small dams in the riverine zone of large reservoirs, which allow the development of a small water body in locations that would be part of the drawdown zone. These water bodies preserve a stable water level since they become independent of the fluctuations occurring in the main reservoir. We have termed these bodies of water “limno-reservoirs” because they rather resemble a lake than a conventional reservoir. First Spanish limno-reservoirs were created in the late 1980s and the early 1990s, with environmental purposes.

The Pareja Limno-reservoir was the first with both environmental and recreational goals. It was built in 2006, next to the village of the same name, in the riverine zone of a sidearm of the Entrepeñas reservoir (province of Guadalajara, central Spain), being fed by the Ompólveda River. It is located in a strategic area, since the Entrepeñas Reservoir and the nearby Buendía Reservoir, built in 1956 and 1957 respectively, play a key role in the Spanish water management. Since the early 1980s, they are especially affected by the abovementioned negative impacts because of the dry climate and the water transfer to southeast Spain through the Tajo-Segura aqueduct.

The Pareja Limno-reservoir has a capacity of 0.94 hm^3 and an inundation area of 26 ha. It constitutes a corrective and/or compensatory action of those negative impacts. Because of the innovative nature of this water management initiative, we set up a research project to acquire knowledge about this water body.

The main aim of this doctoral dissertation is to characterize the Ompólveda River basin and the Pareja Limno-reservoir, assessing its environmental feasibility. The water availability and quality and the sedimentation risk of the limno-reservoir have been analysed to fulfil this objective.

The hydrology and hydrogeology of the Ompólveda River basin were studied in detail through the analysis of available climatic and runoff data, in addition to data obtained *in-situ* during the study. According to the results obtained, Ompólveda River runoff represents 10% of the basin precipitation, with an important contribution of baseflow (60-70%). It maintains a permanent water flow despite the absence of rainfall, which may favour the water renovation in the limno-reservoir. However, the permanence of a constant water level in the Pareja Limno-reservoir cannot be guaranteed during summer and autumn of the dry years, which questions its hydrological feasibility.

The Soil and Water Assessment Tool (SWAT) model was successfully applied to the basin. The simulation of climate change scenarios showed noticeable impact on river flow, which may decrease up to 50% by the end of the 21st century. This would lead to a significant decrease in the average water level of the limno-reservoir during the dry season, complicating the fulfilment of its purposes as a recreational and environmental infrastructure.

The hydrogeochemical behaviour of the Ompólveda River basin was also studied and modelled. The dissolution of calcite and gypsum seems to dominate the hydrochemical processes in the basin, in which water evolves from Ca^{2+}-HCO_3^- to Ca^{2+}-SO_4^- type, increasing consequently the electrical conductivity.

The physico-chemical, limnological and microbiological characteristics of the Pareja Limno-reservoir and the Ompólveda river outlet were studied, performing seasonal sampling surveys. Electrical conductivity, pH, temperature and dissolved oxygen profiles were carried out. Sample analyses included geochemistry, nutrients, chlorophyll *a*, phytoplankton, zooplankton, native and faecal indicator microorganisms. The limno-reservoir showed a warm monomictic stratification pattern. Water was slightly alkaline with high conductivity, especially during summer and autumn. Phytoplankton community was dominated by centric diatoms. Rotifers showed the highest richness and abundance among zooplankton groups. Oligotrophic microorganisms predominated in the microbiological community.

Water quality was analysed and appeared good enough to satisfy the Pareja Limno-reservoir purposes. Trophic indicators suggested an oligo-mesotrophic state and phytoplankton metrics denoted a *High* ecological status in accordance with the Water Framework Directive (although these metrics were not especially designed for this kind of water body). Total coliforms and enterococci concentrations fulfilled the requirements of the EU Bathing Water Directive. Nevertheless, water quality may deteriorate in winter, since high precipitation and runoff favour nutrients and microorganisms transport. During summer, lower water quality was also observed because of the proliferation of phytoplankton (favoured by summer climate and higher water retention time) and a high electrical conductivity.

Nutrient export in the basin was modelled with SWAT. The simulation of several land use change scenarios predicted that an expansion of agriculture would enhance the nutrient load. Additionally, climate change scenarios predicted a deterioration of trophic state conditions in the limno-reservoir in a warming future. These factors may threaten the favourable water quality in the Pareja Limno-reservoir, which may be especially problematic in summer, when the limno-reservoir mainly serves its recreational goals.

The soil loss in the Ompólveda River basin was studied using a simple and affordable methodology. Rill and interrill erosion and sediment deposition were monitored seasonally in representative locations and results obtained were extrapolated to the whole catchment. Sedimentation in the limno-reservoir was studied taking sediment cores.

Average gross hillslope erosion found in the Ompólveda River basin was around 6 T ha^{-1} $year^{-1}$ and some areas with high risk of erosion were detected. However, the annual sedimentation rate estimated for the Pareja Limno-reservoir was around 0.29%, which means that the sediment delivery ratio in the basin was around 3.9%. The low connectivity in the basin seemed to be the main reason for this low ratio. These values seem to guarantee the environmental feasibility of the Pareja Limno-reservoir from the sedimentation risk perspective.

The results obtained in this doctoral dissertation may have relevance in the water management sphere, since they provide knowledge and a multidisciplinary approach to assess this new kind of water bodies.

RESUMEN

Los grandes embalses permiten incrementar notablemente la disponibilidad de recursos hídricos, especialmente en áreas de clima mediterráneo. En España hay cerca de 1200 grandes presas, la mayoría de ellas construidas en la segunda mitad del s. XX. Sin embargo, los grandes embalses conllevan una serie de impactos -ambientales y socioeconómicos- negativos. Muchos de ellos resultan de las amplias fluctuaciones del nivel del agua que generan una banda árida en la franja perimetral de oscilación.

En España se han propuesto algunas actuaciones innovadoras en las últimas décadas para mitigar estos impactos. Entre ellas está la construcción de pequeños diques en sectores de cola de grandes embalses, que conllevan la aparición de una masa de agua en una zona que, de otro modo, estaría abocada a ser parte de la mencionada franja árida. Estos pequeños embalses, individualizados de la dinámica hidrológica y de explotación del embalse principal, están diseñados para mantener una lámina de agua a nivel constante. Por ello, para denominarlos, hemos propuesto el término “limnoembalse”, puesto que se asemejan más a un lago que a un embalse convencional. Los primeros limnoembalses aparecieron en España a finales de los años 80 y principios de los 90, con fines de salvaguarda y mejora ambiental.

El Limnoembalse de Pareja, el primero diseñado con una doble finalidad ambiental y recreativa, fue construido en 2006 junto al pueblo homónimo en la zona de cola de un brazo lateral del embalse de Entrepeñas (provincia de Guadalajara, España central), siendo alimentado por el río Ompólveda. Está localizado en un área de importancia estratégica, puesto que el embalse de Entrepeñas y su vecino embalse de Buendía, construidos en 1956 y 1957 respectivamente, configuran un hiperembalse clave para la gestión del agua en España. Los impactos negativos mencionados afectan a estos embalses, especialmente desde principios de los años 80 debido al descenso generalizado de las aportaciones y al comienzo del trasvase de agua hacia el sureste español a través del acueducto Tajo-Segura.

El Limnoembalse de Pareja, con una capacidad de 0,94 hm^3 y una superficie de 26 ha, constituye una actuación de las llamadas correctoras y/o compensatorias de tales impactos. Por su carácter novedoso, se consideró oportuno afrontar un trabajo de investigación al objeto de adquirir conocimiento acerca del comportamiento de esta masa de agua.

El objetivo principal de esta tesis doctoral es caracterizar la cuenca del río Ompólveda y el Limnoembalse de Pareja, evaluando su viabilidad ambiental. Para ello, se ha analizado la disponibilidad y calidad del agua y el riesgo de aterramiento del limnoembalse.

En aras de lo anterior, en primer lugar, se ha realizado un estudio hidrológico e hidrogeológico de detalle a partir del análisis de los datos meteorológicos y de aforo disponibles y de los obtenidos *in-situ* durante este estudio. De acuerdo con los resultados obtenidos, la aportación del río Ompólveda supone un 10% de la precipitación en la cuenca, con un importante porcentaje de flujo de base (60-70%), que mantiene un caudal permanente en el río a pesar de la

ausencia de lluvias durante el estiaje, lo que *a priori* favorecería la renovación continua de la masa de agua en el limnoembalse. Sin embargo, el mantenimiento de un nivel de agua constante en el mismo no queda garantizado durante el estiaje de los años secos, lo que cuestiona su viabilidad hidrológica.

Se ha aplicado el modelo SWAT (Soil and Water Assessment Tool) en la cuenca con éxito. La simulación de escenarios de cambio climático con este modelo mostró un impacto significativo en el caudal del Ompólveda, que podría disminuir hasta en un 50% a finales del siglo XXI. Ello supondría un descenso notable del nivel del limnoembalse durante el estiaje, dificultando el cumplimiento de sus funciones como infraestructura ambiental y recreativa.

Se ha estudiado y modelizado el comportamiento hidrogeoquímico de la cuenca del Ompólveda. La disolución de calcita y yeso parece dominar los procesos hidroquímicos, en la que el agua evoluciona de bicarbonatada cálcica a sulfatada cálcica, aumentando, consecuentemente, su conductividad eléctrica.

Por otro lado, se han estudiado las características físico-químicas, limnológicas y microbiológicas del Limnoembalse de Pareja y del sector terminal del río Ompólveda antes de su ingreso en el limnoembalse. Se han realizado perfiles de conductividad eléctrica, pH, temperatura y oxígeno disuelto *in-situ* y se han recogido muestras con periodicidad trimestral para la realización de análisis geoquímicos, de nutrientes, clorofila *a*, fitoplancton, zooplancton, microorganismos nativos e indicadores de contaminación fecal. El limnoembalse sigue una dinámica de lago monomíctico templado. El agua es ligeramente alcalina con alta conductividad, especialmente en verano y otoño. La comunidad fitoplanctónica está dominada por diatomeas centrales. Los rotíferos son el grupo de zooplancton de mayor riqueza y abundancia. Los microorganismos oligotrofos predominan en la comunidad microbiológica.

A la vista de los resultados, la calidad del agua resulta adecuada para los usos previstos del limnoembalse. Los indicadores tróficos sugieren un estado oligo-mesotrófico y los índices de fitoplancton aplicados un estado ecológico *Muy Bueno* en consonancia con la Directiva Marco del Agua (a pesar de que los índices utilizados no hayan sido específicamente diseñados para este tipo de masas de agua). Los niveles de coliformes y enterococos se encuentran bajo los estándares de la Directiva Europea de Aguas de Baño. No obstante, la calidad del agua puede empeorar en invierno debido a que elevadas precipitaciones y caudales favorecen el transporte de nutrientes y microorganismos. También se ha observado una calidad inferior en verano a causa de la proliferación de algas (favorecida por las condiciones climáticas y el mayor tiempo de retención) y la elevada conductividad.

Se han modelado el transporte de nutrientes en la cuenca con el modelo SWAT. La simulación de diversos escenarios de cambio de usos del suelo ha permitido descubrir que un aumento de la superficie agrícola conllevaría una mayor exportación de nutrientes en la cuenca. Además, los escenarios de cambio climático predicen un deterioro del estado trófico del limnoembalse. Estos factores pueden amenazar la adecuada calidad del agua en el Limnoembalse de Pareja, especialmente en verano, cuando sobre el mismo recae, principalmente, la satisfacción de sus funciones recreativas.

Finalmente, se ha estudiado la pérdida de suelo en la cuenca del río Ompólveda mediante una metodología sencilla y económica. Se han evaluado estacionalmente la erosión laminar y en regueros y la eventual sedimentación en lugares representativos, extrapolándose los resultados obtenidos al conjunto de la cuenca. Además, se ha estudiado el aterramiento del embalse mediante la toma de testigos de los sedimentos depositados en el fondo del limnoembalse.

La erosión bruta media en la cuenca se estima en unas 6 T ha^{-1} $año^{-1}$, hallando zonas con alto riesgo de erosión (por encima de 45 T ha^{-1} $año^{-1}$). No obstante, la tasa anual de aterramiento en el Limnoembalse de Pareja es de aproximadamente un 0,29%, lo que supone que sólo un 3,9% de los sedimentos movilizados en la cuenca alcanzan el limnoembalse. La poca conectividad en la cuenca se configura como el principal motivo de este bajo porcentaje, lo que garantizaría la viabilidad ambiental del Limnoembalse de Pareja desde el punto de vista del riesgo de aterramiento.

Los resultados obtenidos en esta tesis doctoral podrían tener relevancia en el ámbito de la gestión del agua, puesto que aportan conocimiento y metodologías para la evaluación multidisciplinar de estas nuevas masas de agua.

1. General introduction

1. GENERAL INTRODUCTION

1.1. Mediterranean climate and large reservoirs: issues and mitigation

In the Mediterranean region, the uneven distribution of rainfall -characterized by summer drought- and the existence of numerous dry years have always represented a big challenge for water management (MMA, 2000). Drought is a natural, cyclic phenomenon and requires planning and preventive actions (MMA, 2007). The construction of reservoirs is one of those actions usually undertaken by water managers to face this problem. In Spain, 1515 dams are listed in the National Inventory of Dams and Reservoirs. Nearly 1200 are large dams (i.e. higher than 15 m or higher than 5 m and volume over 3 hm^3) and most of them were built in the second half of the 20th century. Nowadays, Spain is the fifth country, after China, USA, India and Japan, with the highest number of large dams (Aramburu Godínez and Balairón Pérez, 2008; MAGRAMA, 2013a). Without hydraulic infrastructure, only 8% of natural water resources could be used in Spain. The hydraulic development in Spain, led by the construction of large dams, has allowed the use of 40% of natural water resources, the same percentage that would be achieved in wet Europe in a natural regime (Garrote de Marcos, 2012).

However, all that glitters is not gold. The construction and use of large reservoirs in areas with Mediterranean climate causes a number of negative effects. The wide water level fluctuations due to water exploitation and climatic influences are a major determinant of freshwater ecosystem functioning and services (EEA, 2012) and, consequently, one of the main causes of these adverse effects in reservoirs. They include the development of an arid band in the drawdown zone of the reservoir, which is an important landscape impact and leads to the loss of bank vegetation and nesting places for waterfowl, among other effects (MMA and CNEGP, 1996; MMAMRM, 2011). Socioeconomic impacts are also relevant because the construction of large reservoirs raises tourist and recreational expectations that may be unmet because of the water level variation (Molina-Navarro et al., 2010). Since regional climate model simulations have given a collective picture of substantial drying and warming in the Mediterranean region (IPCC, 2007; Somot et al., 2008; van Vliet et al., 2013), the undesirable impacts of Mediterranean reservoirs may be aggravated in a future climate change context.

Water managers have promoted some actions to mitigate these impacts during the last decades in Spain. One such attempt is to construct small dams in the riverine zone of large reservoirs (MMA and CNEGP, 1996), especially in those with strategic interests. These dams are known as “riverine dams”, because of their location, or “flood dams”, since they must be ready to restrain water both upstream and downstream. Riverine dams allow the development of small water bodies in locations that would be part of the drawdown zone of the respective large reservoirs. These water bodies become independent of the management of the main reservoir and are aimed at preserving a constant water level. Thus, the riverine dam must be constructed in a riverine section with enough water supplies. They rather resemble a lake than an ordinary reservoir due to their stable level and the absence of human operations associated with the dam. Because of these specific characteristics we have termed them “limno-reservoirs” (Molina-Navarro et al., 2010).

In Spain, the first initiatives of this kind were proposed in the late 1980s and the early 1990s. Their primary goal was the creation of a suitable habitat for birds (Rodríguez Cabellos, 1995; MMA and CNEGP, 1996). First limno-reservoirs were built in the late 80s and the early 90s in the Tagus River and the Guadiana River basins. Later, the National Hydrological Plan (BOE num. 161, 2001) included new limno-reservoirs again in the Tagus River basin, but also in the Ebro River and the Júcar River basins. There is a rising tendency to build them and nowadays there are 12 limno-reservoirs already operating and another 13 in design or under construction (Fig. 1.1).

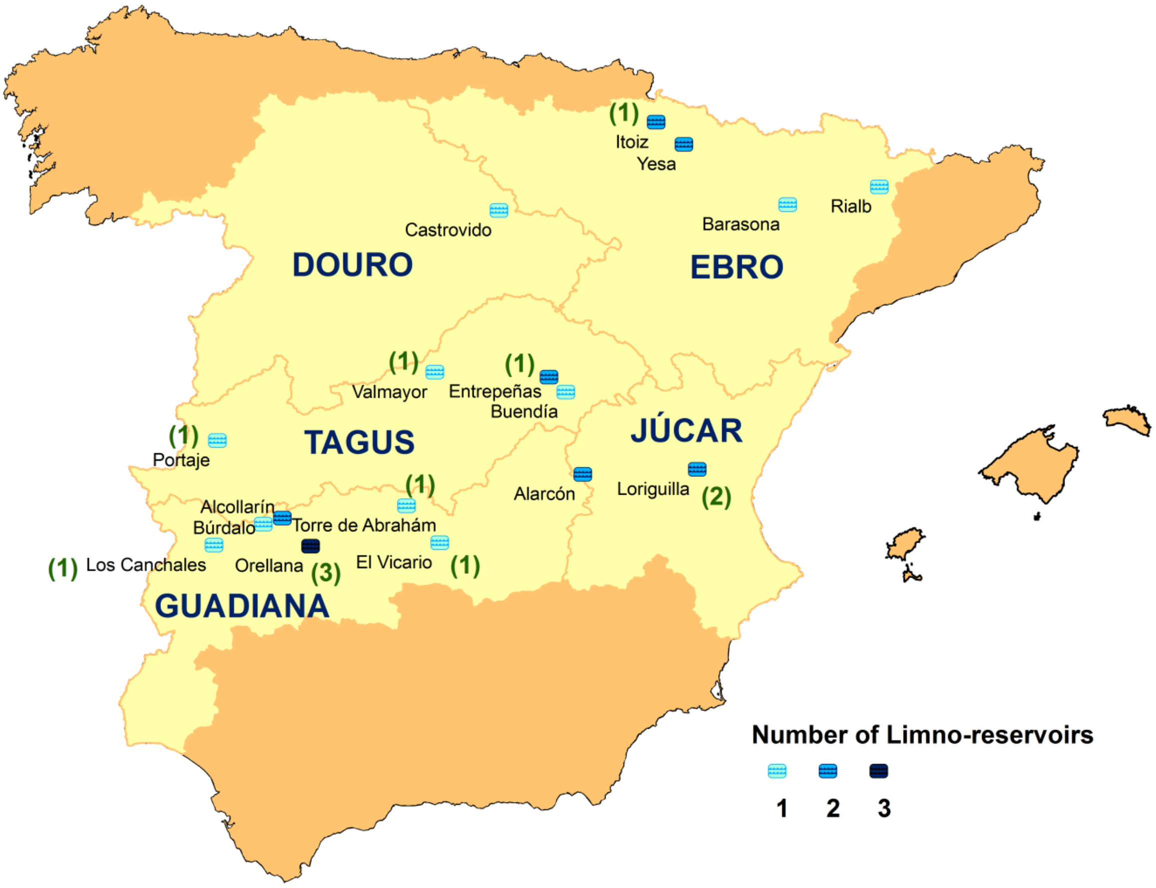

Fig. 1.1. Large Spanish reservoirs with one or various limno-reservoirs. The green digit indicates the number of operative limno-reservoirs. Other limno-reservoirs are in design or under construction.

1.2. The Entrepeñas and Buendía reservoirs matter

The Entrepeñas and Buendía reservoirs are located in the upper Tagus River basin (Guadalajara and Cuenca provinces, central Spain, Fig. 1.2). They have a capacity of 835 hm^3 and 1639 hm^3 respectively, and their potential inundation areas are 3213 ha and 8195 ha. These figures position them among the largest reservoirs in Spain. Their construction finished in 1956 (Entrepeñas) and in 1957 (Buendía) with the primary aim of controlling the flow volumes from upper Tagus River basin (CHT, 2013). Moreover, they created a unique landscape that raised tourist and recreational expectations. The development of residential areas, campsites or boating business, especially during the 1970s, outshined the negative effects of the construction of these large reservoirs (Molina-Navarro et al., 2010).

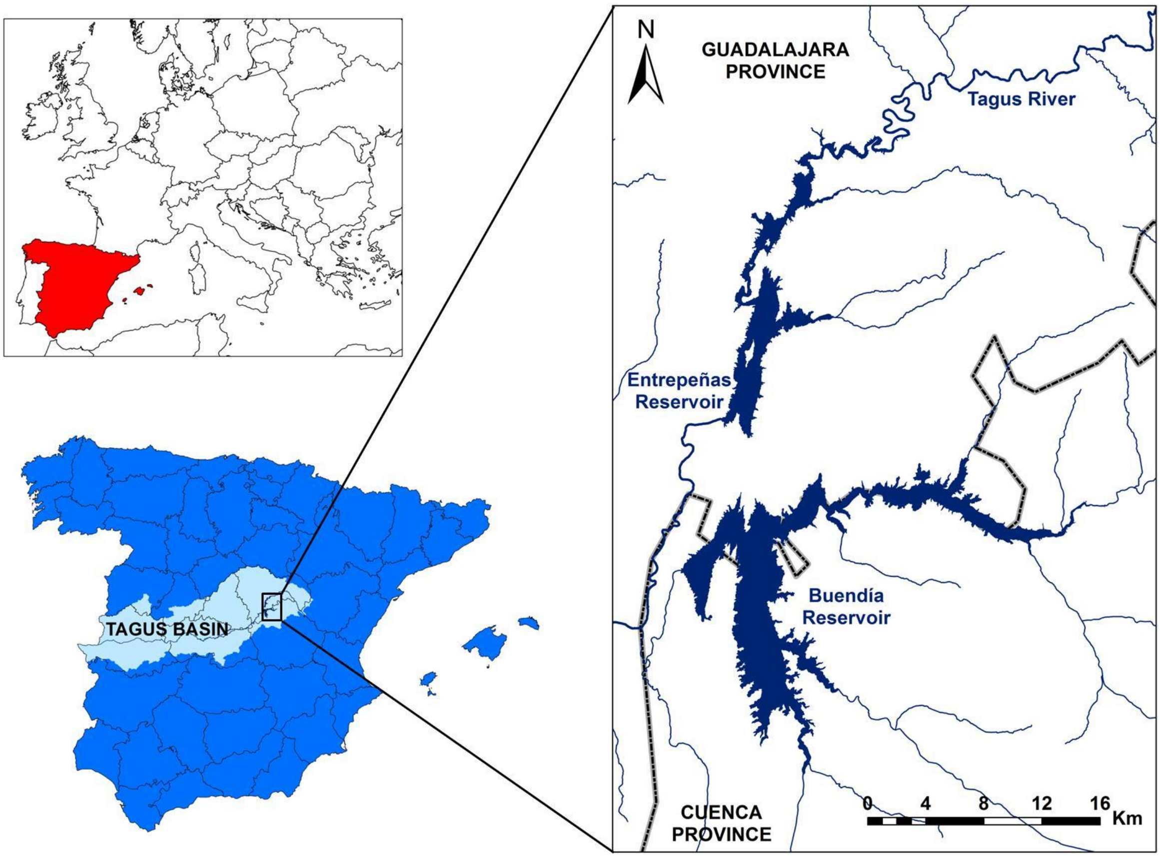

Fig. 1.2. Location of the Entrepeñas and Buendía reservoirs.

However, the climate became drier from the early 1980s and the water inputs in the Entrepeñas and Buendía reservoirs during the last decades have been lower than those considered in their design (CHT, 2008). The average annual water input to both reservoirs between 1980 and 2012 (766 hm^3) was approximately the half of the average annual input between 1959 and 1980 (1518 hm^3) (Fig. 1.3).

The situation was further aggravated by the start of the transfer of large volumes of water to southeast Spain. This transfer is carried out by the Tajo-Segura aqueduct, an emblematic hydraulic structure with 286 Km length. In 1980 the water transfer in the aqueduct became regulated by law (Hernández Soria, 2003). The draft of this initiative (1967) analysed data from 1913-1960 and considered an annual average water input in the Entrepeñas and Buendía reservoirs of 1360 hm^3 (CHT, 2008). Nowadays, the amount of water transferred to southeast Spain is a far from negligible output in the upper Tagus River basin reservoirs. Since 1980 the annual average water volume transferred has been 338 hm^3. Figure 1.4 shows the water volumes transferred per year.

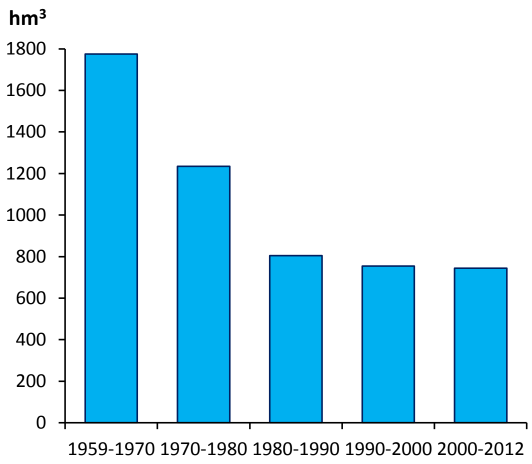

Fig 1.3. Average annual water inputs in the Entrepeñas and Buendía reservoirs (modified from CHS, 2013a).

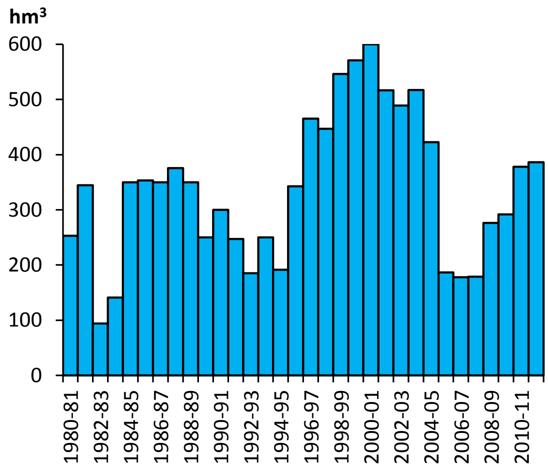

Fig 1.4. Annual water transfer to southeast Spain from the Entrepeñas and Buendía reservoirs (data from CHS, 2013b).

These circumstances have led the Entrepeñas-Buendía reservoir system to be at minimal water levels during the last decades (Fig. 1.5.), enhancing the abovementioned negative environmental impacts and resulting in the failure of the tourist and recreational expectations in the area. The inhabitants of the region began to demand corrective and/or compensatory actions for these environmental and socioeconomic effects in the 1990s. In 2003, their protests led to the construction of a riverine dam next to the village of Pareja, in a sidearm of the Entrepeñas reservoir. The construction finished in 2006, giving rise to the Pareja Limno-reservoir, a water body aimed at preserving a constant water level.

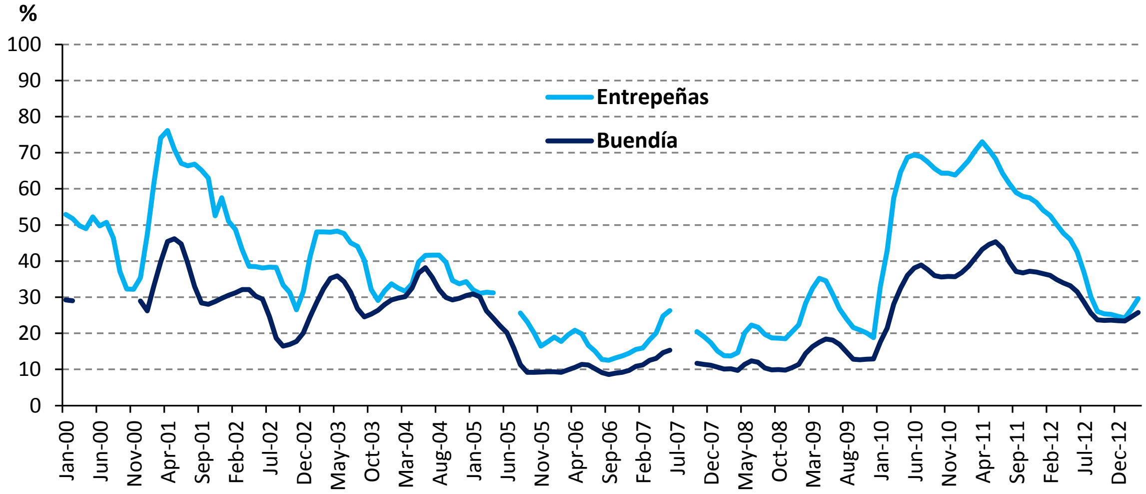

Fig. 1.5. Evolution of the water volumes in the Entrepeñas and Buendía reservoirs (% of maximum capacity) during the last decade (MAGRAMA, 2013b).

1.3. The Pareja Limno-reservoir

The construction of the Pareja Limno-reservoir dam had a cost of 6 million euros and was finished in 2006. It generated a small water body with generally constant water level and located in an area that would be part of arid band developed in the drawdown zone of the Entrepeñas Reservoir (Fig. 1.6). The limno-reservoir is fed by the Ompólveda River.

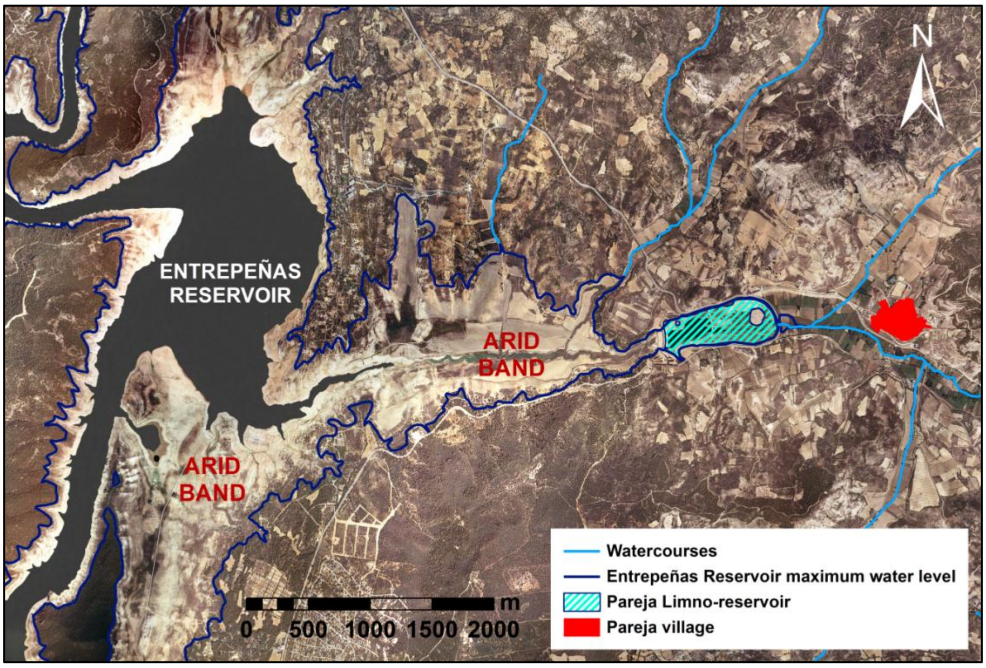

Fig. 1.6. Location of the Pareja Limno-reservoir. Volume of water stored in the Entrepeñas Reservoir in 2006 and its maximum capacity (modified from Molina-Navarro et al., 2010).

The Pareja Limno-reservoir (Fig. 1.7) was the first Spanish limno-reservoir to serve environmental and recreational goals. It has a number of recreational and environmental facilities, described in detail in the next chapter (section 2.1).

Fig. 1.7: Pareja Limno-reservoir view from the riverine dam.

1.4. Thesis objectives and significance

The interest and convenience of limno-reservoirs are unquestionable. Nevertheless, the Pareja Limno-reservoir was not a cheap infrastructure and some uncertainties about its environmental feasibility arose after its construction:

- Is the availability of water in the basin sufficient to preserve a constant water level in the limno-reservoir throughout the whole year? The Mediterranean region is subjected to water scarcity. It is characterized by the uneven distribution of rainfall, which leads to summer drought. Besides, the relatively high frequency of dry years aggravates this situation (Font, 1983; MMA, 2000, 2007). Then, water availability for the Pareja Limno-reservoir may be critical in summer, when it mostly fulfils its recreational functions. The limno-reservoir may be particularly vulnerable in a climate change future (IPCC, 2007). Thus, it seems appropriate to evaluate the water availability in the Pareja Limno-reservoir and the Ompólveda River basin, at the present time and with a future perspective.

- Will be the water quality good enough to meet the environmental and recreational use of the limno-reservoir? The characteristics of its drainage basin (natural vegetation, low population) and the wastewater diversion may favour a good water quality in the Pareja Limno-reservoir. Nevertheless, its water quality must be assessed, especially considering the latest European regulations, such as the Bathing Water Directive (OJEU num. 64, 2006) and the Water Framework Directive (OJEU num. 327, 2000), which requires EU Member States to achieve a good ecological status in all bodies of surface water by 2015.

- Is there any sedimentation risk in the limno-reservoir? In many reservoirs, annual storage capacity loss can go up to 4% or 5%, losing the majority of their capacity after only 25-30 years (Zarris et al. 2011). Spain is one of the countries most severely affected by soil erosion (Solé Benet, 2006) and signs of high soil loss have been observed in the Pareja Limno-reservoir catchment. Thus, the study of soil erosion in the catchment and sediment yield into the limno-reservoir seem very important.

The start of this thesis work coincided with the end of the process of filling the Pareja Limno-reservoir (spring 2008) and its main objectives are:

a) To characterize the Pareja Limno-reservoir and its drainage basin in order to discover the factors that may have relevance in the limno-reservoir environmental quality and feasibility.

b) To respond to the uncertainties listed above, assessing the environmental feasibility of the Pareja Limno-reservoir from a multidisciplinary and holistic approach.

Regarding the characteristics of the study area and the environmental feasibility uncertainties found, these main goals can be divided into six specific objectives:

a1) The study of the hydrology of the Ompólveda River basin, describing and quantifying its water availability.

a2) The physico-chemical, limnological and microbiological characterization of the Pareja Limno-reservoir.

a3) The study of soil erosion in the Ompólveda River basin and its sediment yield.

b1) The assessment of the hydrological feasibility of the Pareja Limno-reservoir by verifying the preservation of a constant water level throughout the year, even in the most unfavourable situations.

b2) The analysis of the water quality in the Pareja Limno-reservoir, checking its suitability to support the environmental and recreational uses of the limno-reservoir.

b3) The assessment of the sedimentation risk of the Pareja Limno-reservoir.

The results obtained in this thesis may provide water managers with holistic assessment tools and may give some guidelines on how to assess the environmental quality and feasibility of a limno-reservoir. Considering the novelty of limno-reservoirs, the absence of data about them in scientific literature and the developing trend of building them, these tools and guidelines may be useful for the planning, design and construction of new similar infrastructures.

1.5. Thesis dissertation structure

This thesis manuscript is organized into eight chapters. A description of the study area (Chapter 2) follows this introductory one. Then, four research chapters (Chapters 3-6) are presented. They contain eight scientific manuscripts that try to fulfil with the thesis dissertation objectives. Each manuscript has its usual sections (abstract, introduction, material and methods, results, discussion and conclusions). Additionally, an abstract in Spanish has been included. They reproduce the content of research papers that have been definitively accepted (4 manuscripts), are under review (3 manuscripts) or have just been submitted (1 manuscript) to peer reviewed journals. The original structure has been preserved so there might be some inevitable redundancy describing the study area and some methodologies. Moreover, different reference styles and word inconsistency (e.g. modeling vs. modelling, acknowledgments vs. acknowledgements, hydrologic vs. hydrological, behavior vs. behaviour) may be found due to different journal requirements. Figure and table numbers have been prefixed with the sub-chapter number to avoid redundancy throughout the thesis manuscript. Chapter 7 compiles the final remarks about the environmental feasibility of the Pareja Limno-reservoir. Finally, Chapter 8 presents the general conclusions of the thesis, both in English and in Spanish. Each chapter except the general conclusions has a references section. A brief description of the papers included in the research chapters is presented.

Chapter 3: Environmental aspects and hydrological characteristics

This chapter includes two scientific papers. The first one was published in *Boletín Geológico y Minero*, vol. 121(1), pages 69-80. Although it was originally published in Spanish, it has been translated into English to ensure a language consistency in the doctoral dissertation. The paper introduces the “Limno-reservoir” concept and its environmental issues. It makes a first approach to the hydrological features of the Ompólveda River basin and the hydrological feasibility of the Pareja Limno-reservoir. It also presents the methodology followed to study the soil loss at a catchment scale. Consequently, it deals with the specific objectives **a1**, **b1** and **a3**. An error in the classification of dry, normal and wet year types was found in the original manuscript. It was not significant for the global meaning of the paper, but it was amended and so it is pointed out throughout the sub-chapter.

The second paper has been recently submitted to *Hydrogeology Journal*. It studies the hydrogeological behaviour of the Ompólveda River basin, estimating groundwater flow and analysing data from springs monitoring. It also deals with the hydrogeochemical characteristics and processes in the basin, checking also their influence in the Pareja Limno-reservoir water. Thus, the paper is mainly related to the specific objectives **a1, a2** and **b2**.

Chapter 4: Water quality in the Pareja Limno-reservoir.

Chapter 4 contains three research manuscripts. The first one was published in 2012 in *Limnetica*, vol. 31(1), pages 95-106. The paper aims to describe the physico-chemical and biological characteristics of the Pareja Limno-reservoir by studying the stratification patterns, the main limnological parameters, the trophic state and the basic phytoplankton dynamics of the water body. Particular emphasis is placed on the study of the zooplankton community investigating its richness, the relative abundance of species and their seasonality. It covers the specific objectives **a2** and **b2**.

The second manuscript is currently under review in *Lake and Reservoir Management*. It analyses the phytoplankton composition in the Pareja Limno-reservoir using the functional group approach (Reynolds et al., 2002), assesses its ecological status in accordance with the European Water Framework Directive (OJEU num. 327., 2000) applying phytoplankton biomass and composition metrics and verifies the suitability of the phytoplankton composition metrics for assessing the ecological status of Mediterranean limno-reservoirs in accordance with the WFD requirements, checking the response of the indices to a trophic gradient. As with the first one, it deals with the specific objectives **a2** and **b2**.

The third manuscript was published in 2011 in the *Journal of Environmental Management*, vol. 92, pages 773-779. The paper describes the microbiology of the Pareja Limno-reservoir. The relationship between nutrients and microorganisms is also studied. Different groups of microorganisms and nutrients (nitrogen compounds and total phosphorus) were analysed over a period of 18 months. The evolution of the microbiological water quality was established by comparing the results obtained with European Union Water Directives requirements (OJEU num. 327, 2000; OJEU num. 64, 2006). However, to give uniformity to Chapter 4, an annex expands the published content up to three years of data. The content mainly deals with the specific objectives **a2** and **b2**.

Chapter 5: Catchment erosion and limno-reservoir sedimentation risk

This chapter contains one scientific paper, currently under review in *Water Resources Management.* The main aim of the chapter is to perform a sedimentation risk assessment of the Pareja Limno-reservoir at a catchment scale. This objective is fulfilled through the estimation of soil erosion and deposition rates in the Ompólveda River basin with a simple and affordable in-situ methodology, locating the areas with the most significant erosion problems. Then, the relationship between catchment erosion and the sediment yield in the Pareja Limno-reservoir is studied to assess the sediment delivery to the limno-reservoir. Consequently, it covers the specific objectives **a3** and **b3**.

Chapter 6: Catchment modelling and scenarios simulation.

This chapter includes two research manuscripts. The first one was definitively accepted in 2010 in the *Journal of Environmental Quality*, doi:10.2134/jeq2011.0360. With the construction of the Pareja Limno-reservoir, the flow gauging station located in the Ompólveda River became inoperative. A hydrological model could be used to estimate the water yield in the following years and in the future. In this manuscript, the Soil and Water Assessment Tool model (SWAT, Arnold et al., 1998; Winchell et al., 2009) is developed for the Ompólveda River basin, checking its suitability to model small Mediterranean basins. Then, its usefulness as a tool to assess the hydrological feasibility of the Pareja Limno-reservoir is evaluated. Finally, the hydrological feasibility of the Pareja Limno-reservoir is assessed. The manuscript is related to the specific objectives **a1** and **b1**).

The last research paper analyses the potential effects on water discharge and availability, nutrient loads and water quality in the Pareja Limno-reservoir of both climate and land use management changes, checking also for their synergistic effects. It has been recently submitted to *Journal of Hydrology*. The SWAT model developed in the previous paper is expanded to fulfil these purposes. Water balances were performed to estimate the water level fluctuations under climate change in the Pareja Limno-reservoir. Besides, the approach by Nielsen et al. (2013) to couple the SWAT model with the simple and empirical model by Vollenweider and Kerekes (OECD, 1982) is used to estimate limno-reservoir TP concentrations, which are used as a proxy for the trophic status. Consequently, the paper is related to the specific objectives **b1** and **b2**.

1.6. Funds

This Thesis has been supported by the agreement between the University of Alcalá and the Ibercaja Social Action (2007 funds) and by the Castilla-La Mancha Government (project num. PAI 08-0226-1758). Eugenio Molina Navarro received additional support from the University of Alcalá FPI predoctoral fellowships programme.

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2. STUDY AREA

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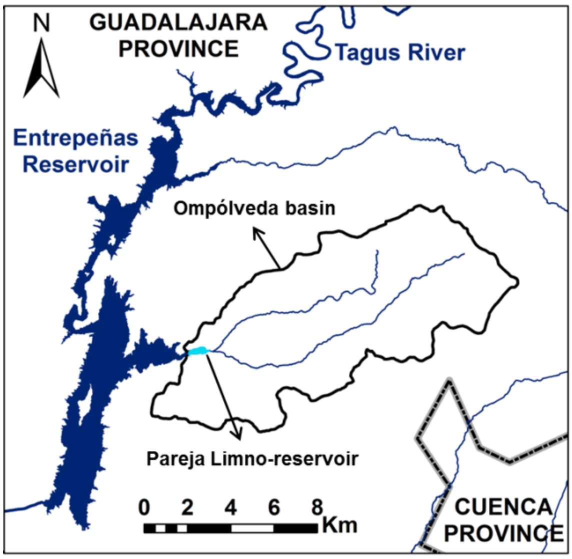

The Pareja Limno-reservoir is located in the riverine zone of a sidearm of the Entrepeñas Reservoir (Fig. 1.2), where the Ompólveda River discharges. The study area not only includes the Pareja Limno-reservoir, but also the whole Ompólveda River basin (Fig. 2.1). The main characteristics of the limno-reservoir and the basin are described in this chapter.

Fig. 2.1. Location of the Pareja Limno-reservoir and the Ompólveda River basin.

2.1. The Pareja Limno-reservoir

The Pareja Limno-reservoir is located next to the village of the same name (Fig. 2.2). It has a capacity of 0.94 hm^3 and a potential inundation area of 26 ha. It reaches a maximum depth of 12.5 m near the dam, becoming progressively shallower towards the inflow section. The average depth is around 4 m (Fig. 2.3). The average retention time of the limno-reservoir is around 70 days, although this may vary considerably as the discharge of the Ompólveda River shows high inter-annual variability.

Fig. 2.2. Pareja village and limno-reservoir. Entrepeñas Reservoir in the background.

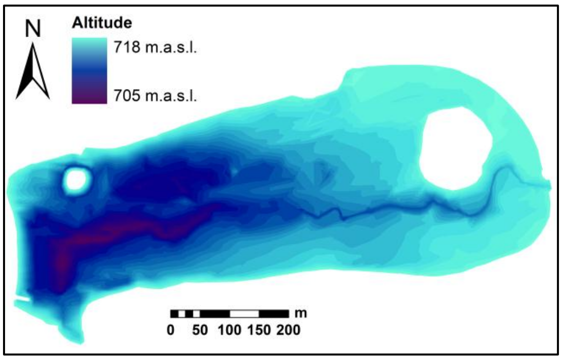

Fig. 2.3. Bathymetric survey carried out in autumn 2010 in the Pareja Limno-reservoir.

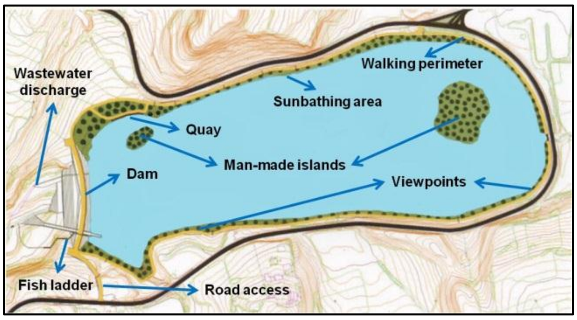

Fig. 2.4. Sketch of recreational and environmental facilities in the Pareja Limno-reservoir (modified from MMA, 2002).

The limno-reservoir tries to provide the inhabitants of Pareja and the surrounding areas with an infrastructure that favours a hydrologic-environmental recovery in addition to an economical promotion of the area. It is open for swimming or for walking, and it has a quay for motorless craft, a sunbathing area and a couple of viewpoints. These features aim to promote the economic development of the area in terms of nature tourism. From an environmental perspective, it has two man-made islands that act as bird refuges and a fish ladder. In addition, the wastewater of Pareja village was diverted downstream past the dam after a primary treatment in order to preserve the limno-reservoir water quality (Molina-Navarro et al., 2010, 2011) (Fig. 2.4)

2.2. The Ompólveda River basin

The Ompólveda River basin features, described below, make it representative of small basins in central Spain.

2.2.1. General characteristics

The Ompólveda River basin has an approximate area of 88 km2. The altitude ranges between 718 and 1137 m.a.s.l. in a rather small basin, which means that the existing valleys have steep hillsides. The Ompólveda River, a tributary of the Tagus River, flows to the Pareja Limno-reservoir from a northeast-southwest direction. Its main tributary is the Valdetrigo stream, merging from the northeast. Figure 2.5 shows the digital elevation model of the basin, its drainage network, and the location of the Pareja Limno-reservoir (40°33’17’’ N, 2°40’17’’ W, 718 m.a.s.l.).

2.2.2. Climate and hydrology

Climate in the basin has Continental Mediterranean characteristics. Annual average temperature is around 13.0 °C, with cold winters (daily average around 5.0ºC) and warm summers (daily average around 23.0ºC). Average annual precipitation recorded at the 3066-Escamilla station (in the upper catchment) is around 600 mm, showing high intra- and inter-annual variability (figure 2.6). Periods with maximum amount of rainfall do not follow a precise pattern and can be found in winter, spring or even in both seasons (Molina-Navarro et al. 2010). Storms are not as frequent and intense as in other Mediterranean areas, but may happen in summer or early autumn.

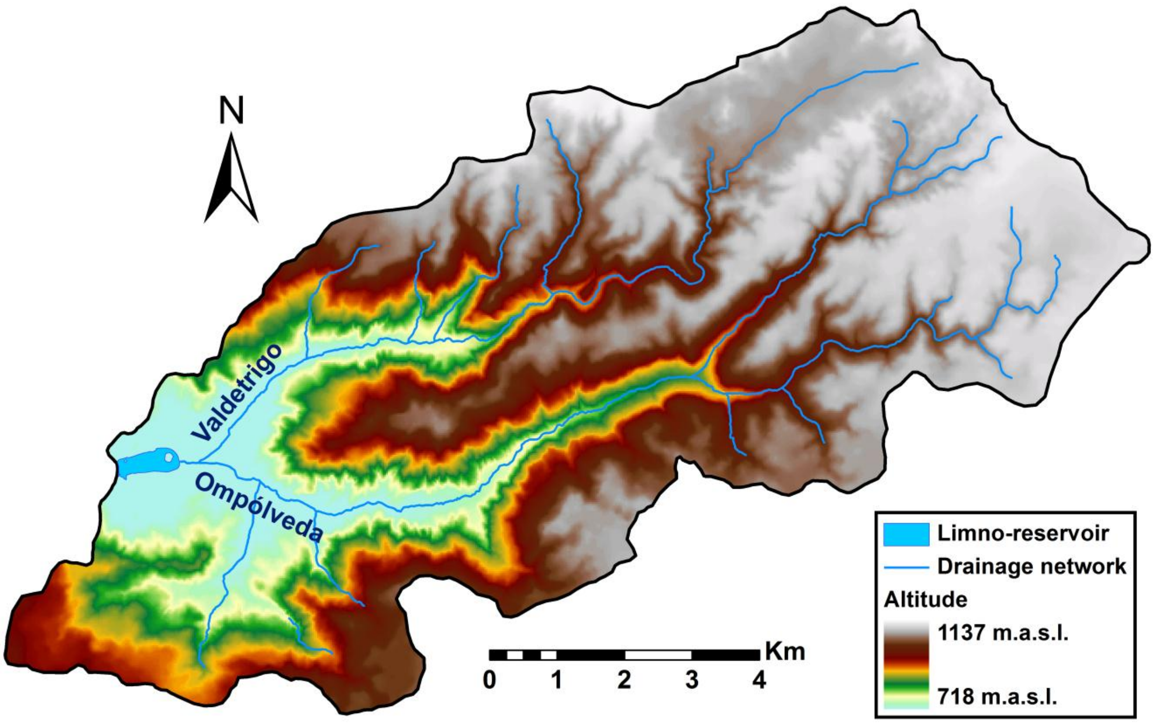

Fig. 2.5. Digital elevation model of the Ompólveda River basin, drainage network and current location of the Pareja Limno-reservoir. Drainage network and digital elevation model files were provided by the Instituto Geográfico Nacional.

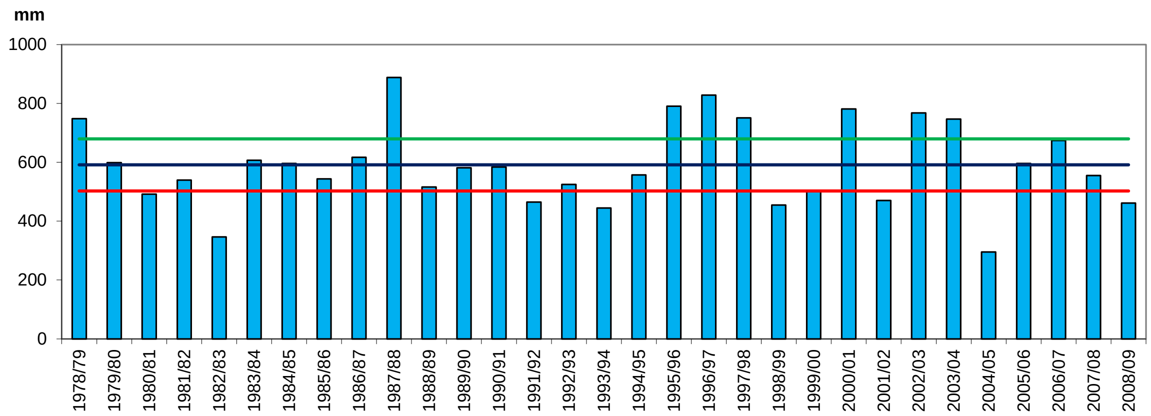

Fig. 2.6. Precipitation recorded in the Escamilla station during the last three decades. The lines indicate the average precipitation (blue), average+15% (wet years, green) and average-15% (dry years, red). Data provided by AEMET.

Average annual value of the Ompólveda River discharges recorded at the E-3270-Pareja gauging station between 1980 and 2003 was around 5.0 hm^3, approximately 10% of the average annual precipitation. Annual river discharge also showed high variability, ranging from 1.1 hm^3 (1992-93) to 13.7 hm^3 (1987–88) (CEH-CEDEX, 2008) (Fig. 2.7a). It was generally low from June to November and, matching up with rainfall data, peaks of highest flow volumes did not show a specific temporal pattern. As an example, figure 2.7b shows the 1995/1996 hydrograph. Despite summer drought, the Ompólveda River presents a permanent regime, which suggest a noticeable importance of baseflow

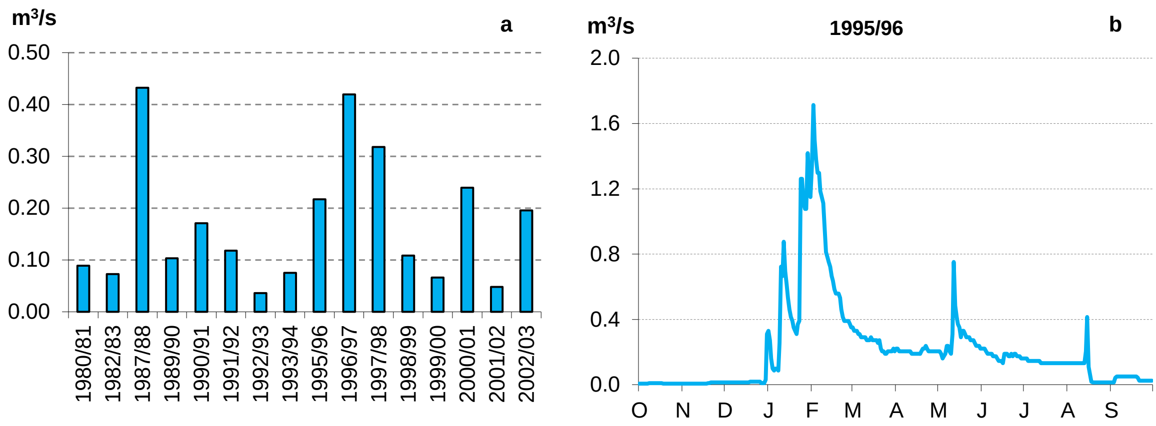

Fig. 2.7. a) Ompólveda River average annual discharge (only years with full data are represented). b) 1995/95 hydrograph. Data from CEH-CEDEX (2008).

A Davis Vantage Pro2 Weather Station was installed next to the Pareja Limno-reservoir in October 2009 to have more thorough knowledge of weather conditions.

2.2.3. Geology and soils

The study area is located in a region called "La Alcarria". The Ompólveda River basin has the two principal geomorphological characteristics of this region. The first one is a carbonate plateau that dominates the highest altitudes and constitutes a karstic aquifer (CHT, 2007; Martín-Loeches and Rebollo, 2008). The second one is the presence of valleys with steep hillsides that break with the uniformity of the plateau (Fig. 2.5).

The geology of the basin was described in detail by Hernaiz Huerta et al. (1998). Most of the basin is compound by Neogene (Miocene) deposits, divided in 4 lithological units:

- "First Neogene Unit". It consists of gypsum and red clay from the Lower Miocene and barely surfaces in the basin, as a result of an anticline (López Olmedo et al., 2008).

- "Second Neogene Unit". It surfaces in the lower basin. This unit includes clay, silt, gypsum and sand levels from the Lower Miocene as well. Red clay and gypsum predominates in the Ompólveda River Basin, including levels of massive gypsum.

- "Third Neogene Unit". It surfaces over the previous lithological unit and is compound by alternations of clay, silt, sand, marlstone and limestone levels from the Middle Miocene. This unit is often crowned by a limestone level of relatively high thickness (up to 50 m) that developed a karstification surface.

- "Fourth Neogene Unit" or "Páramo Unit". This lithological unit results in a high carbonate plateau mainly composed by limestone from the Upper Miocene. Its average maximum thickness in the basin is around 50 m. The unit may present a thin detrital level in its base or "Páramo" limestones may be lying directly on the upper limestones from the "Third Neogene Unit", being difficult to differentiate both of them. The limestone plateau presents karst features such as sinkholes filled with clays of decalcification (Cabra Gil, 1998) or poljes.

Other lithological units present in the Ompólveda River basin are in minority. In the middle part of the Ompólveda and Valdetrigo valleys, Paleogene (clay, silt, sandstone and conglomerate) and Upper Cretaceous (clay, marls and gypsum) deposits surface as a result of the abovementioned anticline. Quaternary sediments are mainly found in the alluvial plains of the largest valleys. Figures 2.8 and 2.9 show a simplified geological map of the basin and the corresponding geological section, respectively

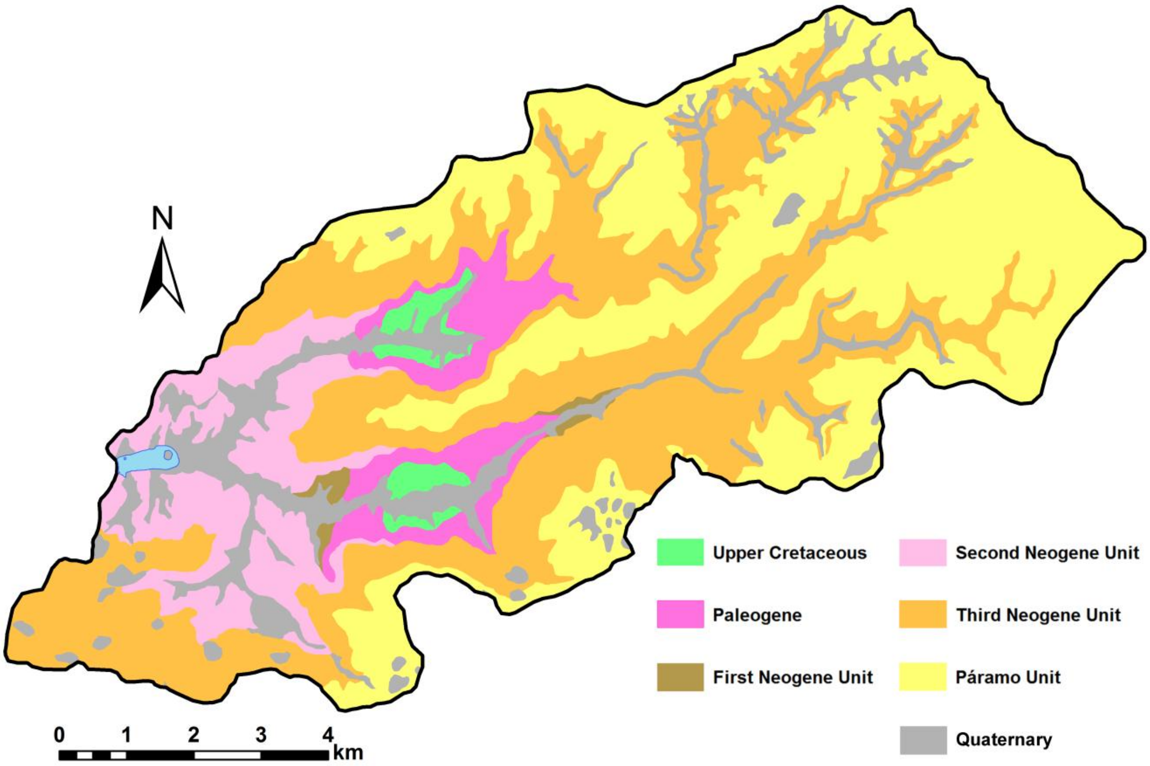

Fig. 2.8. Geological scheme of the Ompólveda River basin (data provided by Instituto Geológico y Minero de España)

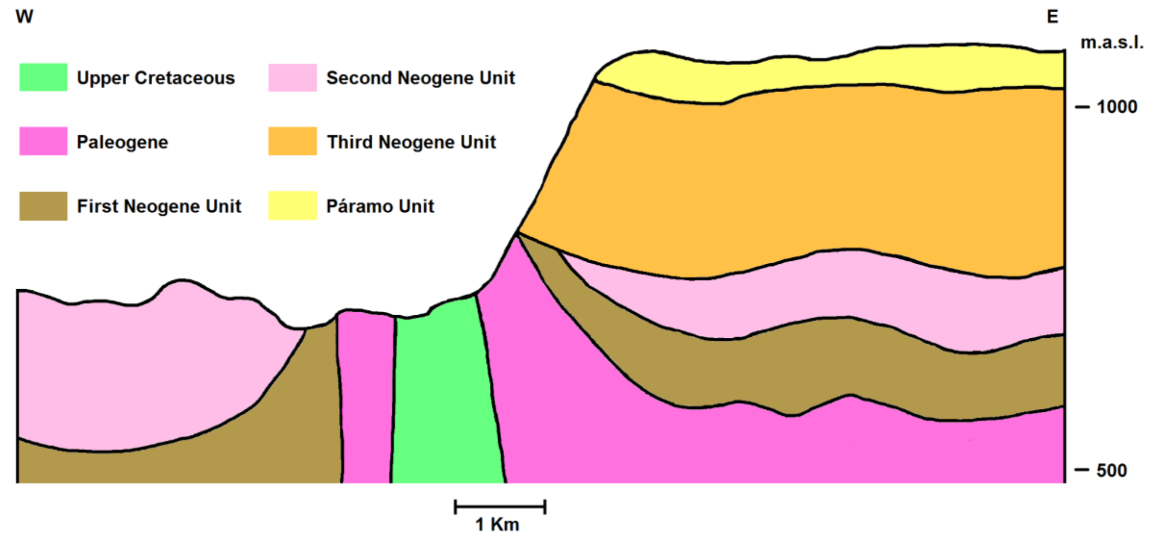

Fig. 2.9. Simplified geological section of the Ompólveda River basin, adapted from Hernaiz Huerta et al. (1998). Vertical scale has been exaggerated to favour a simple view.

Information about Ompólveda River basin soils prior to the research was limited to the Guadalajara Province soils map, scale 1:200,000 (Guerrero et al., 1970). Thus, linked to this research, soils in the basin were initially studied by Arévalo Illana (2008) and later they have been categorized and mapped during the thesis work. 61.5% of the catchment is covered by entisols and 38.5% by alfisols (Fig. 2.10). Chapter 5 provides more detailed information about basin soils.

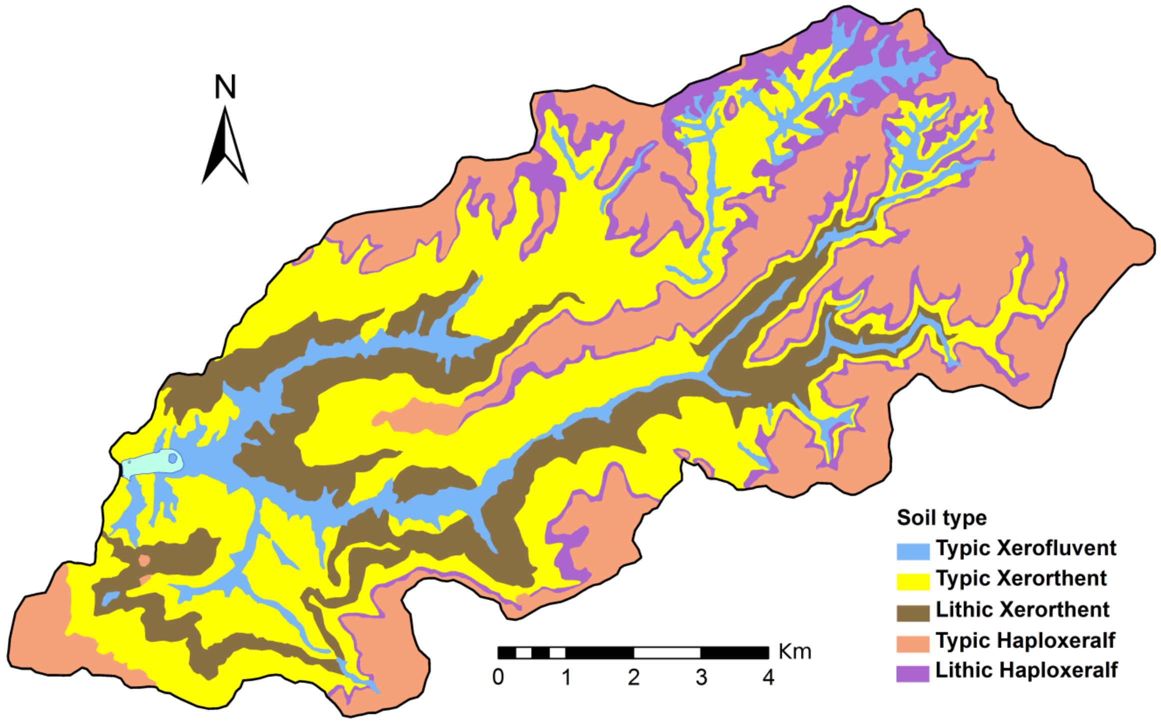

Fig. 2.10. Main soil types in the Ompólveda River basin (modified from Molina Navarro et al., in press).

2.2.4. Population and Land Uses

The Ompólveda River basin has rural features. There are about 300 inhabitants in the basin, mostly living in the village of Pareja (whose population quadruples in summer). Recent history in the catchment shows how people have moved from the villages to the cities (rural exodus). Figure 2.11 shows the existence of five other small villages in the basin. Except for Casasana (around 30 inhabitants) they have become almost abandoned and are today inhabited just by one or two families.

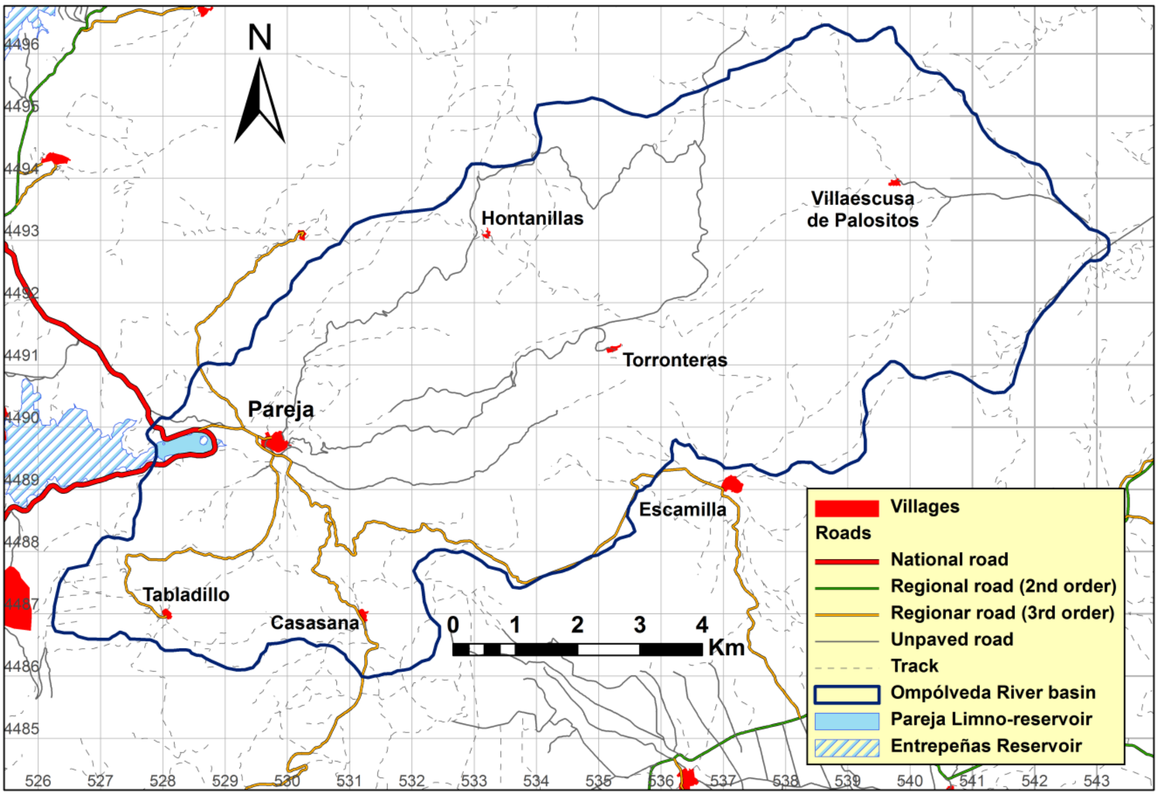

Fig. 2.11. Villages and main roads in the Ompólveda River basin (information provided by the Instituto Geográfico Nacional).

As a consequence of the rural exodus, agricultural land use has been reduced and natural vegetation is the main land coverage. Thus, 37% of the basin is covered by forests (pine and holm oak). Most of the pine forests in the catchment came from a reforestation program, and some of them were planted in terraces. Scrubland covers 36% of the basin, occasionally combined with pasture. Twenty five percent of the catchment is cultivated, mainly including non-irrigated cereal crops (17%) and olives orchards (7%, many of them abandoned). Figure 2.12 shows these and other minority land uses.

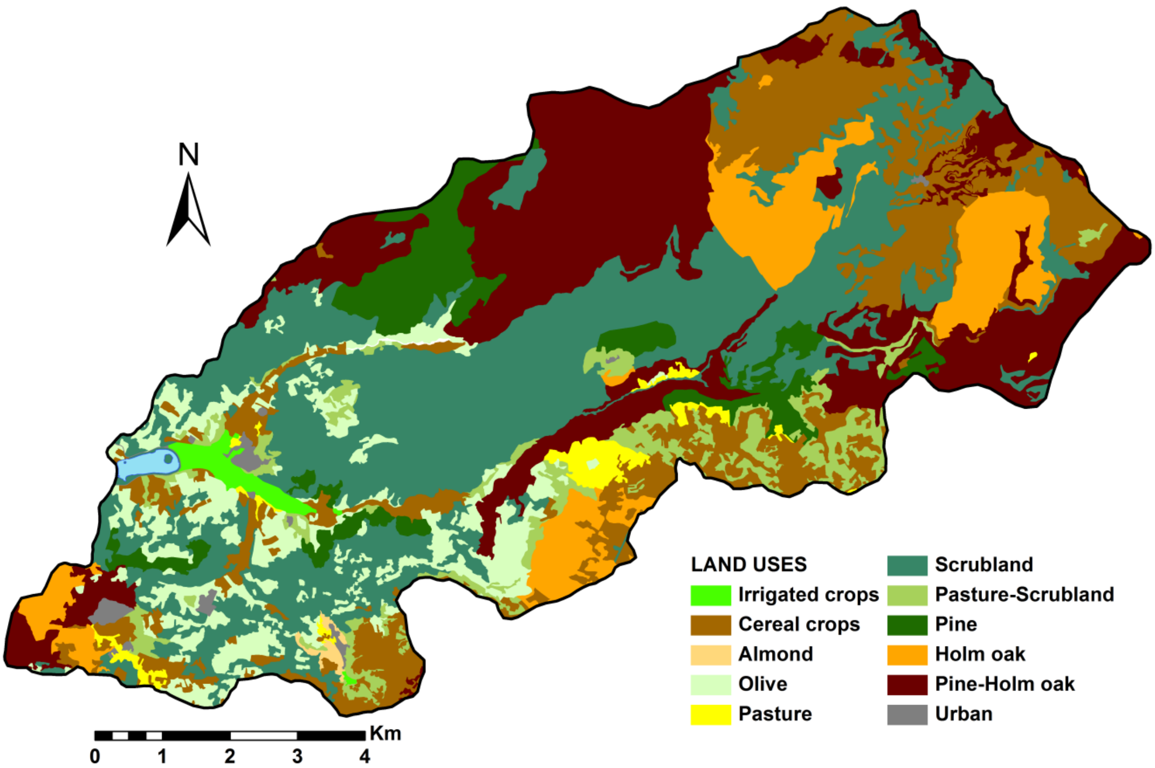

Fig. 2.12. Land uses in the Ompólveda River basin (information provided by the Ministerio de Medio Ambiente).

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- Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A. and Bienes-Allas, R. Hydrologic Modeling in a Small Mediterranean Basin as a Tool to Assess the Feasibility of a Limno-Reservoir. Journal of Environmental Quality, in press.

3. Environmental issues and hydrological characteristics

3.1. Environmental and hydrological features

This section reproduces the text (translated into English) of the following manuscript:

Molina-Navarro, E., Martínez Pérez, S. and Sastre Merlín, A. El Limnoembalse de Cola de Pareja (Guadalajara): Aspectos medioambientales e hidrológicos. Published in *Boletín Geológico y Minero* 121 (2010), 69–80.

Abstract

The construction of small reservoirs in the riverine zone of large ones is an innovative idea designed to counteract some of the negative impacts caused by the construction and use of reservoirs. The denomination "Limno-reservoirs" is proposed here, as these water bodies are created to maintain a natural lake dynamics. The Pareja Limno-reservoir is among the first limno-reservoirs in Spain, and its construction raises some questions about hydrological viability and sedimentation risk. The proposition of methodologies to answer them and the evaluation of the first results are the aims of this study. A detailed water balance makes it possible to affirm that, in a first approach, the limno-reservoir seems feasible from a hydrological point of view. The Ompólveda River basin -a tributary of Tagus River at Entrepeñas reservoir- seems to have enough water resources to guarantee the permanence of the water body, even in the dry year-type. To assess the sedimentation risk, a soil loss monitoring network will be monitoring the Ompólveda basin for the next three years to evaluate the net erosion in the catchment and the sediment delivery to the reservoir.

Keywords: limno-reservoir, Ompólveda River, reservoir sedimentation, soil loss, water balance.

Resumen

Los embalses de cola constituyen una reseñable novedad en el elenco de actuaciones encaminadas a mitigar algunos aspectos negativos derivados de la construcción y operación de embalses. Se propone la denominación de "limnoembalses" para los mismos, toda vez que estas masas de agua se crean con vocación de comportamiento de lago más que de embalse. El limnoembalse de Pareja es una de las primeras materializaciones de este tenor construidas en España, existiendo algunas indeterminaciones acerca de su viabilidad hidrológica y de su posible aterramiento. El objetivo de este trabajo es plantear la metodología para la resolución de las mismas y evaluar los primeros resultados. Tras la realización de un balance de agua detallado en el limnoembalse, puede afirmarse que, en una primera aproximación, es hidrológicamente viable, dado que la cuenca del río Ompólveda -tributario del Tajo en el embalse de Entrepeñas- parece disponer de recursos hídricos suficientes como para garantizar la permanencia y estabilidad de la lámina de agua, incluso en los años "tipo" caracterizados como secos. Con el fin de caracterizar la erosión neta en la cuenca y, con ello, el aporte de sedimentos al limnoembalse, ha sido instalada una red de observación de la pérdida de suelo en la cuenca del Ompólveda, la cual estará operativa, al menos, durante los próximos tres años.

Palabras clave: aterramiento, balance hidrológico, limnoembalse de cola, pérdida de suelo, río Ompólveda.

3.1.1. INTRODUCTION

There are some possibilities to mitigate the negative effects caused by the construction and use of reservoirs. The development of an "arid band" stands out because of its visual impact. This band arises because of the water level fluctuations in the reservoir, which creates a drawdown zone.

Water administrations in Spain have been promoting for some years a unique action: the construction of small dams in the riverine zone of reservoirs -especially in those with strategic interests-, known as "riverine dams" or "flood dams". First initiatives of this kind were proposed in the late 1980s and the early 1990s in the Tagus River and Guadiana River basins. Then, the idea was adopted in other basins. In the list of investments of the National Hydrological Plan (BOE num. 161, 2001) several riverine dams are included in the Tagus River, Ebro River and Júcar River basins.

The riverine dams are constructed preferably in a tributary of the main watercourse which provides enough water contribution. The riverine dam creates a water body independent from the main reservoir. The water body covers an area that would be part of the abovementioned "arid band". Thus, this area is part of the inundation area of the main reservoir. It means that the design of the riverine dams may consider the possibility of retaining water upstream and downstream. This is the reason why they are also called "flood dams".

3.1.2. ENVIRONMENTAL PERSPECTIVE AND CASE OF STUDY

From an environmental perspective, it may be highlighted that the man-made water body is independent from the main reservoir. This water body may preserve a constant water level throughout the year in order to avoid the development of an arid band. We did not find any term in the literature for this kind of water body. Since they are created to behave as a lake rather than a reservoir, we suggest the term "limno-reservoir".

A few limno-reservoirs are already operating in Spain. For instance, three limno-reservoirs were built in the Orellana Reservoir (Guadiana River basin) and another one in the Portaje Reservoir (Tagus River basin), both located in the Extremadura region. They have the main goal of preventing the water level fluctuations, along with creating a habitat for waterfowl (Rodríguez Cabellos, 1995; MMA and CNEGP, 1996). We have not found scientific literature about this kind of infrastructures. However, they could be considered innovative initiatives for hydrological and environmental recovery, so it seems appropriate to assess their usefulness.

One of the first limno-reservoirs created in Spain is the Pareja Limno-reservoir, close to the village of the same name. It is located in the south of the province of Guadalajara, central Spain, in the upper Tagus River basin (Fig. 3.1.1). The Ompólveda River, tributary of the Tagus River in its left bank, flows into the Pareja Limno-reservoir, whose water surplus reaches the Entrepeñas Reservoir (Molina-Navarro et al., 2009). The Ompólveda River basin has an approximate area[1] of 85.5 Km^2. The Pareja Limno-reservoir has a volume of 0.94 hm^3 and an inundation area of 26 ha. The maximum depth in the dam zone[2] is around 9 m, becoming progressively shallower towards the inflow section, where depth is around 1.5 m. Six million euros were spent on the construction of the dam and additional facilities.

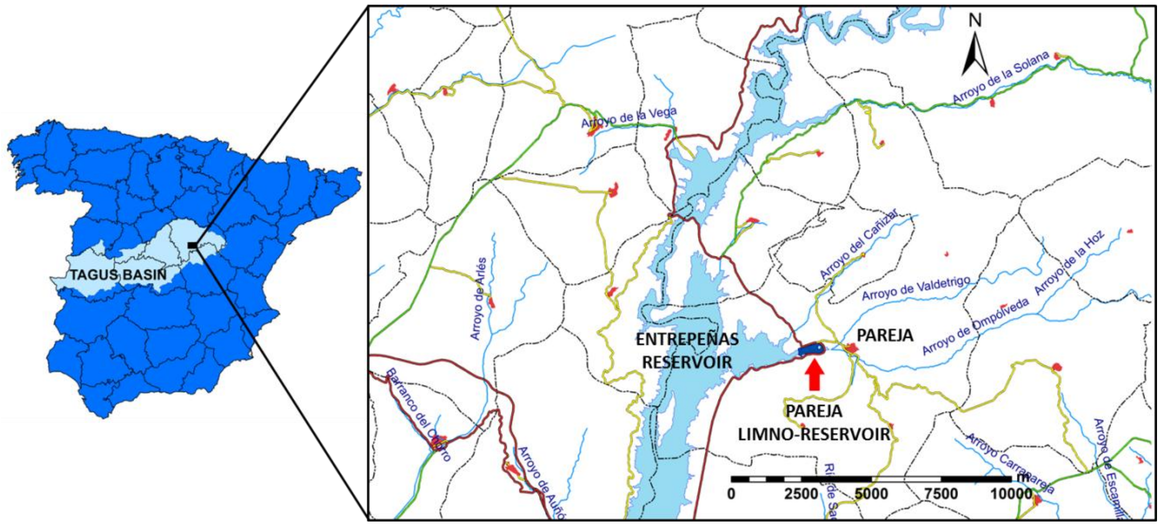

Fig. 3.1.1. Location of the Pareja Limno-reservoir.

The Pareja village is located in the influence area of two large reservoirs, Entrepeñas and Buendía. The construction of these large reservoirs raised tourist expectations, especially during the 1970s, that outshined their negative effects. However, the climate became drier and the transfer of water to southeast Spain started, which led the Entrepeñas-Buendía reservoir system to be at minimal water levels during extended periods (Fig. 3.1.2). This situation shattered the tourist and recreational expectations. Then, the population started asking for corrective and/or compensatory actions to mitigate the negative effects of the Entrepeñas and Buendía reservoirs.

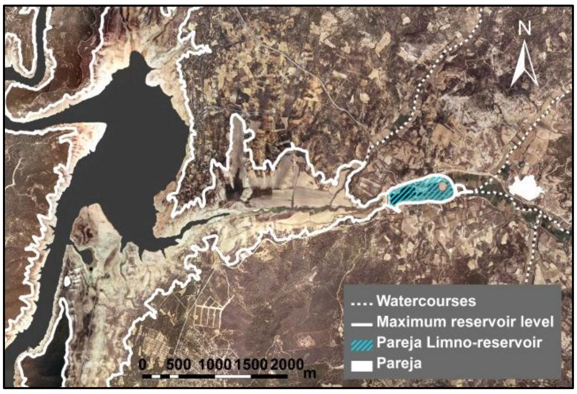

Fig. 3.1.2. Maximum Entrepeñas reservoir level and real situation in 2006. Source of aerial photography: IDR (2008).

[1] A further more accurate study showed that the basin area is around 88 Km^2

[2] A further more accurate study showed that the maximum depth is around 12.5 m

The main goal of the Pareja Limno-reservoir is the hydrological and environmental recovery of the surroundings. Two man-made islands were constructed to serve as a refuge for waterfowl, as well as a fish ladder (Fig. 3.1.3). In addition, the economic development linked to nature tourism is promoted: it has a swimming area, a quay and a walking perimeter.

Fig. 3.1.3. View of the Pareja Limno-reservoir. Entrepeñas Reservoir in the background.

Research on limno-reservoirs is innovative, but in the Pareja Limno-reservoir case is of particular interest since it includes tourist and recreational goals. It seems appropriate to monitor the environmental behaviour of the limno-reservoir and its socio-economic impact. A research project was conceived, designing an environmental observatory to assess the environmental performance of the limno-reservoir from and holistic approach. This assessment would include not only the limno-reservoir but its drainage basin as well. The study has five perspectives: water availability, sedimentation risk, limnology, chemical and microbiological quality and socio-economic analysis. Besides, a geographic information system is being developed to facilitate the results interpretation (Molina Navarro et al., 2009). This paper presents the initial achievements in the two first perspectives.

3.1.3. OBJECTIVES

The main goals of this paper are:

- To perform a water balance in the Ompólveda River basin and in the Pareja Limno-reservoir. This may be essential to analyse and quantify the water availability, considering the peculiarity of the hydraulic infrastructure studied.

- To describe the methodology developed to study the soil loss and deposition in the basin, with the final aim of assessing the sedimentation risk of the limno-reservoir.

- To present the guidelines followed in the design of the geographic information system. It is aimed to collect and manage efficiently the information emerged from the development of the research project.

3.1.4. METHODOLOGY

The following methodologies were applied to achieve the goals described.

3.1.4.1. Water availability analysis and quantification

The basic hydrological parameters in the Ompólveda River basin were calculated. The precipitation and temperature data provided by the *Agencia Estatal de Meteorología* (AEMET) and the Ompólveda River flow data from the gauging station located in Pareja (E-3270-Pareja, CEH-CEDEX, 2008) were used. Precipitation data came from Cifuentes, Viana de Mondéjar, Budia, Pantano de Entrepeñas and Escamilla station, covering the period 1950/51-2004/05. Hydrological years were classified in normal, dry (precipitation less than average - 15%) and wet (precipitation more than average + 15%) year-types. Thus, it would be possible to assess the water availability under different climatic circumstances, especially those more unfavourable. The year-type classification was done with the software Hidrobas (Alonso Martínez et al., 2000), which calculates a fictitious year for each year-type category from the precipitation data.

The potential evapotranspiration (PET) was calculated with the Thornthwaite method with monthly temperature data from the Entrepeñas and Viana de Mondéjar stations (period 1956/57-1973/74). Soil properties in the study area were obtained from the Guadalajara Province soils map (Guerrero et al., 1970) and field observations. Then, field capacity was estimated following Urbano Terrón (1992) and actual evapotranspiration (AET) was calculated.

In addition, a water balance was performed in the Pareja Limno-reservoir for each year-type. Evaporation data in the adjacent Entrepeñas Reservoir was provided by the Confederación Hidrográfica del Tajo (years 2003/04 and 2004/05). Evaporation and water surplus via the fish ladder (and occasionally via the spillway) are the only water outputs when the limno-reservoir is at its maximum capacity. The water inputs in the balance are the runoff and the direct precipitation on the limno-reservoir surface. Runoff data from the Ompólveda River gauging station (period 1979/80-2005/06) covers almost the entire basin. However, there is a small area (around 3.5 Km^2) between the gauging station and the riverine dam whose runoff is not gauged in the station (Fig. 3.1.4). Runoff in this area was calculated applying the runoff coefficient (runoff/precipitation) obtained for the remaining basin: 0.08 for dry and normal years and 0.18[3] for dry, normal and wet year-types, respectively.

Finally, hydrographs were represented with the data provided by the E-3270-Pareja gauging station. Baseflow was estimated through hydrograph separation techniques, following approximately the curvature of the recession curve (Remeneiras, 1974; Custodio and Llamas, 1983) in arithmetical coordinates.

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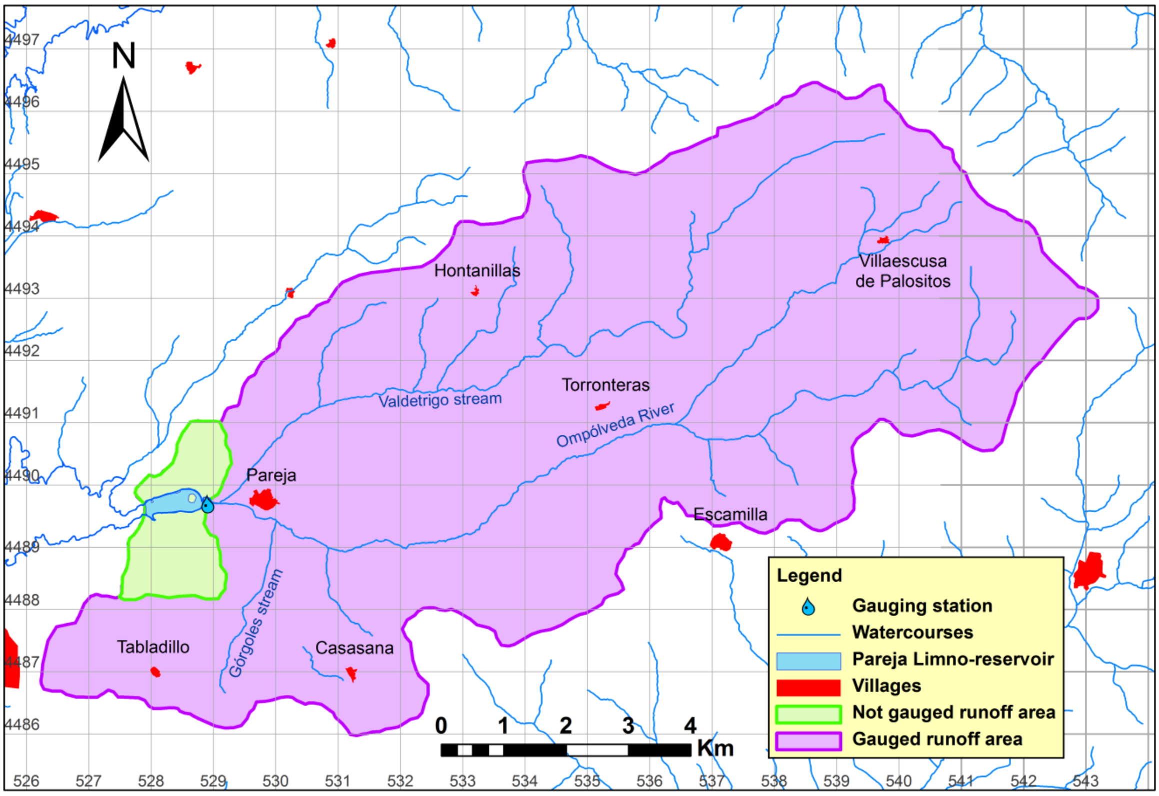

Fig. 3.1.4. Gauged and not gauged runoff areas in the Ompólveda River basin.

3.1.4.2. Limno-reservoir sedimentation risk assessment

The limno-reservoir sedimentation risk depends on the sediment load from its drainage basin. Prior to this study but linked to the research project, Arévalo (2008) performed a theoretical analysis of the soil loss in the Ompólveda River basin. However, to track the real soil loss, we have set up two methodologies to estimate *in-situ* soil erosion and deposition, considering the basin characteristics (topography, lithology, orientation, land use and accessibility, among others).

The first methodology used serves to estimate interrill erosion and ordinary sedimentation. Erosion plots were installed, each plot containing 16 iron erosion pins (30 cm length), standing out around 10 cm above the soil. Pins are separated from each other 25 cm, forming a sampling plot of 75x75 cm (Fig. 3.1.5). These plots were installed in locations representative of the basin characteristics, considering both erosive and deposition environments. A global soil loss will be assessed evaluating the soil erosion and deposition in each plot and considering the soil bulk density.

The second methodology deals with the rill erosion and the consequent sedimentation. Nine rills were selected and the rill section is drawn with a needle micro-profiler (Fig. 3.1.6), calculating its area afterwards. A continuum monitoring of the rill section allows the evaluation of possible changes. In addition, erosion pins were installed in the terminal zone of each rill to estimate sediment deposition. In this case, the pins were displayed following the shape of the deposition zone. The total soil loss will be estimated considering the bulk densities.

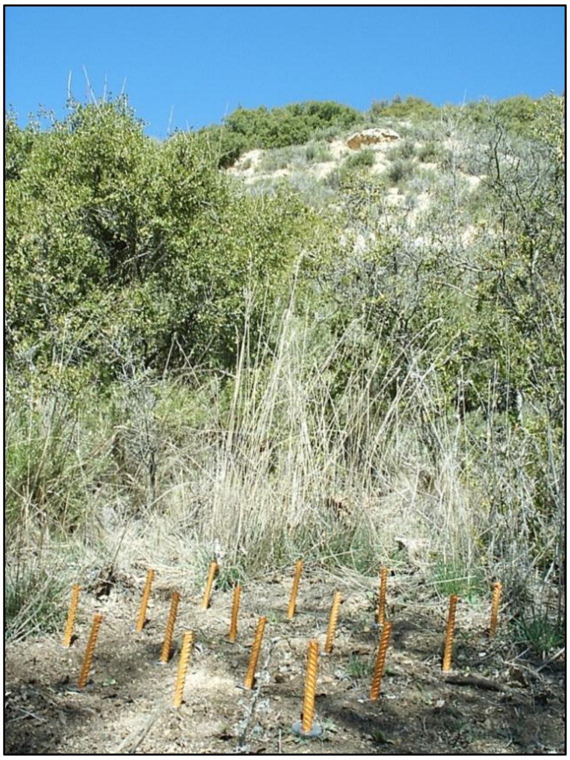

Fig. 3.1.5. Sedimentation sampling plot after a slope break in Cretaceous lithology.

Fig. 3.1.6. Measurement of rill erosion with a needle micro-profiler.

Five measurements per year will be taken during three years. Results obtained will be extrapolated to similar areas in the basin, using the most recent aerial photography available (PNOA 2006; IDR, 2008). Additionally, we will carry out a detailed bathymetric survey in the Pareja Limno-reservoir. The comparison of this survey with a previous one (carried out by the Confederación Hidrográfica del Tajo prior to the limno-reservoir filling) would allow the estimation of the sedimentation rate.

3.1.4.3. Design of the geographic information system

We have collected digital geographic information from several public administrations and institutes, including the *Instituto Geográfico Nacional*, the *Instituto Geológico y Minero de España*, the Dirección *General del Catastro del Ministerio de Economía y Hacienda*, the *Ministerio de Medio Ambiente y Medio Rural y Marino*, the *Junta de Comunidades de Castilla-La Mancha* and the European Environment Agency.

The information is being processed with ArcGIS 9.2 (ESRI, 2006). Every vector file has been converted to *Shapefile* format, creating layers. The geographic database has been restricted to the area covered by the 537(I, II, III and IV) and the 538(I and III) sheets of the National Topographic Map, scale 1:25000. The digital elevation model and the PNOA 2006 aerial photography (IDR, 2008) are in raster format. The geology of the area from the MAGNA digital maps has been synthesized in a unique vector file.

3.1.5. RESULTS AND DISCUSSION

3.1.5.1. Water availability analysis and quantification

The precipitation station 3066-Escamilla has the largest data series (1963/64-2004/05). It is located in the south border of the Ompólveda River basin (1017 m.a.s.l.). It was chosen to depict the variability of the precipitation in the study area (Fig. 3.1.7).

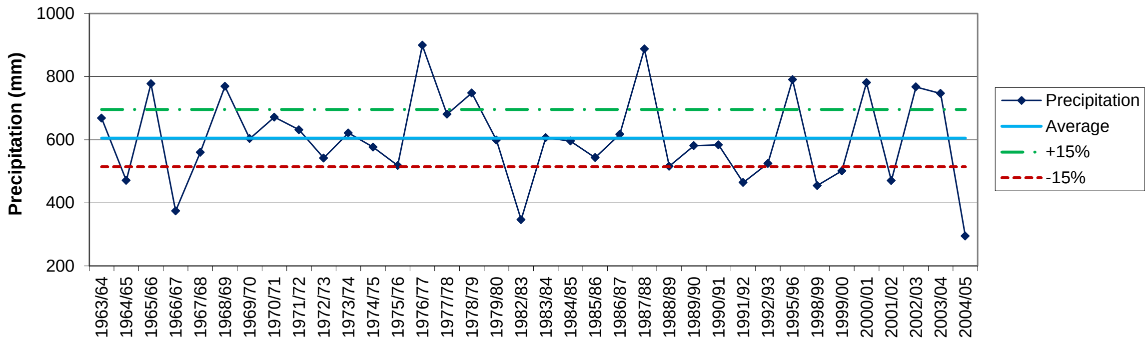

Fig. 3.1.7. Annual precipitation at Escamilla rainfall station.

Rainfall shows great inter-annual variability. This fact justifies the need for year-types description, which make possible to study the hydrological parameters especially under unfavourable circumstances.

Lithosols (Rendzina and Xerorendzina soils) predominate in the study area. They lack horizon development and its depth ranges from 20 to 120 cm. These soils do not have a structure able to retain water and thus they show good drainage (Guerra Delgado et al., 1970). These characteristics and field observation allowed the estimation of an average soil depth of 70 cm, a field capacity of 22%, a wilting point of 10% and an average bulk density of 1.3 g/cm^3. With these data, soil available water capacity was estimated between 50 and 75 mm according to Urbano Terrón (1992).

Basic hydrological parameters in the Ompólveda River basin for each year-type were calculated (Table 3.1.1).

Table 3.1.1. Main hydrological parameters at Ompólveda basin, in hm^3. P = precipitation, PET =Potential evapotranspiration, AET50 = Actual evapotranspiration determined by the Thornthwaite method with available water capacity equal to 50mm, AET75 = idem but 75 mm, and Q = runoff measured at E-3270 gauging station.

	Dry years	Normal years	Wet years
P	34.2	45.3	55.7
PET	60.0	60.0	60.0
AET_{50}	29.2	35.0	36.7
AET_{75}	31.3	37.1	38.8
Q*	2.64	3.64	8.88

*Differs from the originally published because of an error amendment

It must be highlighted that a 19% and 25% decrease in rainfall (from wet to normal year-type and from normal to dry year-type, respectively) causes a runoff decrease of 59% and 27%[4], respectively. This result matches up with those obtained by other authors throughout Spain (MMA, 2000) and they indicate that runoff is very sensitive to rainfall decreasing and there is not a linear relationship between them. Average runoff represents around 10% of average rainfall. It reveals that using rainfall-runoff relationships calculated in extensive areas is not appropriate in detailed hydrological studies. Table 3.1.1 also shows that AET is noticeably lower in dry years, while it showed similar values for normal and wet years. However, AET percentage related to precipitation varies among year-types, being 85-92% during dry years, 77-82% during normal years and 66-70% during wet years. The Thornthwaite method is very useful because only requires temperature data, but it must be acknowledged that it tends to underestimate PET in arid zones and overestimates it in wet areas (Alkaeed et al., 2006).

The water balance in the Pareja Limno-reservoir was calculated for each year-type, considering the present situation (maximum water level, 0.94 hm^3). Figure 3.1.8 shows the water balances results.

The water balances reveals that there is water surplus in every month, including during dry years. This surplus will flow out the limno-reservoir through the fish ladder and, occasionally, through the spillway too. *A priori*, this result guarantees the permanence of a stable water level throughout the year. Maximum and minimum water surpluses were observed during spring in wet years and during summer in dry years, respectively. Figure 3.1.8 reveals a noticeable parallelism between the surplus and the Ompólveda River runoff. Results suggest that a permanent water regime is reached once the limno-reservoir achieves its maximum capacity. Then, most of the water input from the Ompólveda River, except from the evaporation loss, flows out the limno-reservoir to the Entrepeñas reservoir. Nevertheless, the water supply of the Pareja village comes

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from the Ompólveda River and the wastewater is sent downstream the limno-reservoir. It seems appropriate to perform a further evaluation of this fact in the water balance.

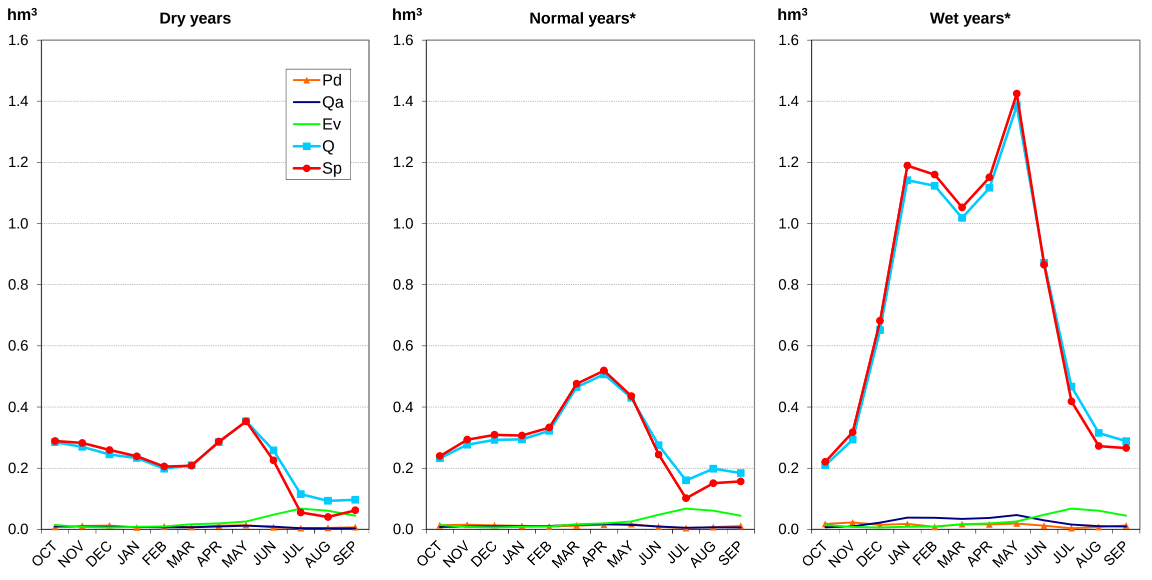

Fig. 3.1.8. Water balance in the Pareja Limno-reservoir for dry, normal and wet years (Pd = direct precipitation in the reservoir, Qa =runoff not measured at 3270-Pareja gauging station, Ev = evaporation, Q = runoff at the cited station and Sp = water surplus) (*Differs from the originally published because of an error amendment).

The annual values of the Ompólveda River discharge showed great inter-annual variation, as it was expected after the precipitation analysis. They ranged between 1.13 hm^3 in 1992/93 and 13.66 hm^3 in 1987/88. Besides, runoff peaks did not follow a precise temporal pattern, happening in spring, in winter or in both stations. Table 3.1.2 shows the total runoff measured and the baseflow estimated following Remeneiras (1974) and Custodio y Llamas (1983) in humid and wet years. The separation of flow components during dry years was difficult because of the absence of flow peaks. Figure 3.1.9 shows the hydrograph separation done for year 2002/03.

The baseflow varies inversely to the precipitation, representing a lower percentage during wet years (55-60 %) and a higher percentage during normal and dry years (70-80%). It may be over 80% in the driest years, when the Ompólveda River maintains a permanent regime despite the absence of rainfall. In any case, the baseflow percentage is high. It was expected because the Ompólveda River basin is dominated by a limestone plateau. Baseflow approximately corresponds to 9% of precipitation during wet years and 7% of precipitation during normal and dry years.

Table 3.1.2. Total runoff (Q) and baseflow (Qb) at the E-3270-Pareja gauging station in some of the years recorded.

Year	Q	Q_b	% Q_b	Year-type*
1987/88	13.66	8.0	58.6	Wet
1989/90	3.25	2.6	80.0	Normal
1995/96	6.86	2.8	40.8	Wet
1996/97	13.22	7.6	57.5	Wet
1997/98	10.03	7.0	69.8	Wet
2000/01	7.55	4.1	54.3	Wet
2002/03	6.17	3.9	63.2	Wet
2003/04	9.10	6.4	70.3	Wet
2005/06	1.85	1.3	70.3	Normal

*Differs from the originally published because of an error amendment

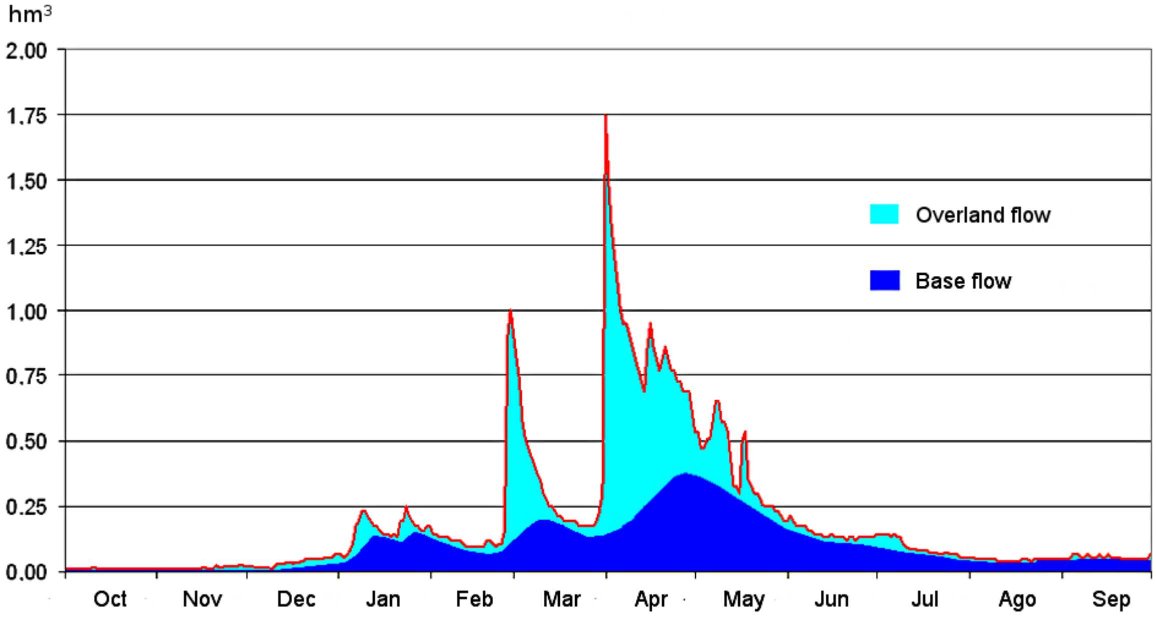

Fig. 3.1.9. 2002/03 hydrograph separation.

3.1.5.2. Limno-reservoir sedimentation risk assessment

Once the installation criteria and the monitoring plan were decided, 14 erosion plots and 7 sedimentation plots were installed. Nine rills were monitored, measuring 2-4 profiles in each rill depending on its length and heterogeneity. The number of pins installed in the rill deposition varied according the size of the deposition area.

Further measurements and its extrapolation to the whole catchment will allow the calculation of the global soil loss. Figure 3.1.10, created with ArcGIS, indicates the location of the soil loss monitoring points.

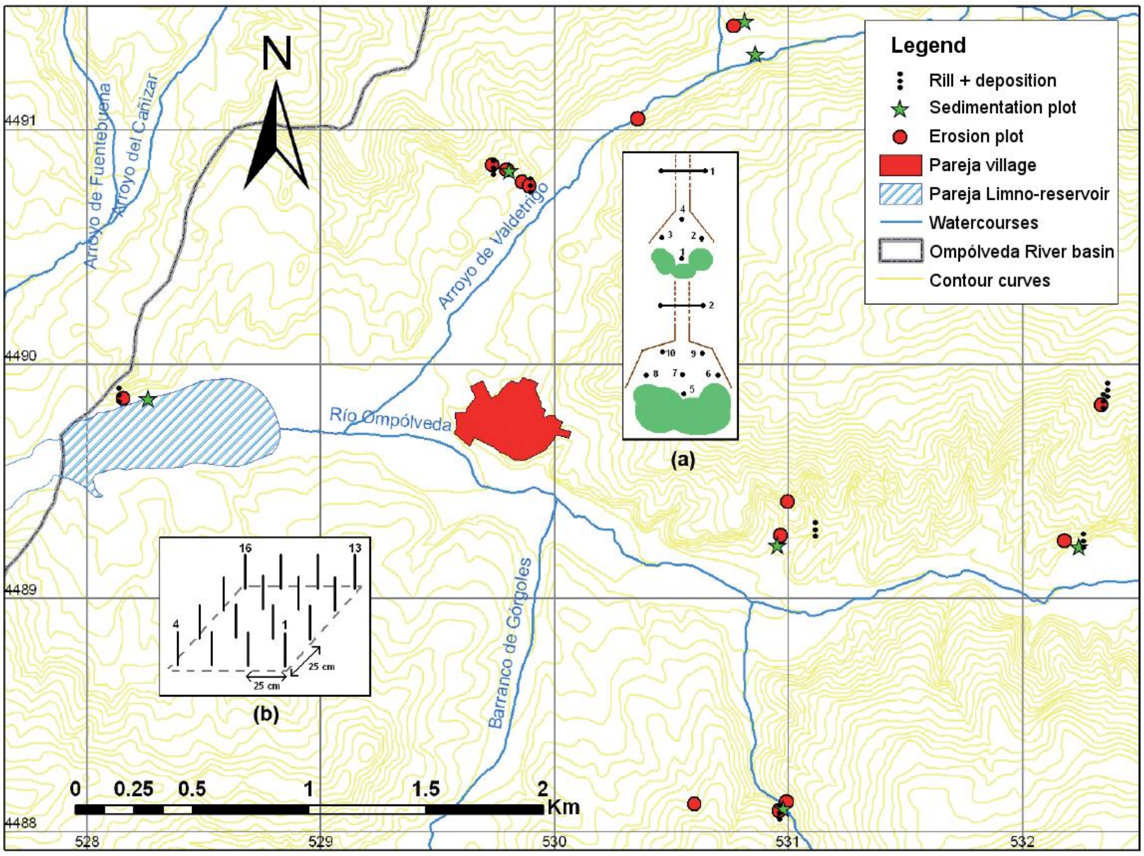

Fig. 3.1.10. Location of the soil loss control points -erosion and sedimentation plots, monitored rills and their deposition areas- and their diagrams: (a): Profiles (lines) and pins (points) measurement in rills and (b): pins location in erosion and sedimentation plots.

Soil erosion has been widely assessed, but studies under real circumstances and at catchment scale are scarce. Many studies use the (R)USLE (Universal Soil Loss Equation) experimental equation or modifications (e.g. Agnese et al., 2006). Since USLE was developed to predict long-term erosion in agriculture plots, it may not be suitable for catchment scale studies and other models have been developed (de Vente et al., 2005). They include the FSM model (Factorial Scoring Model, Verstraeten et al., 2003) or the PSIAC model (PSIAC, 1968). Some authors use more simple soil erosion indicators, such as the reservoir sedimentation (de Vente et al., 2005) or dendrochronological methods (Pérez-Rodríguez et al., 2007). *In-situ* experiments are also frequent, but mostly linked to agricultural activities (de Alba, 2000) or using plots rather different from those used in this study, even simulating rainfall (Marques et al., 2007).

Some authors are currently studying real erosion in extreme rainfall events (Barbero et al., 2008). However, the achievement of significant results in this project will have special relevance in the soil erosion studies, since an innovative approach has been proposed to study real erosion at a catchment scale in a long time frame.

3.1.6. CONCLUSIONS AND FURTHER WORK

3.1.6.1. Concerning water availability

The analysis of runoff and rainfall suggest that the preservation of a constant water level in the Pareja Limno-reservoir is guaranteed, on condition that significant water removals in the Ompólveda River do not occur.

The hydrograph separation revealed that the baseflow has a noticeable importance, ranging from 55% and 80% of total runoff and being even higher during the driest years.

3.1.6.2. Concerning sedimentation risk

A soil loss monitoring network has been installed and an initial measurement has been performed. It will be the reference for the future monitoring campaigns (five per year) to be carried out during the next three years.

Nevertheless, results obtained with this monitoring network will be compared to those obtained after a bathymetric survey that will be performed in the Pareja Limno-reservoir.

3.1.7. Acknowledgements

Funds for this research came from the agreement between the University of Alcalá and the Ibercaja Social Action (2007 funds) and from the Castilla-La Mancha Government (project num. PAI 08-0226-1758). The research team wants to thank the Confederación Hidrográfica del Tajo and the Pareja City Hall for their support. Thanks to Prof. Dr. Ramón Bienes for his implication and advice in the soil monitoring network set up and to Andrew Sadler for his valuable English language comments.

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3.2. Hydrogeology and hydrogeochemistry

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Sastre-Merlín, A., Vicente, R. and Martínez-Pérez, S. Hydrogeology and hydrogeochemistry in a site of strategic importance: the Pareja Limno-reservoir drainage basin (Guadalajara, central Spain). Submitted to *Hydrogeology Journal* on 16/04/2013 and currently under review (Manuscript ID: HJ-2013-2799)

Abstract

The hydrogeological and hydrogeochemical behaviour of a small calcareous basin located in central Spain was studied in order to acquire knowledge about the role of groundwater in a new kind of water body: the Pareja Limno-reservoir. Groundwater flow contribution was derived by recharge estimation. A spring inventory was carried out and hydrogeological units (HGU) were defined. *In-situ* measurements (spring discharge, electrical conductivity and sulphate) were done and discharge was compared with a drought index. Average groundwater flow contribution was estimated around 60%. Twenty eight springs were monitored and three HGUs were defined. HGU1, a carbonate plateau, was found as the main aquifer and may play a relevant role in the preservation of the limno-reservoir water level. The underlying HGU2 seem to behave as an aquitard. Hydrogeochemical sampling was conducted and the model PHREEQC was applied to describe the main geochemical processes. Weathering and dissolution of calcite and gypsum seemed to control the hydrogeochemical processes in the basin. Water evolves from Ca^{2+}-HCO_3^- in the upper basin to Ca^{2+}-SO_4^{2-} in the lower basin, where gypsum enriched deposits (HGU3) surfaces. A clear temporal pattern was observed in the limno-reservoir, decreasing salinity in winter and increasing in summer but also showing a buffer effect.

Keywords: basin hydrogeology, carbonate aquifer, hydrogeochemistry, limno-reservoir, Spain.

Resumen

Se ha estudiado el comportamiento hidrogeológico e hidrogeoquímico de una pequeña cuenca desarrollada sobre la plataforma carbonatada de "La Alcarria" (región central española) para adquirir conocimiento sobre el papel que juega el agua subterránea en la viabilidad de un nuevo tipo de masa de agua que hemos denominado "limnoembalse" (Limnoembalse de Pareja). Se calculó la aportación subterránea mediante estimación de la recarga, se realizó un inventario de manantiales y se definieron unidades hidrogeológicas (HGU). Se tomaron medidas in-situ (caudal, conductividad eléctrica y sulfatos) y se comparó el caudal de manantiales y zonas de rezume con un índice de sequía. El porcentaje medio estimado procedente de la descarga de agua subterránea fue aproximadamente 60%. Se realizó el seguimiento de 28 manantiales y se definieron tres HGUs. La HGU1, correspondiente a la porción superior de la paramera alcarreña - con rasgos kársticos reconocibles- , resultó ser el principal acuífero, pudiendo jugar un papel relevante en el mantenimiento del nivel de agua del limnoembalse. Bajo ella, la HGU2 parece comportarse como un acuitardo. También se realizó un muestreo hidrogeoquímico y los principales procesos geoquímicos fueron descritos aplicando el modelo PHREEQC Interactive. La meteorización y disolución de la calcita y el yeso parecen controlar los procesos hidrogeoquímicos en la cuenca. El agua es bicarbonatada cálcica en la cuenca alta y evoluciona a sulfatada cálcica en la cuenca baja, donde toma protagonismo un sustrato arcillo-yesífero (HGU3). Se observó un claro patrón temporal en la zona del limnoembalse, disminuyendo la salinidad en invierno y aumentando en verano; se observa, no obstante, el efecto amortiguador ejercido por el limnoembalse.

Palabras clave: acuífero carbonatado, comportamiento hidrogeológico de cuenca, España, hidrogeoquímica, limnoembalse.

3.2.1. INTRODUCTION

In the Mediterranean region, water scarcity and drought represents a big challenge for water management (EEA 2012; MMA 2007). Besides, it seems that river flow regime will be strongly affected by climate change. Several reports have predicted noticeable reductions in water resources, which would lead to more intermittent regime in the future (IPCC 2007; Schneider et al. 2013). In this context, groundwater plays a vital role, especially during the dry season. Groundwater contributes nearly 30% of total water resources in Spain and is emerging as the principal regulator capable of mitigating the climate change effects (López-Vera 2012).

The chemistry of groundwater depends on a number of factors which includes the nature of recharge, hydrologic gradient, residence time of groundwater in the aquifer, rock-water interactions beneath the surface and anthropogenic activities (Andre et al. 2005; Krishna Kumar 2012). Water quantity and quality are closely linked and related issues can provoke socio-economic and environmental problems (EEA 2012; Schneider et al. 2013). In view of these adversities, groundwater quantity and quality studies become essential to understand its role in the aquatic ecosystems and could lead to effective management of water resources (Alexakis 2011; Shanmugam and Ambujam 2012). The scientific community in Spain has recognized this need and a number of related publications have arisen in the last years (e.g. Lambán et al. 2009; López-Geta and Fornés Azcoiti 2009; Sastre Merlín et al. 2008).

In a different vein, water level fluctuation is one of the major determinants of aquatic ecosystem function and services (EEA 2012). They are especially noticeable in large reservoirs under Mediterranean climate, causing undesirable environmental and socioeconomic impacts (Molina-Navarro et al. 2010). Water Administrations in Spain have taken some actions to mitigate these impacts. One of them has been the construction of small dams in the riverine zone of large reservoirs, generating a small water body with a constant level that is independent from the management of the main reservoir. We have termed these water bodies “limno-reservoir”, since they resemble a lake more than an ordinary reservoir (Molina-Navarro et al. 2010). The Pareja

Limno-reservoir (Guadalajara Province, central Spain) was the first Spanish limno-reservoir to serve environmental and recreational goals. Its construction finished 2006 as a response to the claims of the inhabitants of the Entrepeñas Reservoir area. They were enduring the environmental and socio-economic effects of the construction and exploitation of this large reservoir (835 hm3, 3213 ha of potential inundation), including large water volumes diverted to Southeast Spain. Consequently, the Pareja Limno-reservoir has a strategic importance (Molina-Navarro et al. 2010). The interest and convenience of this kind of novel initiatives are unquestionable, so acquiring knowledge about their behaviour seems necessary.

Prior to this study, a first approximation to the hydrological features of the Pareja Limno-reservoir drainage basin was done, whose main watercourse is the Ompólveda River. Average annual discharge of the river at the E-3270-Pareja gauging station was around 5.0 Hm^3 (period 1980-2003), representing approximately a 10% of the average annual rainfall. Loss via actual evapotranspiration (AET) has been estimated to assume a high percentage (89%) of average rainfall, matching up with the measured river discharge (Molina-Navarro et al. in press). Through hydrograph separation techniques, groundwater flow was estimated to account for a 55-60% of total discharge during wet years and 70-80% during mid and dry years, even higher than 80% in the driest years (Molina-Navarro et al. 2010). This reveals a noticeable quantitative importance of groundwater in the Ompólveda River basin. Investigating the existing hydrogeological system and the hydrogeochemical features is the next step to study the role that groundwater plays in the Ompólveda River basin and in the Pareja Limno-reservoir.

The Pareja Limno-reservoir is located in a region called “La Alcarria”. “La Alcarria” is characterized by the presence of a carbonate plateau, which constitutes a karstic aquifer of regional interest (CHT 2007; Martín-Loeches and Rebollo 2008). Actually, karst springs are among the most important water-supply sources for a large part of the Mediterranean region (Fiorillo and Doglioni 2010). However, the Ompólveda River basin was not included in the “La Alcarria Hydrogeological Unit” defined by the Spanish Water Administration. This unit covers approximately 3075 km^2 beyond the right bank of the Tagus river, 2112 of them in the Guadalajara Province (IGME 2013), while the Ompólveda River flows into its left bank in the Entrepeñas Reservoir.

Hydrogeological and hydrogeochemical studies of the “La Alcarria” aquifer are relatively scarce, and most of them from the late 70s and the 80s (e.g. Maestro Salmerón et al. 1986; Villarroya and Rebollo 1978). More recently, along with the publication of the 1:50000 scale geological map Hernaiz Huerta et al. (1998), del Pozo (1998) described the basic hydrogeological characteristics of a broad area (≈522 Km^2) that includes our study area (≈88 Km^2). Álvarez Díaz and Galán Vergara (2007) published basic data on the carbonate plateau aquifer in the northern part of “La Alcarria” region, more affected by anthropogenic activity. Specific hydrogeochemical studies in the study area have not been found. Nevertheless, since the anthropogenic activity is scarce, hydrogeochemistry may be primarily controlled by water-rock interaction (Krishna Kumar et al. 2012).

The objective of this study is to make an approach to the hydrogeological behaviour of the Ompólveda River basin and its hydrogeochemical characteristics and processes, checking also their influence in the Pareja Limno-reservoir water. To achieve it, groundwater flow was estimated following Custodio and Llamas (1983). A spring inventory was carried out and hydrogeological units were defined. In-situ measurements were taken and analysed and spring discharge was compared with a drought index (SPI, McKee et al. 1993). Hydrogeochemical sampling was conducted in selected points from the springs inventory, the river network and the limno-reservoir, and the model PHREEQC Interactive (Parkhurst and Appelo 2013) was used to discover the main hydrogeochemical processes in the basin.

3.2.2. MATERIAL AND METHODS

3.2.2.1. Study area

The study area is the Pareja Limno-reservoir and its drainage basin, located in the upper Tagus River basin (South of Guadalajara, central Spain) (Fig. 3.2.1). The Pareja Limno-reservoir is fed by the Ompólveda River, whose main tributary is the Valdetrigo stream. The area has a typical Mediterranean climate characterized by dry and warm summers and a wet period occurring in winter and spring. Average temperature is around 13 ºC and mean annual rainfall recorded is around 600 mm in the upper basin (Escamilla station). The Ompólveda River basin has rural features and natural vegetation (scrubland and pine and holm oak forest) is the main land coverage. About 300 inhabitants live in the basin, most of them in the village of Pareja.

The Pareja Limno-reservoir was built in 2006 in the riverine zone of a sidearm of the much larger Entrepeñas Reservoir (Fig. 3.2.1), where the Ompólveda River discharges. The limno-reservoir has a capacity of 0.94 hm^3, a potential inundation area of 26 ha and an average depth around 4 m.

The Ompólveda River basin has the two principal geomorphological characteristics of "La Alcarria" region: the carbonate plateau and the valleys with steep hillsides that break with the uniformity of the plateau. The geology of the basin was described in detail by Hernaiz Huerta et al. (1998). Most of the basin is compound by Neogene (Miocene) deposits, divided in 4 lithological units:

- "First Neogene Unit". It consists of gypsum and red clay from the Lower Miocene and barely surfaces in the basin, as a result of an anticline (López Olmedo et al. 2008).

- "Second Neogene Unit". It surfaces in the lower basin. This unit includes clay, silt, gypsum and sand levels from the Lower Miocene as well. Red clay and gypsum predominates in the Ompólveda River Basin, including levels of massive gypsum.

- "Third Neogene Unit". It surfaces over the previous lithological unit and is compound by alternations of clay, silt, sand, marlstone and limestone levels from the Middle Miocene. This unit is often crowned by a limestone level of relatively high thickness (up to 50 m) that developed a karstification surface.

- “Fourth Neogene Unit” or “Páramo Unit”. This lithological unit results in a high carbonate plateau mainly composed by limestone from the Upper Miocene. Its average maximum thickness in the basin is around 50 m. The unit may present a thin detrital level in its base or “Páramo” limestones may be lying directly on the upper limestones from the “Third Neogene Unit”, being difficult to differentiate both of them. The limestone plateau presents karst features such as sinkholes filled with clays of decalcification (Cabra Gil 1998) or poljes.

Other lithological units present in the Ompólveda River basin in a minority. In the middle part of the Ompólveda and Valdetrigo valleys, Paleogene (clay, silt, sandstone and conglomerate) and Upper Cretaceous (clay, marls and gypsum) deposits surface as a result of the abovementioned anticline. Quaternary sediments are mainly found in the alluvial plains of the largest valleys. Figure 3.2.2 shows a simplified geological section of the study area.

More detailed features of the study site can be found in Molina-Navarro et al. (in press).

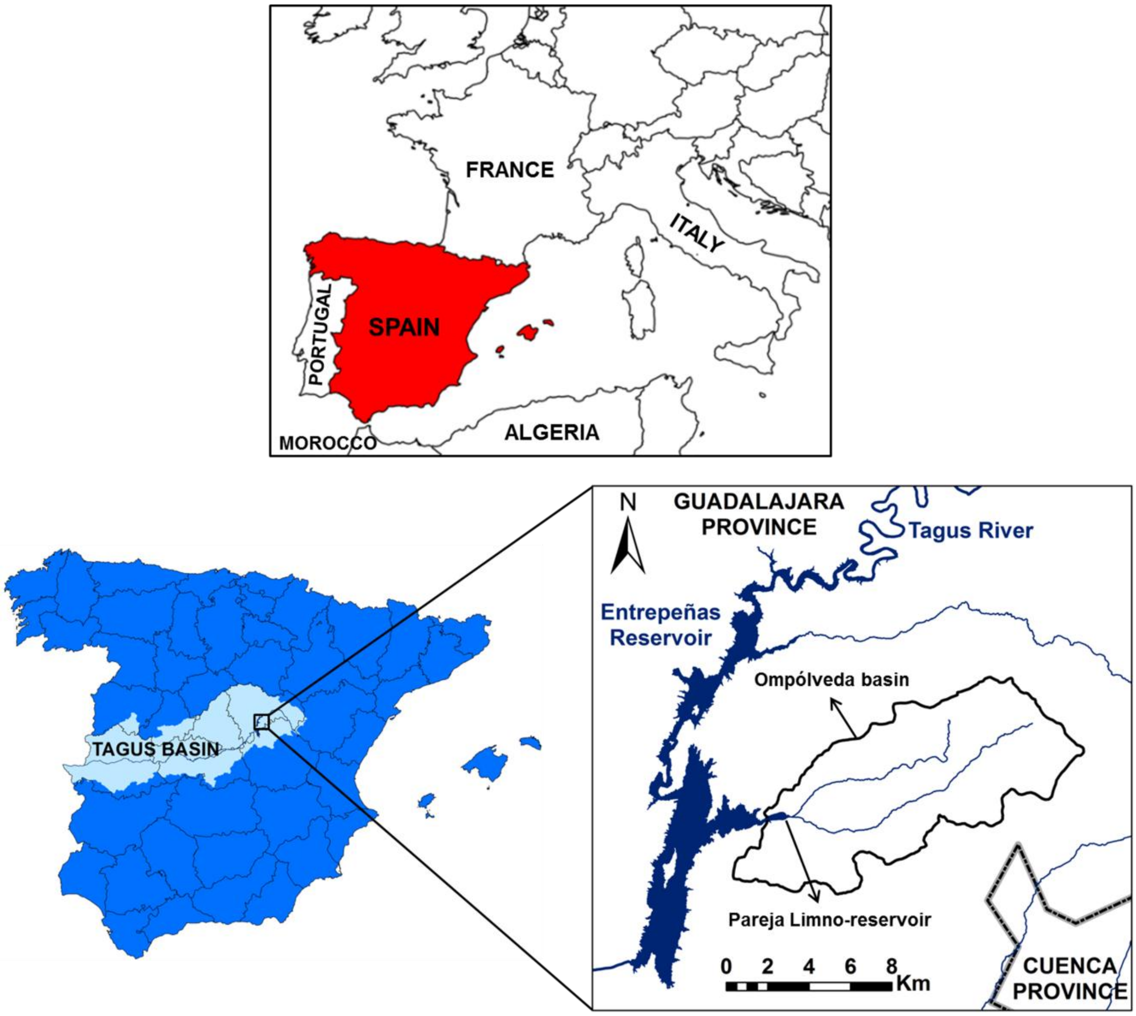

Fig. 3.2.1. Location of the Ompólveda River basin and the Pareja Limno-reservoir within Spain and within the Tagus River basin.

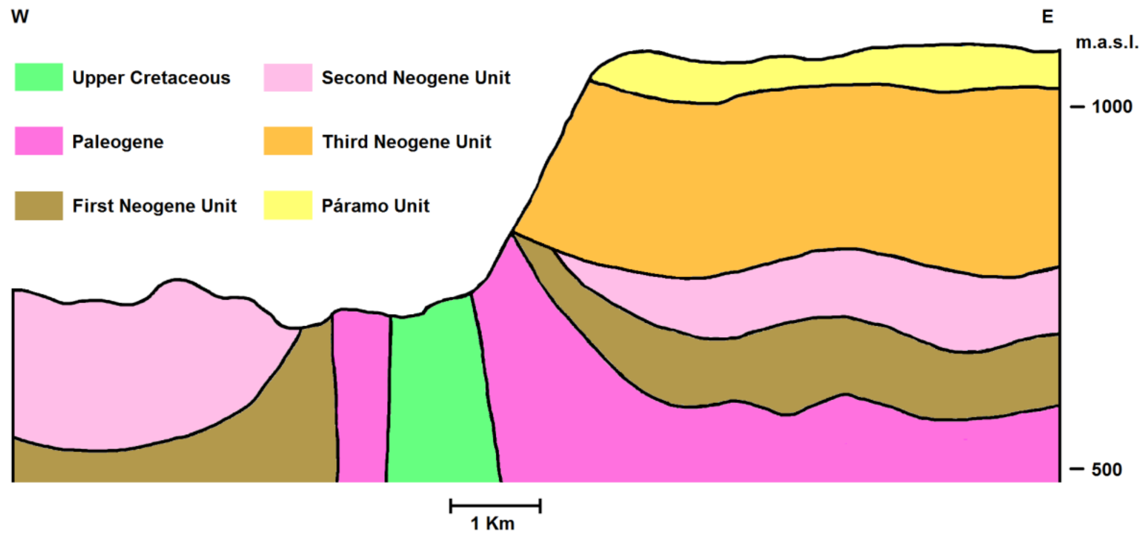

Fig. 3.2.2. Geological section of the study area, adapted from Hernaiz Huerta et al. (1998). Vertical scale has been exaggerated to favour a simplified view.

3.2.2.2. Springs inventory, definition of hydrogeological units and groundwater estimation

Springs included in the National Topographic Map (scale 1:25000, IGN) and in the MAGNA Geological Map (scale 1:50000, IGME) were examined in-situ to confirm their presence. Additional field work was carried out in collaboration with local citizens to locate the maximum number of springs in the Ompólveda River basin. Every spring was georeferenced with a Silva GPS. Considering the geological features of the basin (described in section 3.2.2.1) and the presence of springs, main hydrogeological units (HGUs) in the basin were defined.

Once HGUs were defined, recharge area was determined and the average contribution of groundwater flow was estimated. The meteorological and hydrological data already available for the basin (Molina-Navarro et al. in press) were used to estimate the groundwater flow via spring discharge with the equation provided by Custodio y Llamas (1983), $Q=A \times R \times 31.5$, where Q is the springs discharge in l/s, A is the recharge area in Km^2 and R is the annual recharge in m. We considered that infiltration may be almost equal to the difference between precipitation and AET (Maestro Salmerón et al. 1986). Following Lovelli et al. (2010), potential evapotranspiration (PET) was decreased by 6%, since the recharge area may be located in the upper basin and AET data were recorded in the lower basin (≈400m altitude difference and temperature lapse rate of 9.1 ºC km^{-1}, Molina-Navarro et al. in press). We compared the result obtained with the percentages of groundwater flow previously estimated through hydrograph separation (Molina-Navarro et al. 2010).

3.2.2.3. *In-situ* measurements

The springs discharge was measured twice a year, in autumn (lowest discharge expected) and in spring (highest discharge expected). Depending on the magnitude and the spring characteristics, discharge was measured with volumetric recipients or with an OTT C2 Small Current Meter. Electrical conductivity (EC) was determined in-situ with a Crison Conductivity Meter. Sulphate concentration was also analysed in-situ with Hanna Sulphate Test Kit. Measurements started in autumn 2009 and finished in autumn 2011.

3.2.2.4. Hydrogeochemistry sampling strategy and analysis

Several sampling points were chosen to check the evolution of hydrogeochemistry in the Ompólveda River basin and in the Pareja Limno-reservoir. Regarding the latter, six sampling points were defined: One in the Ompólveda River outlet, one in the inflow zone and four next to the limno-reservoir dam, at 0, 2, 5 and 8 m. depth. At these points, samples were taken during winter, spring, summer and autumn in the period spring 2008 – summer 2011. The magnitude of runoff was measured in the Ompólveda River outlet with an OTT C2 Small Current Meter and following the procedure in Dussaubat and Vargas (2005).

Once an initial view of limno-reservoir hydrogeochemistry was obtained and the first spring’s in-situ measurements were available, additional samples were taken in the river network: Ompólveda River lower reach (winter and spring 2009), Valdetrigo stream lower reach (winter, spring and summer 2011) and Ompólveda River mid reach (summer and autumn 2009 and spring 2010). During river and limno-reservoir sampling, EC, pH and temperature were measured in-situ with multi-parameter water quality probes (YSI 6920) or Schott Handylab and Crison portable meters.

Five springs were initially selected as representative to analyse their hydrogeochemistry in autumn 2010 and spring 2011. After the first results preview, additional analyses from two other springs were included to complete the hydrogeochemistry sampling.

The water samples were stored in 0.13 l new polypropylene bottles provided by CAASA Laboratory. Bottles were rinsed out with sample water prior to storage and were transported to the laboratory within 24 h of their collection. Hydrogeochemical analyses for major ions were carried out in the CAASA laboratory. HCO_3^- and CO_3^{2-} were measured by acidimetry, SO_4^{2-} and Cl^- were analysed by ionic chromatography, Ca^{2+} and Mg^{2+} were determined by complexiometry and K^+ and Na^+ were measured by absorption atomic spectroscopy.

3.2.2.5. Data analysis and representation

Springs were grouped according to the hydrogeological units defined and average and total discharge values were obtained per measuring survey and per season. Discharges and EC were mapped using ArcGIS 9.3, developed by ESRI. Average discharges per spring and geological formation were also plotted over time to observe seasonal patterns. Seasonal discharge variations were compared with the Standardized Precipitation Index (SPI). The SPI quantifies precipitation deficits (deviation from the mean of the cumulative rainfall) over a specific time-interval, using only series of monthly rainfall. It has been already used to evaluate the groundwater recharge and its relation with groundwater droughts in karstic springs (Fiorillo and Guadagno 2010). It moves above and below zero and negative values indicate drought periods. Drought intensity is defined for SPI values with the categories in Table 3.2.1 (McKee et al. 1993). The SPI was calculated for the time series 1979-2011 with the SPI_SL_6 software developed by The National Drought Mitigation Center (NDMC 2013) for 1, 2, 3, 6, 9 and 12 months time scale. More information about SPI calculation can be found in Lloyd-Hughes and Saunders (2002). The dependence of spring discharge on the different time scale of SPI was evaluated according to Fiorillo and Guadagno (2010), correlating each SPI series with the average spring discharge in each geological context.

Table 3.2.1. Drought categories according to SPI values (McKee et al. 1993).

SPI values	Drought category
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

Hydrogeochemical analyses were processed using the INAQUAS software, developed by the ICOG (Moreno Merino and de la Losa Román, 2008). Average values in every spring, river and limno-reservoir area were obtained and represented in Stiff hexa-diagrams (Stiff 1951). They were mapped to give an overview of hydrogeochemical evolution in the basin. The Piper trilinear diagram (Piper 1944) was also used to characterize the hydrogeochemical facies in the study area.

Geochemical modelling was performed with the hydrogeochemical equilibrium model PHREEQC Interactive V.3. (Parkhurst and Appelo 2013). Saturation indices (SI), which indicate the capacity of water to dissolve minerals, were calculated. SI help to identify which geochemical reactions may play an important role in water chemistry (Langmuir 1997), so they were mapped. Inverse modelling was also performed to evaluate the mole transfer between the mineral phases that may play most significant roles according to the previous hydrogeochemical characterization.

Since data on chemical composition of rainfall are not available, distilled water was used as initial solution.

Hydrogeochemical sampling was more exhaustive in the Pareja Limno-reservoir area and a detailed study was performed there, including the Ompólveda River outlet, before flowing into the limno-reservoir. The temporal evolution of EC, main major ions and river discharge was represented to evaluate differences inside the limno-reservoir system and the existence of seasonal patterns and its possible causes.

3.2.3. RESULTS AND DISCUSSION

3.2.3.1. Hydrogeological features

Thirty five springs were inventoried (Fig. 3.2.3), 11 located thanks to existing cartography and 23 during fieldwork. Three of them (2, 13, 20) showed absence of flow during the whole study. Another four (3, 7, 33, 34) were located but we were unable to measure them because of access difficulties. The 28 remaining springs were monitored.

The geological features of the basin and the springs layout let us to define three main hydrogeological units (HGU) in the Ompólveda River Basin (Fig. 3.2.3):

- HGU1: This HGU comprises primarily the “Páramo” lithological unit, which mainly includes limestones. The Third Neogene Lithological Unit is often crowned by a calcareous level. When this level is in direct contact with the “Páramo” unit, it was considered that they have homogeneous hydrogeological behaviour, being also part of the HGU1. The presence of sinkholes and other karst features provide evidence that the HGU1 aquifer is karstic.

- HGU2: It comprises the remaining sedimentary deposits from the Third Neogene Lithological Unit. Since it includes an alternation of different facies, particularly clay, marls and limestone, it may have a different hydrogeological behaviour.

- **HGU3:** Mainly matches up with the Second Neogene Lithological Unit, which is also an alternation of sedimentary facies: clay and gypsum, as well as the small proportion of the First Neogene Unit that surfaces in the basin. This lithology was considered as an individual HGU because gypsum may a special role in the hydrogeochemistry (del Pozo 1998).

Then, among the 28 active springs monitored, 13 were located in the fringe corresponding to the contact between the HGU1 and the HGU2, 12 corresponded to the discharge of the HGU2, and just three were located in the HGU3 (Fig. 3.2.3). The absence of springs in other geological locations of the basin may indicate that they not have relevant hydrogeological properties. Quaternary deposits may have hydrogeological importance in nearby larger rivers (García de la Torre 1976), but in the study area springs associated were not found.

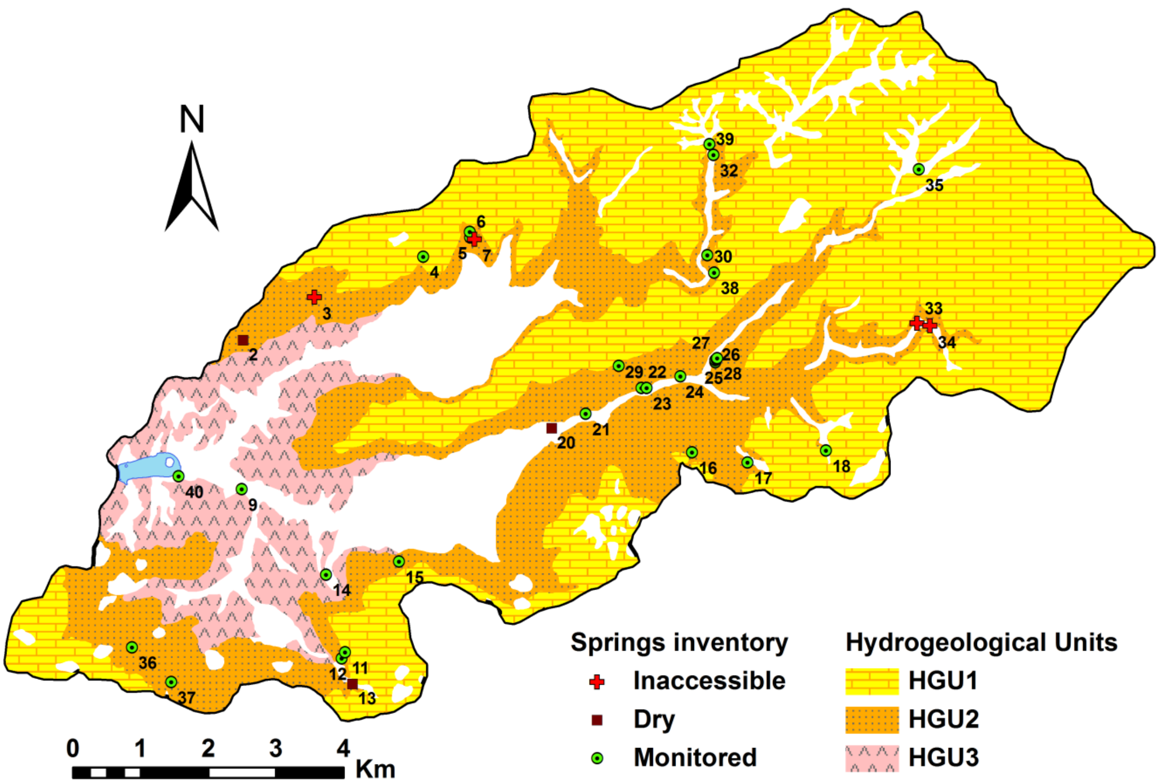

Fig. 3.2.3. Hydrogeological scheme and springs inventory in the Ompólveda River basin.

HGU1 is the most permeable unit and it is located in the upper basin, so it may act as the recharge area (approximately 41 km^2). After reduction of PET by 6% and recalculation of AET, average effective infiltration obtained was 74 mm. Estimated annual average groundwater flow via spring discharge following Custodio and Llamas (1983) was 95.5 l/s, which represents around 60% of total discharge measured at the E-3270-Pareja gauging station. This percentage is slightly lower than the previous estimated through hydrograph separation (Molina-Navarro et al. 2010), but contribution of quaternary deposits, although may be small, is not being considered. This result corroborates the quantitative importance of groundwater in the Ompólveda River basin, which may play an essential role in the maintenance of the Pareja Limno-reservoir, especially in summer, when baseflow is almost the unique water and high evaporation may provoke a decrease in the limno-reservoir water level (Molina-Navarro et al. in press)

Total spring discharge measured during field work was approximately 32 l/s in the hydrological year 2009/2010 and 13 l/s in 2010/2011. The drainage area of the springs monitored covers around 17% of the total recharge area. Ompólveda River discharge predicted with SWAT (Molina-Navarro et al. in press) was 280 l/s and 55 l/s in the respective years. Considering the contribution of groundwater flow estimated above and in Molina-Navarro et al. (2010), spring discharge measured accounts for 20-30% of the groundwater flow expected, which appears reasonable. Thus, it seems that all the springs existing in the Ompólveda River basin were not found, possibly because of the roughness of the territory (lack of accessibility), the existence of private properties (e.g. farms and private hunting preserves) and the difficulty to find out springs with diffuse discharge. Nevertheless, we have monitored a considerably high number of them that seem representative of the basin and have allowed us to describe the basin hydrogeological and hydrogeochemical features.

Figure 3.2.4 shows the average discharges in autumn (a) and spring (b). Springs in theHGU1 showed the highest discharges, with a mean discharge of 0.20 l/s in autumn and 1.99 l/s in spring. Average spring discharge in HGU2 was 0.19 l/s in autumn and 0.88 l/s in spring. In the HGU3, corresponding values were 0.15 l/s in autumn and 1.20 l/s in spring. These results match up with del Pozo (1998), who said that the limestone plateau formation is the most relevant aquifer in the area and older deposits underneath only have local importance. For this basin and similar ones in the surroundings, del Pozo (1998) said that spring discharge may reach 20 l/s, although most of springs do not exceed 5 l/s. These values also are in agreement with our results. In other areas with similar hydrogeological configuration located in the same physiographic region ("La Alcarria"), Villarroya and Rebollo (1978) and Maestro Salmerón et al. (1986) also pointed the limestone plateau as the main aquifer.

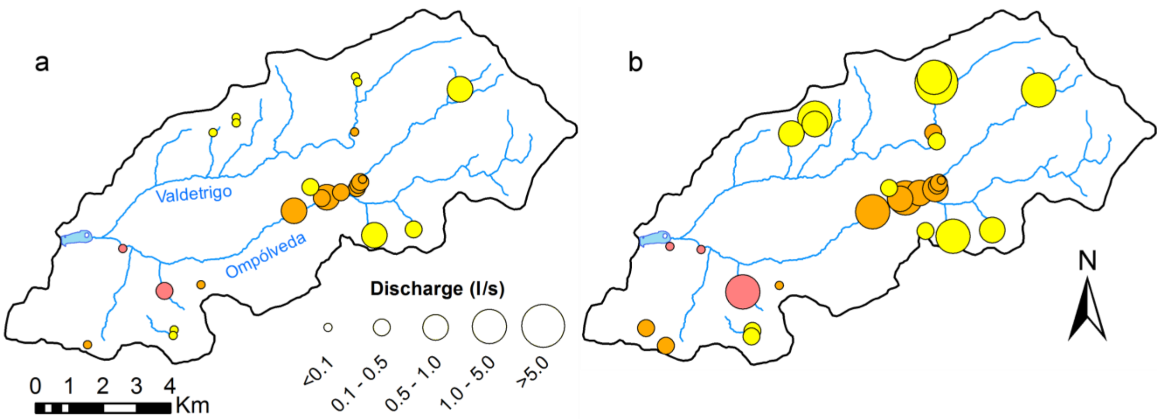

Fig. 3.2.4. Average discharges in autumn (a) and spring (b) in the springs corresponding to HGU1 (yellow), HGU2 (orange) and HGU3 (pink).

These results also reveal some differences depending on the spring location. Average discharges seasonal variability in the HGU1 were higher than in the springs located in the underlying HGU2. Looking at the temporal evolution of average discharges (Fig. 3.2.5), it can be also observed a larger difference between spring 2010 and spring 2011 in the HGU1 than in the HGU2 springs. 2009-10 and 2010-11 were wet and dry years (707 mm and 459 mm rainfall, respectively). During the wet spring (2010), the limestone plateau (HGU1) showed a higher response to recharge than the underlying deposits (HGU2). However, during the dry spring (2011), both responses were similar, even higher in HGU2. Response in the springs located in the

HGU3 (Lower Miocene) seems similar than in the HGU1. Nevertheless, the number of springs monitored in this unit was low and did not let us to give a consistent interpretation about its hydrogeological behaviour.

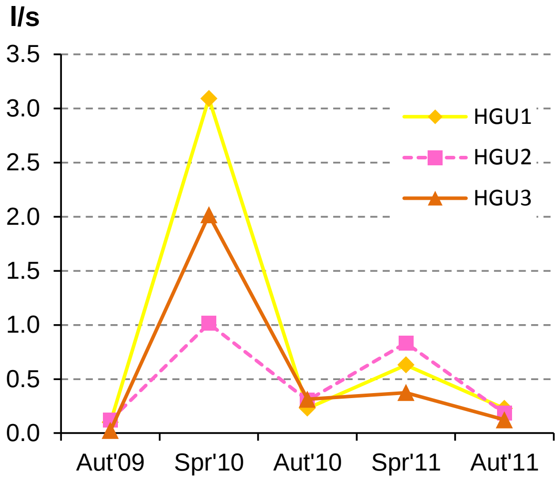

Fig. 3.2.5. Average spring discharge series in the different hydrogeological units.

The described hydrogeological behaviour matches up with the model of groundwater motion described by Villarroya and Rebollo (1978) and Maestro Salmerón et al. (1986) in areas belonging to the "La Alcarria" region: The carbonate plateau constitutes an unconfined and perched aquifer whose recharge comes from direct precipitation; there is a radial flow towards the border of the plateau where the discharge takes place as springs; below, the Middle Miocene deposits constitutes an aquitard. Our results suggest that the flow to the plateau aquifer (HGU1) borders is relatively fast after recharge events. The surface of this aquifer constitutes the recharge area. Thus, following a rainy period, the infiltrating water raises the piezometric level relatively fast and consequently increases spring discharge. According to Fiorillo and Doglioni (2010), the quick response of springs to intense rainfall events can be associated to the rapid rise and lowering of the water level inside the conduits above the saturated zone. When recharge ceases, both the piezometric level and the spring discharge follow a continuous slow decreasing trend (Fiorillo and Gaudagno, 2010). The spring flow during this slow decrease may be due to emptying the matrix, fissures, fractures, and small conduits by laminar flow (Fiorillo and Doglioni, 2010). Nevertheless, this slow discharge seems enough to maintain a permanent flow during the dry period, albeit low. In fact, 2009-10 and 2010-11 were respectively wet and dry years, but average discharge in autumn in 2010 and 2011 was identical (0.23 l/s). This fact may have special relevance for the conservation of a constant water level in the Pareja Limno-reservoir during summer, the season when it mainly fulfils its recreational purposes.

In spring 2011, recharge seemed to be not as high as that needed to raise the piezometric level enough to provoke a noticeable increase of calcareous springs discharge. However, it was apparently sufficient to provoke diffuse recharge to the aquitard (HGU2). Thus, flow in this aquitard may be minor but suffering lower seasonal variations than the main aquifer. In autumn 2011, HGU2 and HGU3 shoed lower average discharges (0.18 l/s and 0.12 l/s) than in autumn 2010 (0.30 l/s and 0.31 l/s). The progressive emptying of the overlying aquifer (in which the discharge flow is preferential) may lead to the reduction of the saturated thickness, exerting less pressure for diffuse recharge (Cherry et al., 2004).

Following Fiorillo and Guadagno (2010), the SPI index was used to evaluate the groundwater recharge over specific time-intervals and its relation with groundwater droughts. Figure 3.2.6a shows the results of the correlation of the different SPI series (1, 2, 3, 6, 9 and 12 months) with the average spring discharge in HGU1 and HGU2. The first showed the highest correlations with SPI1 and SPI3, while average spring discharge in HGU2 showed the highest correlations with SPI3 and SPI6. SPI3 revealed that the basin suffered from drought (SPI -1.0 or less, McKee et al. 1993) during May'09-Aug'09, Oct'09-Nov'09 and Sep'09-Oct'09 (Fig. 3.2.6b). The differences in correlation results reinforce the aforementioned interpretation: the calcareous aquifer response to recharge is faster, while the underlying Middle Miocene aquitard shows a smoother behaviour.

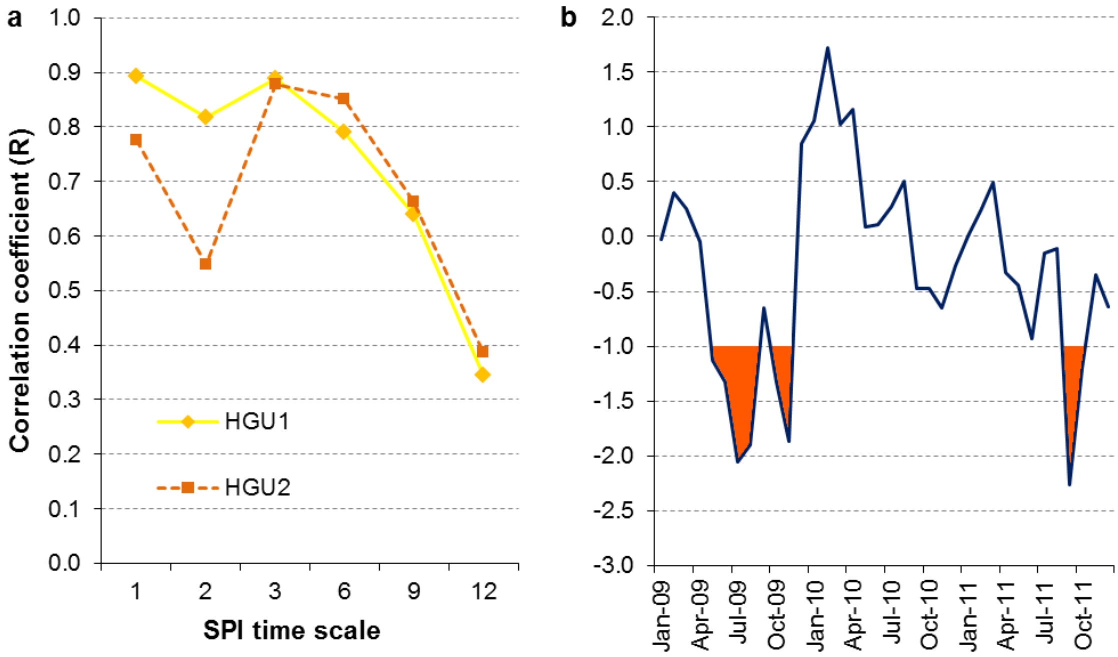

Fig. 3.2.6. Results of the correlation between spring discharges and SPI computed for different time scales (a) and SPI computed for time scale of 3 months (b). Orange areas indicate drought periods.

These results contrast with Fiorillo and Gaudagno (2010) findings. They found the best correlations between SPI and karst spring discharges for a time scale of 9 and 12 months. However, hydrogeological features of the karst system studied by these authors are different: over 600 km^2 wide and 2500 m thick vs. 41 km^2 wide and 40-100 m maximum thick in our study area. Additionally, they found a high density of fractures and fissures that yields poor development of karst conduits and thus a very low component of quick flow. Consequently, it seems that SPI remains useful when forecasting groundwater drought in smaller aquifers with faster response. Nevertheless, our research covered a time-frame of two years and these results must be taken with caution.

3.2.3.2. Hydrogeochemical characterization

a) Hydrogeochemical evolution in the Ompólveda River basin.

EC and SO_4^{2-} measurements in the springs did not show significant differences between seasons. Average values of EC in the HGUs were 500, 528 and 1691 µS/cm in the HGU1, HGU2 and HGU3, respectively. These EC differences matched up with the changes observed in SO_4^{2-} content: HGU1 and HGU2 springs always showed SO_4^{2-} concentrations below 100 mg/l (majority of them under 20 mg/l), while average SO_4^{2-} content in HGU3 springs was 707 mg/l. These results reveal the remarkable influence of the Lower Miocene deposits enriched in gypsum on water chemistry, as del Pozo (1998) suggested, and may suppose a threat to water quality (La Moneda González 1989). Maestro Salmerón et al. (1986) found a very similar average SO_4^{2-} concentration (730 mg/l) in springs located in Lower Miocene deposits from other areas of “La Alcarria” region. Figure 3.2.7 represents the average conductivity in the springs and in the selected sampling points of the hydrographic network and the limno-reservoir. It shows the increasing of EC in the springs towards the lower part of the basin, where the gypsum-enriched deposits surfaces. The river network becomes consequently affected, increasing the conductivity towards its outlet.

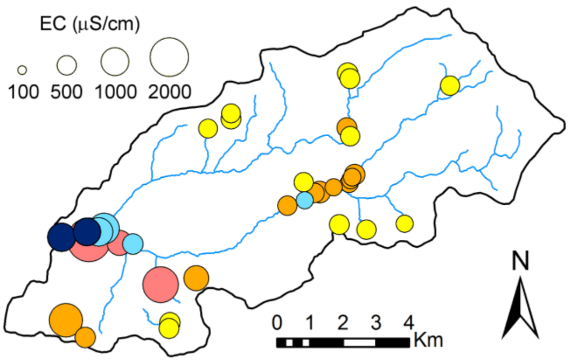

Fig. 3.2.7. Average electrical conductivity (EC, µS/cm) in the springs of HGU1 (yellow), HGU2 (orange) and HGU3 (pink) and other sampling points in the watercourses (light blue) and the limno-reservoir (dark blue)

Average concentrations of major ions were obtained for each sampling location and Stiff hexa-diagrams (Stiff 1951) were depicted and mapped (Fig. 3.2.8). All the springs located in HGU1 showed a dominance of Ca^{2+} and HCO_3^-, which was expected since water passes through the limestone aquifer. The concentrations of Mg^{2+}, Ca^{2+} and especially SO_4^{2-} increased towards the lower basin, as it was described for EC, and Ca^{2+} and SO_4^{2-} became the dominant ions. SO_4^{2-} concentration ranged from 14 mg/l in El Quemadal spring (nº 4) to 640 mg/l in the outlet of the Valdetrigo stream. On the other hand, maximum HCO_3^- average concentration was found in the upper part of the basin (321 mg/l in El Gamellón spring, nº 35) and the inflow zone of the limno-reservoir showed the minimum one (170 mg/l). K^+, Na^+ and Cl^- always showed very small concentrations. Chemical data was also presented by plotting them on a Piper trilinear diagram (Piper 1944) (Fig. 3.2.9). This diagram revealed the change from Ca^{2+}-HCO_3^- type to Ca^{2+}-SO_4^{2-} type. It also showed small increasing of Mg^{2+} over Ca^{2+} towards the outlet of the catchment. Since there is not magnesium lithology in the basin, it may reflect Ca^{2+}-Mg^{2+} ion exchange in the clayey deposits, which is in accord with the concept that in the homovalent system the preferentially adsorbed ion is usually the ion with smaller hydrated radius (Helfferich 1962).

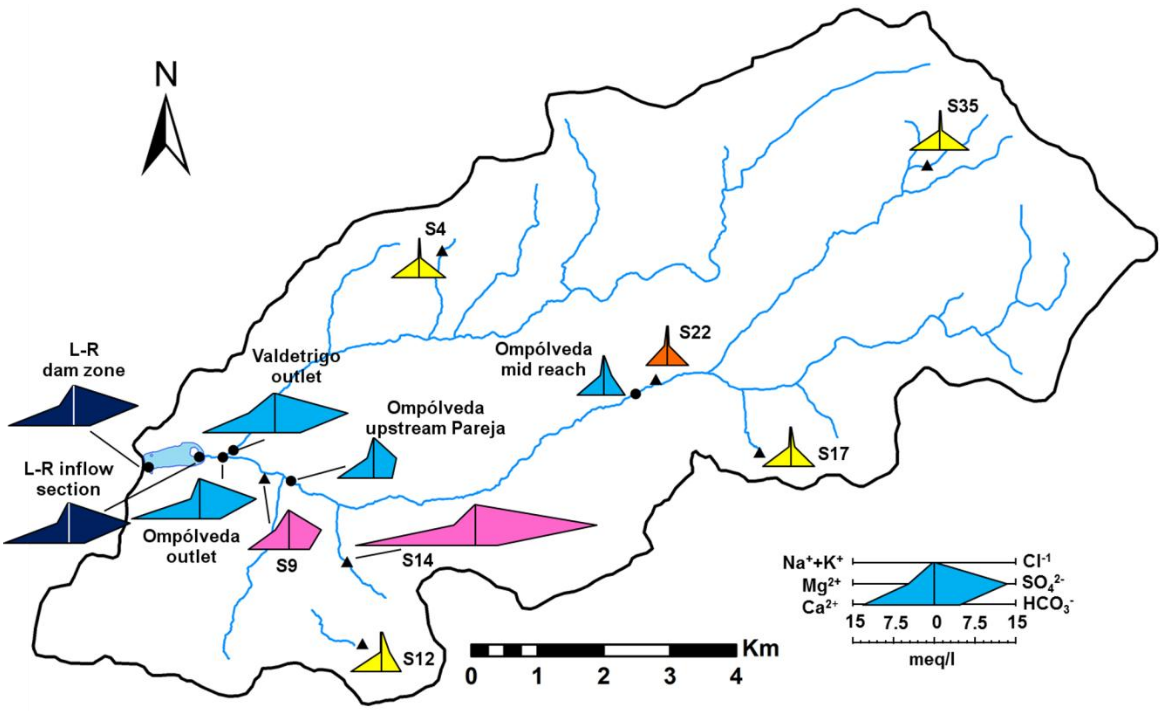

Fig. 3.2.8. Stiff hexa-diagrams of the average major ions composition in the Ompólveda River basin (yellow=springs in HGU1, orange=springs in HGU2, pink=springs in HGU3, light blue: watercourses, dark blue: limno-reservoir) (S = spring).

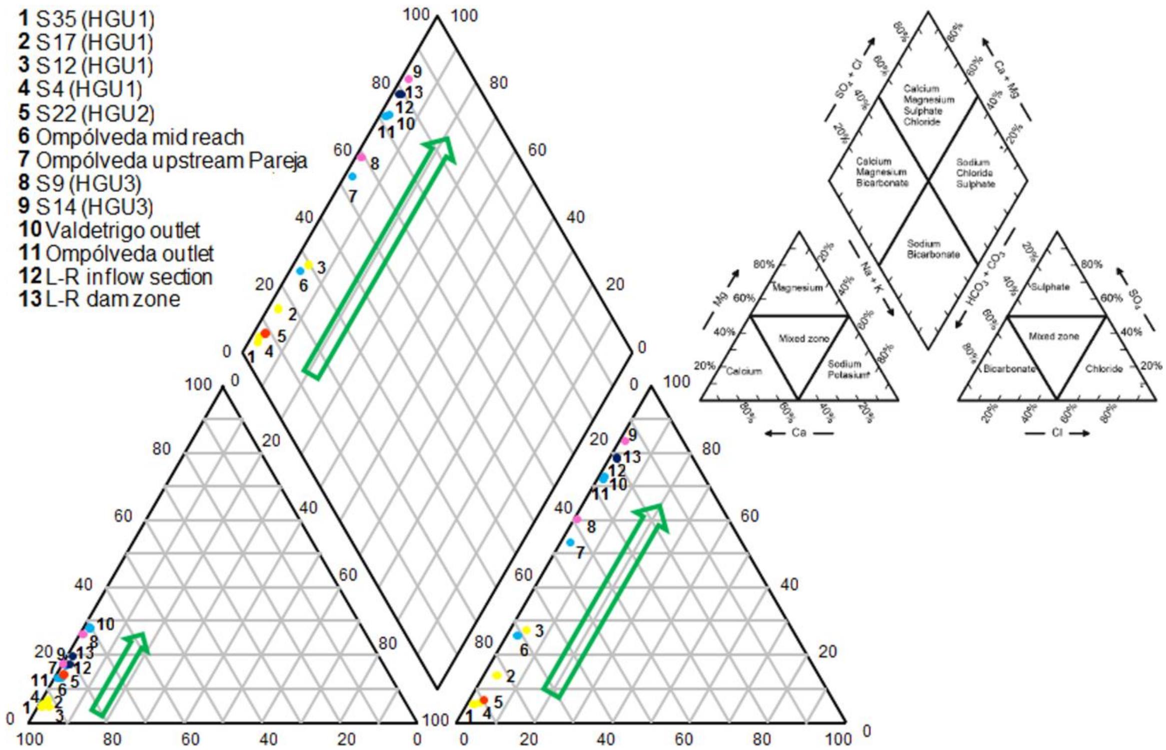

Fig. 3.2.9. Average major ions composition in the hydrogeochemistry sampling locations represented in a Piper trilinear diagram. Arrows indicate the water evolution towards the outlet of the basin (S = spring)

These results corroborate that water hydrogeochemistry in the Ompólveda River basin -with scarce anthropogenic activity- is primarily controlled by water-rock interaction (Krishna Kumar et al. 2012): Ca^{2+}-HCO_3^- type in the upper basin, related to water-limestone interactions, turning into Ca^{2+}-SO_4^{2-} type in the lower basin associated with the dissolution of gypsum.

Since calcite and gypsum seem to be the main mineral phases in the basin, their saturation indices (SI) were obtained (through geochemical modelling with PHREEQC Interactive) and mapped (Fig. 3.2.10). Calcite was always oversaturated (positive values) and may tend to precipitate, revealing the influence of the carbonate plateau in the hydrogeochemistry. The highest values of calcite SI were obtained around the inflow zone of the limno-reservoir. There, groundwater from HGU3 mixes with the Ompólveda River water and then calcite precipitation may be enhanced by the common-ion effect: Ca^{2+} contributed by gypsum dissolution causes calcite to precipitate during groundwater-surface water mixing (Jin et al. 2010). On the other hand, gypsum always showed a tendency to dissolve (negative values), so there was a possibility to further SO_4^{2-} concentration increase.

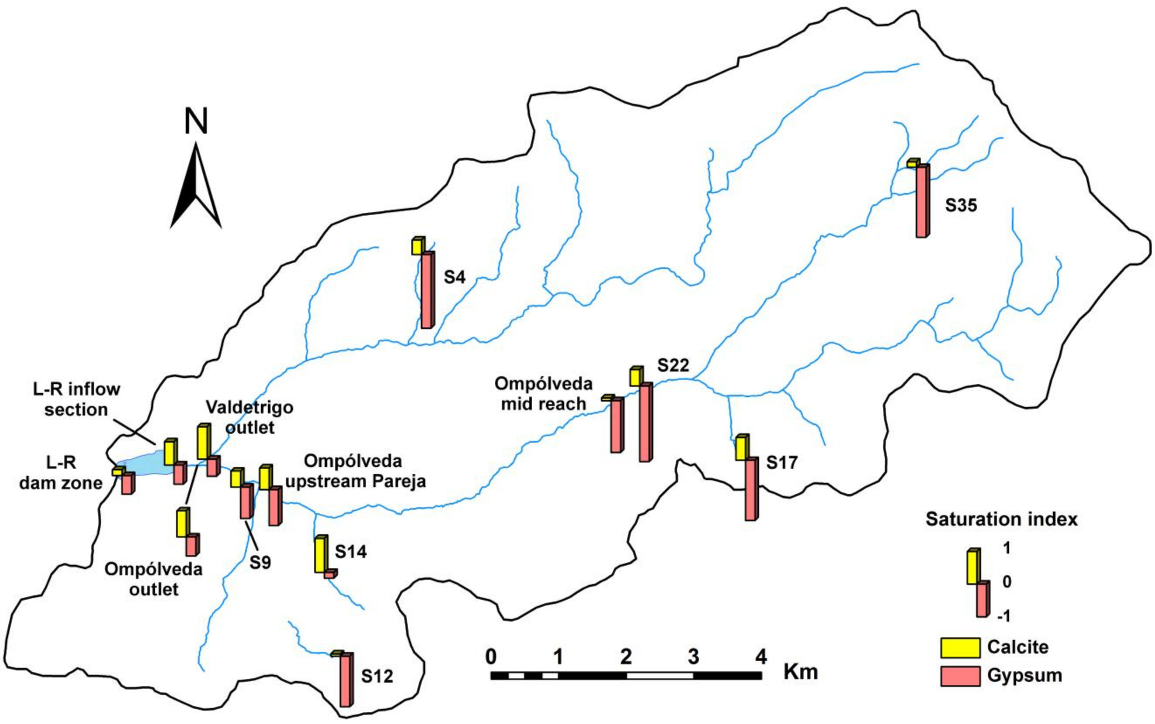

Fig. 3.2.10. Calcite and gypsum saturation indices estimated with PHREEQC Interactive (Parkhurst and Appelo 2013) in the Ompólveda River basin (S = spring)

Mineral phases mole transfer between rainfall and the upper aquifer (HGU1) and among different locations was estimated performing inverse modelling (Table 3.2.2). The Ca^{2+}-Mg^{2+} ion exchange observed in the Piper diagram (Fig. 3.2.9) was also included in the model, along with CO_2 to allow calcite dissolution. Inverse modelling confirms the hydrogeochemical framework proposed for the catchment. There is positive transfer (dissolution) of calcite from rainfall to HGU1, where becomes oversaturated, and then tends to precipitate. This precipitation supposes a slight decreasing of HCO_3^- concentration in the underlying HGUs. Gypsum dissolution is negligible in the upper basin (HGU1-HGU2), but very noticeable in the gypsum enriched HGU3, altering the chemical composition of the lower basin. A slight Ca^{2+}-Mg^{2+} cation exchange is observed between HGU1 and HGU2, which may be a sign of the clay presence in the aquitard. Mole transfer between this units and HGU3 revealed higher cation exchange, as it was anticipated after hydrogeochemical analyses (Fig. 3.2.9). The mole transfer between a mixture of HGU3 and river water and the dam zone of the limno-reservoir was also modelled. The precipitation of calcite in this transfer revealed again the common ion effect (Jin et al. 2010).

Table 3.2.2. Mole transfer (in mmol) obtained with inverse modelling with PHREEQC Interactive (Parkhurst and Appelo 2013). Positive values mean dissolution (or cation desorption) and negative values mean precipitation (or cation adsorption). % in the last row represents the fraction of each type of water used in the mixture.

	Calcite	Gypsum	CO_2	CaX2	MgX2
Rainfall – Spring 35 (HGU1)	2.37	0.18	2.89	-0.08	0.08
Spring 35 (HGU1) – Spring 22 (HGU2)	-0.62	-	-	-0.18	0.18
Spring 22 (HGU2) – Spring 14 (HGU3)	-	10.95	-	-1.74	1.74
Spring 35 (HGU1) – Spring 14 (HGU3)	-0.63	10.95	-	-1.93	1.93
Spring 14 (5.6%) + Ompólveda River outlet (94.4%) – Dam zone	-0.56	-	-	-	-

b) Hydrogeochemical patterns in the Pareja Limno-reservoir area

Since the Pareja Limno-reservoir was built to create a water body suitable for environmental and recreational purposes, an in-deep hydrogeochemical study was carried out there. Figure 3.2.11 shows the temporal evolution (spring 2008-summer 2011) of the EC and the predominant major ions concentrations (SO_4^{2-}, HCO_3^- and Ca^{2+}) in the Pareja Limno-reservoir samples and in the Ompólveda River outlet, besides the magnitude of runoff in the latter sampling point.

Figure 3.2.11 confirms that the variation in the ions provided by gypsum (SO_4^{2-} and Ca^{2+}) is the main driver of the EC variability in the Pareja Limno-reservoir. The same seasonal pattern in EC, SO_4^{2-} and Ca^{2+} was observed, increasing in summer and autumn and decreasing in winter and spring. It was especially noticeable in the Ompólveda River outlet. This pattern revealed the influence of runoff seasonality on water chemistry: River flow was the highest in winter, having an important percentage of surface flow that diluted SO_4^{2-} and Ca^{2+} yielded by the Lower Miocene deposits (HGU3). Consequently, EC decreased. When runoff was the highest (matching up with a wet year), dilution was high enough to turn the water type from Ca^{2+}-SO_4^{2-} into Ca^{2+}-HCO_3^- (winter 2010, river outlet and inflow section, figure 3.2.11). In summer and autumn, river discharge was essentially groundwater runoff, which is salt-enriched (Shanmugam and Ambujam 2012). The variation of other hydrological parameters (water residence time and channel velocity) may have also affected processes implicated in salt dissolution (Gómez et al. 2009). Evaporation may play a role in summer favouring salt enrichment in the limno-reservoir as well. The HCO_3^- concentration in the limno-reservoir remains more or less constant due to the calcite saturation already observed in the upper basin.

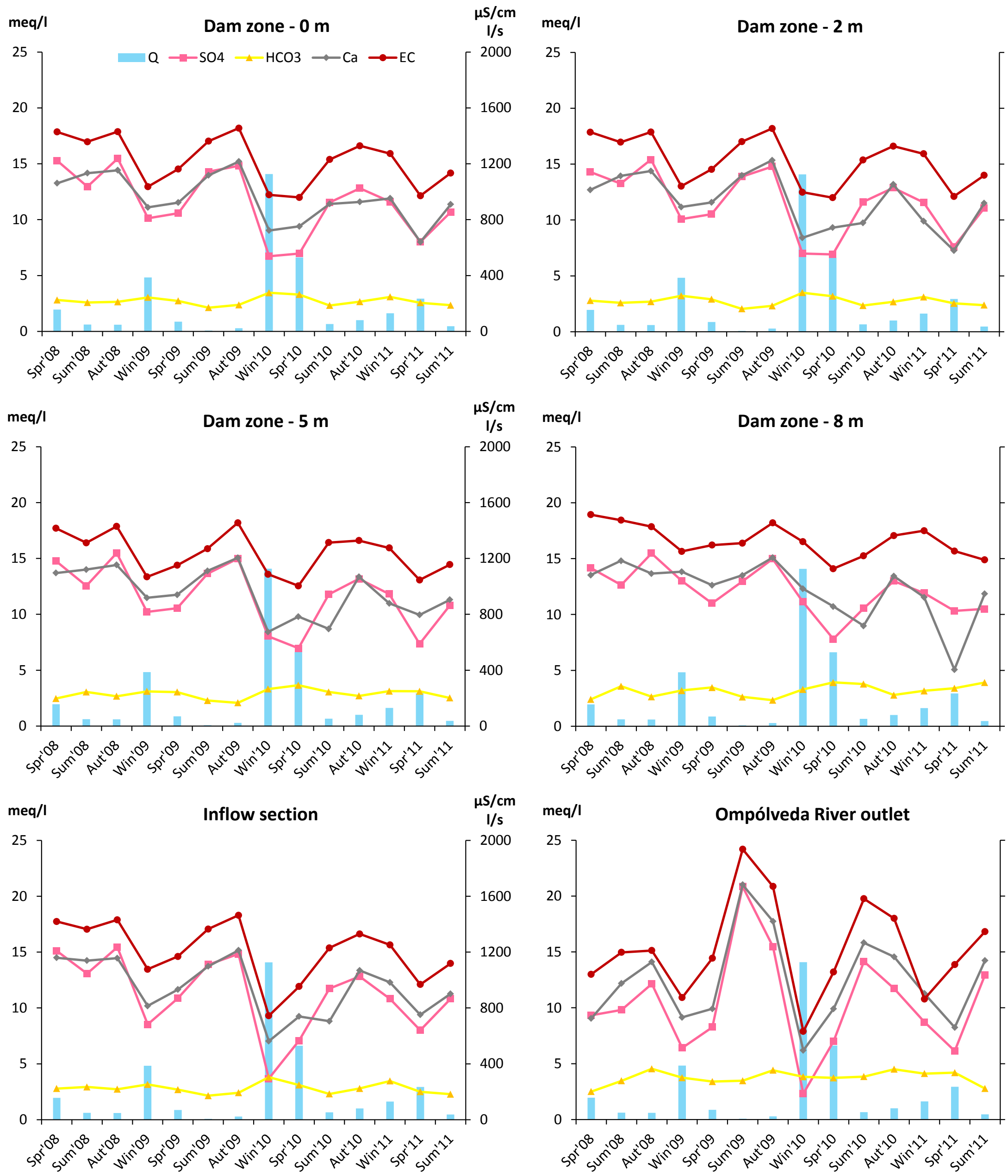

Fig 3.2.11. Temporal evolution of electrical conductivity (EC, µS/cm) and SO_4^{2-}, HCO_3^- and Ca^{2+} (meq/l) in the Pareja Limno-reservoir and in the Ompólveda River outlet. The Ompólveda River discharge (Q, l/s) is plotted in bars.

Figure 3.2.11 also reveals the buffer effect that the Pareja Limno-reservoir had in water hydrogeochemistry. The mixing of Ompólveda River discharge with water previously stored in the limno-reservoir softened the seasonal variations observed in the river outlet. This buffer effect was more noticeable in the dam zone than in the inflow section. Temporal profiles at 0, 2 and 5 m in the dam zone showed very similar patterns. At 8 m, seasonal variations were even softer. Two facts may have played an additional role in this buffer effect at 8 m depth: a higher resistance to water renovation and the possible existence of direct inputs of groundwater from the HGU3 in the bottom of the limno-reservoir. Further research could focus on these hypotheses.

Sánchez-Montoya et al. (2012) has recently established the physico-chemical reference conditions in Mediterranean streams according to the European Water Framework Directive. For evaporite-calcareous streams, reference value of EC was established in 585 µS/cm. Maximum EC registered in the river outlet in summer was higher than this reference value. This may suppose a threat to the water quality in the Pareja Limno-reservoir in summer, the season when this water body mainly serves its recreational functions. Thus, the buffer effect of the Pareja Limno-reservoir in hydrogeochemistry has special relevance to soften the increasing of EC in summer and, consequently, the worsening of water quality.

3.2.4. CONCLUSIONS

Average groundwater flow contribution derived by recharge estimation was around 60%, which confirms the quantitative importance of groundwater in the Ompólveda River basin. Three HGUs were defined: HGU1, corresponding to the carbonate plateau, and the underlying HGU2 and HGU3. The springs discharge monitoring results and the relationships of this discharge with the drought index SPI depicted a hydrogeological framework for the basin: HGU1 was found as the main aquifer, showing a relatively fast response to recharge. After recharge, spring discharge follows a continuous slow decreasing trend but maintaining a permanent flow during the dry period, which may favour the conservation of the limno-reservoir water level. HGU2 showed lower interannual variability and seems to behave as an aquitard. A consistent interpretation about HGU3 hydrogeology could not be done, but it showed a great impact on water chemistry, increasing SO_4^{2-} and Ca^{2+} concentrations. This hydrogeological behaviour matches up with previous descriptions done in similar areas and helps to improve the knowledge in this kind of hydrogeological systems.

Regarding hydrogeochemical features, weathering and dissolution of calcite and gypsum minerals seem to control the concentration of major ions in the basin. Hydrogeochemical facies in both groundwater and surface water evolves from Ca^{2+}-HCO_3^- in the upper basin to Ca^{2+}-SO_4^{2-} in the lower basin. Geochemical modelling confirmed this hydrogeochemical behaviour, revealing the calcite oversaturation in the whole basin, an increasing dissolution of SO_4^{2-} towards its outlet and the existence of Ca^{2+}-Mg^{2+} cation exchange. The main drivers of the EC variability in the limno-reservoir area were SO_4^{2+} and Ca^{2+}. A temporal pattern was observed. Lower salts enrichment occurs in winter favoured by high river discharge and higher ions concentration during the dry season, when the water input is mainly groundwater runoff. This pattern was especially remarkable in the Ompólveda River outlet, while in the Pareja Limno-reservoir showed a buffer effect.

The concluding remarks of this study should be taken into account when developing management options for the water resources on the Ompólveda River basin and the Pareja Limno-reservoir or any other area that projects the construction of a similar infrastructure. Special attention may be paid in summer, when the limno-reservoir mainly serves its recreational goals but when it suffers from water shortage and worsening of water hydrogeochemical quality.

3.2.5. Acknowledgments

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4. Water quality in the Pareja Limno-reservoir

4.1. Limnology, trophic state and zooplankton

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A. and Martín del Pozo, D. The limnological characteristics and zooplankton community of a newly created site: The Pareja Limno-reservoir. Published in *Limnetica* 31(1) (2012), 95–106.

Abstract

The creation of dams in the riverine zone of large reservoirs is an innovative action whose primary goal is to create water bodies that ensure a stable level of water there.. We have termed these bodies of water "limno-reservoirs" because their water level becomes constant and independent of the fluctuations occurring in the main reservoir. In addition, limno-reservoirs represent environmental initiatives with corrective and/or compensatory effects. Pareja Limno-reservoir, located near the left side of Entrepeñas Reservoir (Guadalajara province, central Spain), is one of the first initiatives of this type. We are investigating the hydrology, limnology, microbiology, siltation risk and other aspects of this site.

This paper focuses on the limnological study of the Pareja Limno-reservoir. To conduct this research, twelve seasonal sample collections at two sampling points (the dam and inflow zones) have been made in Pareja Limno-reservoir (spring 2008-winter 2011). The primary goal of this study is to describe the limnological characteristics of the limno-reservoir, with especial interest in the study of the zooplankton community.

The results of the study show that the Pareja Limno-reservoir follows a warm monomictic water stratification pattern. The highest nutrient concentrations were found in the winter, whereas the highest chlorophyll *a* and phytoplankton biomass values (dominated by *Bacillariophyta)* were found in the summer and autumn. The results obtained suggest that the Pareja Limno-reservoir is oligo-mesotrophic. The total zooplankton species richness was high, especially in the inflow zone. The most frequently found species are in agreement with those described in other studies performed on the Iberian Peninsula. Rotifers and copepods showed higher relative abundances than cladocerans.

Keywords: limnological characteristics, limno-reservoir, zooplankton.

Resumen

Los denominados diques de cola constituyen una actuación novedosa cuyo objetivo es generar una lámina de agua constante en sectores de cola de grandes embalses. Para dichas masas de agua hemos propuesto el término "limnoembalses", pues con ellos se genera permanencia en el nivel del agua frente a las variaciones inherentes a la gestión del embalse ordinario, suponiendo además una actuación ambiental de carácter compensatorio y/o corrector. El Limnoembalse de

Pareja, ubicado en la margen izquierda del embalse de Entrepeñas (provincia de Guadalajara, España central), es una de las primeras actuaciones de este cariz. Por ello, nuestro equipo está realizando estudios relacionados con el comportamiento hidrológico, limnológico, microbiológico y su riesgo de aterramiento, entre otros aspectos.

Este artículo se centra en el estudio limnológico del Limnoembalse de Pareja. Para llevar a cabo dicha investigación, se han realizado en dos puntos de muestreo (presa y cola) doce muestreos estacionales (primavera 2008-invierno 2011). El principal objetivo del estudio es describir las características limnológicas del limnoembalse, poniendo además especial interés en el estudio de la comunidad zooplanctónica.

Los resultados obtenidos muestran que el Limnoembalse de Pareja sigue una dinámica de lago monomíctico templado. Las concentraciones más elevadas de nutrientes se encontraron en invierno, sin embargo, los mayores valores de clorofila *a* y biomasa de fitoplancton (dominada por *Bacillariophyta*) fueron obtenidos en verano y otoño. Los resultados sugieren un estado oligo-mesotrófico de las aguas del limnoembalse. La riqueza total de especies de zooplancton fue elevada, especialmente en la zona de cola. Las especies más frecuentemente encontradas coinciden con aquellas descritas en otros lagos y embalses de la Península Ibérica. Los rotíferos y los copépodos mostraron abundancias relativas mayores que los cladóceros.

Palabras clave: características limnológicas, limnoembalse, zooplancton.

4.1.1. INTRODUCTION

The water levels of large reservoirs in areas with a Mediterranean climate vary widely due to exploitation and climatic conditions. These variations produce undesirable effects on the environment, on the landscape (including the “arid band” phenomenon) and on the socio-economic development of their surroundings. The Entrepeñas Reservoir (south of Guadalajara province, central Spain), with a capacity of 835 hm^3 and 3213 hm^2 of potential inundation area, is one of these reservoirs. In addition, this reservoir shows higher vulnerability because of the transfer of significant volumes of water to southeastern Spain. The inhabitants of the region began to demand corrective and/or compensatory actions for these environmental effects in the 1990s. In 2006, their protests led to the construction of a small dam in a sidearm of the Entrepeñas Reservoir, in its riverine zone, next to the village of Pareja, which allows the development of a small body of water with a constant level. Dams of this type are known as “riverine dams” or “flood dams” (incorrectly translated from Spanish as “edge dams” by Molina-Navarro *et al.*, 2010) and produce a body of water that is independent of the management of the main reservoir. We have termed these bodies of water “limno-reservoirs” because they resemble a lake more than a reservoir (Molina-Navarro *et al.*, 2010).

The first initiatives of this type in Spain were proposed in the late 1980s and the early 1990s. Their primary aim was the creation of a suitable habitat for birds (Rodríguez Cabellos, 1995; Ministerio de Medio Ambiente y Comité Nacional Español de Grandes Presas, 1996). Nevertheless, the Pareja Limno-reservoir is the first to have a dual function: environmental and recreational. It is open for swimming or for walking, and it has a jetty for motorless craft. These features promote the economic development of the area in terms of nature tourism. From an environmental perspective, it has two artificial islands that act as bird refuges. In addition, it has a fish ladder. No data describing this type of initiative worldwide have been found in the literature.

Because of the innovative nature of this water management initiative and coinciding with the end of the process of filling the reservoir, we have set up an environmental observatory at the Pareja Limno-reservoir. Our main aim is to study its feasibility from a multidisciplinary perspective. This project started in 2008 and is still being conducted. A number of studies are included in the project, including a monitoring program that addresses the physico-chemical, limnological, and microbiological aspects of the water body.

The limnological study is of particular interest in the light of the European Water Framework Directive (OJEU num. 327, 2000), whose objective is to achieve a "good ecological status" in every aquatic ecosystem by 2015. Hence, at the beginning of 2008, a sampling protocol was designed to monitor a large number of limnological variables. These variables included the water body's physicochemical characteristics, nutrient content, transparency, chlorophyll *a* content and taxonomic determinations of phytoplankton and zooplankton.

The purpose of this paper is to describe the physico-chemical and biological characteristics of the Pareja Limno-reservoir by studying the stratification patterns, the main limnological parameters, the trophic state and the phytoplankton population dynamics of the water body. However, particular emphasis is placed on the study of the zooplankton community, as recent zooplankton studies in Iberian lakes and reservoirs are scarce (e.g., Conde-Porcuna *et al.*, 2004; Baião & Boavida, 2005; Parra *et al.*, 2009). The richness and the relative abundance of the different species in the three primary groups (copepods, rotifers and cladocerans) and the seasonality of these groups of zooplankton were investigated in this study.

4.1.2. MATERIALS AND METHODS

4.1.2.1. Study site

The Pareja Limno-reservoir is adjacent to the village of the same name, southern Guadalajara province (Spain) at the head of the Tajo River Basin (Fig. 4.1.1). It has a capacity of 0.94 hm^3 and a potential inundation area of 26 hm^2. Its maximum depth is approximately 9 m near the dam[5]. It becomes progressively shallower towards the inflow section, where it measures 1.5 m. It is fed by the Ompólveda River, which has an 87.8 km^2 basin. The main tributary of the river is the Valdetrigo stream, which flows from the northeast.

[5] A further more accurate study showed that the maximum depth is around 12.5 m

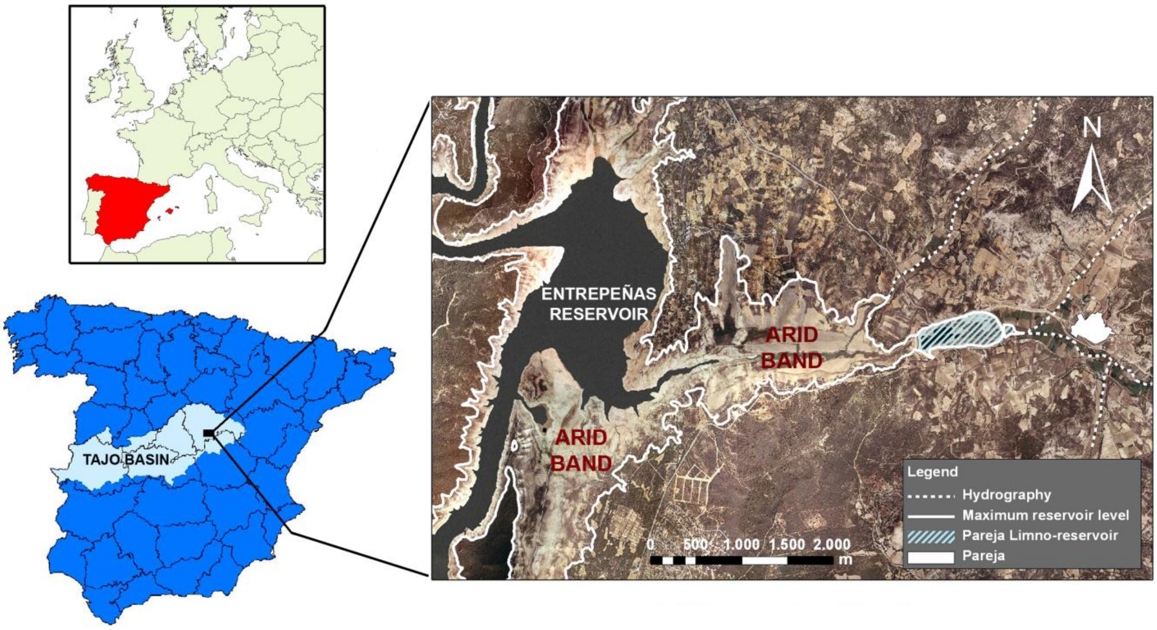

Fig. 4.1.1. The location of the Pareja Limno-reservoir and a comparison of the volume of water stored in the Entrepeñas reservoir in 2006 with its maximum capacity (modified from Molina Navarro *et al.*, 2010).

4.1.2.2. Sampling strategies

The sampling and laboratory analyses were performed in collaboration with a specialised team of the Centro de Estudios Hidrográficos (Spanish Ministry of the Environment). Twelve sample collections were made seasonally. These collections began at the beginning of the study in spring 2008 and ended in winter 2011. Two sampling points were selected. One of these points was located next to the dam of the limno-reservoir, and another was located in the inflow section. All of the samples were collected between 10:00-11:30 am.

Samples of 250 ml were collected in plastic bottles from the surface of the water body to analyse nitrogen compounds, whereas 100 ml sterile plastic containers were used to collect samples for total phosphorus (TP) determinations. Samples for geochemical analyses were collected in 125 ml plastic bottles. Depth profiles of temperature, pH, dissolved oxygen and conductivity were measured in 1 m increments with a YSI 6920 Multi-Parameter Water Quality Sonde probe (YSI Incorporated, Yellow Springs, OH, USA). During the 2009-2010 hydrological year, nearly monthly profiles of temperature and dissolved oxygen were made to better determine the stratification pattern. The transparency of the water body was measured using a Secchi disk in the two selected sampling sites. To analyse chlorophyll *a* (CHL *a*) concentrations, 1 l samples were collected and filtered *in-situ* with Whatman GF/F 47 µm filters. A vacuum pump was connected to a car battery and used with a Millipore funnel. Subsequently, the filter was kept in tubes of dry ice and transported to the laboratory.

To analyse the phytoplankton, 250 ml samples were collected in dark glass containers from the surface of the water body in the inflow and dam zones. The samples were fixed with acid Lugol's iodine. Zooplankton samples were collected with a 55 μm mesh size net at the same sampling points. To collect these samples, the entire water column was sampled in the inflow zone. In the dam zone, vertical hauls were made from depths between the surface and approximately one metre from the bottom to avoid the effect of vertical migrations. At both sampling points, horizontal samples were also collected between depths of 1 and 2 metres. The net contents in each zone were combined to produce a unique sample. The sample was fixed with acid Lugol's iodine for transportation and preservation.

4.1.2.3. Sample analysis

Nitrogen compounds (nitrate, nitrite, and ammonia) were analysed *in-situ* with a LASA 100 portable photometer (HACH LANGE LTD, Manchester, UK). TP was determined in the laboratory following standard procedures with the LASA DR 2800 photometer method (HACH LANGE LTD, Manchester, UK). The geochemical analyses were performed by the "Centro de Análisis de Aguas S.A." laboratory. CHL *a* was extracted from filters with 90 % acetone (15 ml, kept in the dark for 24 hours) and measured using the Parsons and Strickland formula (1965).

Phytoplankton samples were analysed with the Utermöhl technique (Utermöhl, 1958) and a Leica DMRIB microscope (Leica Microsystems, Wetzlar, Germany). A total of 25 or 50 ml of the samples was allowed to settle depending on the content of inorganic matter. The largest species were counted at 100, 200 or 400× (depending on their size and density), and the smallest were counted at 1000×. For the species counted at 100×, the entire surface of the chamber was examined. For 200× or more, phytoplankton individuals were counted in transects or per field to achieve a total of at least 100 for the most common species (if possible). After settling, the zooplankton samples were analysed with a Leica Labovert microscope (Leica Microsystems) under a magnification of 100 to 400×. Taxonomic determinations were made at the species level in the three primary zooplankton groups (copepods, rotifers and cladocerans). These identifications were based on several sources, including Dussart (1964), Koste (1978) and Alonso (1996). A total of 10 ml of a fixed and homogenised sample was settled after every sampling survey. A taxonomic determination was performed for all zooplankton individuals found in the settling chamber. A semi-quantitative analysis of the settled sample was also performed with the Utermöhl technique.

4.1.2.4. Data analysis

Carlson's (1977) Trophic State Index (TSI) was calculated from the CHL *a* and TP concentrations found at the dam and inflow zones of the Pareja Limno-reservoir. The limiting values specified in the trophic classification system of the OECD were also incorporated in the analysis (OECD, 1982), as were considerations of nitrogen compounds (e.g. Camargo & Alonso, 2006).

To calculate the algal biovolume, the dimensions of at least 20 individuals per species (cells, filaments or colonies) were measured at 400 or 1000× magnification. Each species was assigned a geometric shape. The appropriate dimensions (length, width and diameter) were measured and used in formulae to calculate the cell volume. The measurements were made by image analysis with the LAS (Leica Application Suite) program. A number of the geometric shapes in Rott (1981) and Edler (1979) were used for reference. An abundance category was assigned to each zooplankton species according to the species' relative abundance. The categories of "low", "mid", "high" or "very high" were used for species whose individuals represented 0-5 %, 5-15 %, 15-40 % or >40 %, respectively, of the total number of zooplankton individuals found in the settling chamber (the sample collected in autumn 2009 in the inflow zone showed an exceptionally low zooplankton density; only two zooplankton species were found and were assigned to the "low" and "mid" categories).

4.1.3. RESULTS AND DISCUSSION

4.1.3.1. Physico-chemical and biological characteristics

Figures 4.1.2a and 4.1.2b show the depth-time distributions of the isopleths of temperature and dissolved oxygen, respectively, in the dam zone of the Pareja Limno-reservoir. The summer temperature stratification begins to disappear at the beginning of autumn. A period of vertical mixing follows. This period ends at the beginning of spring, when stratification begins again. The distribution of dissolved oxygen generally follows the temperature pattern. However, the dissolved oxygen concentrations decrease during the late winter and early spring at the bottom of the limno-reservoir. It is probable that high precipitation caused cool, silt-laden runoff from the Ompólveda River to flow into the hypolimnion. The decomposition of the organic matter in the suspended solids may explain the decrease in the oxygen concentrations (Molina-Navarro *et al.*, 2011). This phenomenon is discussed in Hobson *et al.* (2010).

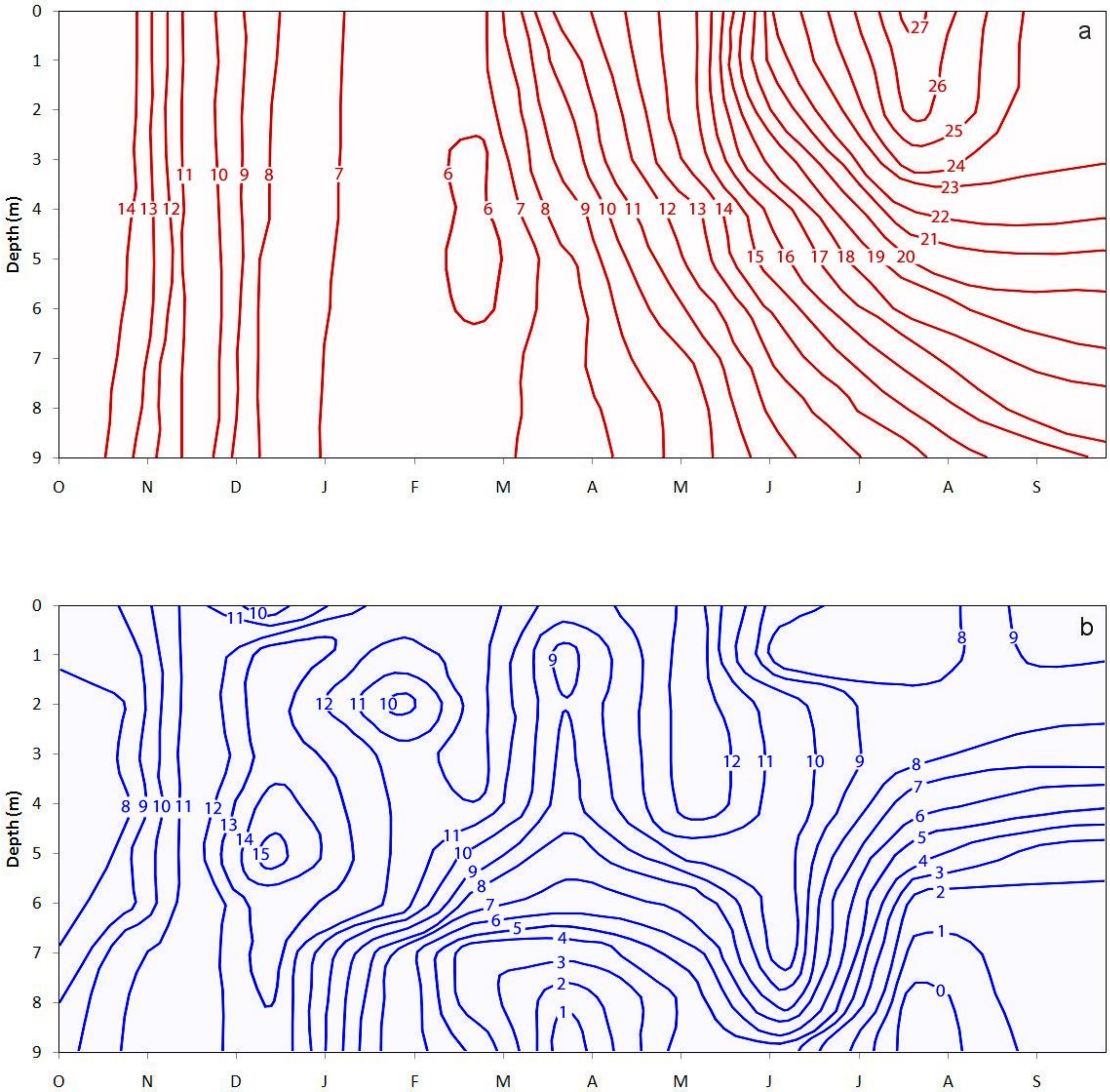

Fig. 4.1.2. Depth-time distributions of isopleths of temperature (◦C) (a) and dissolved oxygen (mg/l) (b) in the dam zone of the Pareja Limno-reservoir during the hydrological year 2009-2010.

The mean seasonal values for the principal limnological parameters at the surface at both sampling points are shown in Table 4.1.1. The results obtained were generally similar in the dam and the inflow zones. The water was slightly alkaline, with pH ranges of 7.3-8.4 in the dam zone and 7.5-8.4 in the inflow zone. The conductivity values oscillated between 959 µS/cm and 1455 µS/cm in the dam zone, whereas the range of conductivity values in the inflow zone was 744-1464 µS/cm. Temporal differences in conductivity were observed. Lower values of conductivity occurred during the spring and winter, whereas higher values occurred during the summer and autumn (Table 4.1.1) due to the summer drought and the predominance of base flow. The water was sulphated-calcic, with average concentrations of SO_4^{2-} and Ca^{2+} of 561 mg/l and 262 mg/l, and it was calcite-saturated.

Table 4.1.1. Average seasonal values for the main physico-chemical and biological parameters in the Pareja Limno-reservoir.

	Dam Zone				Inflow Zone			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
Temperature (ºC)	17.3	24.6	10.4	7.1	17.0	24.6	10.4	7.7
Dissolved O_2 (mg/l)	10.5	9.4	10.7	12.5	10.9	8.9	10.6	12.3
pH	8.0	7.5	7.7	7.7	8.1	7.7	7.9	7.9
Conductivity (µS/cm)	1183	1317	1405	1096	1181	1320	1408	1024
Ionic composition type	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca
N-NO_3^-	<0.31	<0.23	<0.23	1.220	<0.31	<0.23	<0.23	<0.64
N-NO_2^-	<0.015	<0.015	<0.015	<0.024	<0.017	<0.018	<0.016	<0.015
N-NH_4^+	0.070	0.072	0.111	0.027	0.065	0.079	0.113	0.290
TP (mg/l)	<0.015	<0.015	<0.010	<0.017	<0.013	<0.023	<0.013*	<0.052
Secchi depth (m)	2.57	1.23	1.87	1.66	1.38	0.71	1.03	1.03
Chlorophyll a (µg l^{-1})	1.30	1.93	2.28	1.16	1.20	3.52	2.38	1.73
Phytoplankton biomass (mg/l)	0.24	0.79	0.63	0.16	0.38	0.81	0.53	0.12

* It was not possible to detect TP in autumn 2009 because of the interference of another chemical compound in the analytic method.

Table 4.1.1 also shows the mean seasonal nutrient concentrations. The nitrate (N-NO_3^-) and nitrite (N-NO_2^-) concentrations were usually below the detection levels (0.23 mg/l and 0.015 mg/l, respectively). Except for a peak of 0.809 mg/l during winter 2009 in the inflow zone, the ammonium (N-NH_4^+) concentrations always ranged between 0.023 mg/l and 0.179 mg/l. The highest concentrations of nitrogen compounds were found during the winter, when the Ompólveda River has its highest flow volume and increases the nutrient load into the limno-reservoir. According to the criteria in Dodds *et al.* (1998) and Camargo & Alonso (2006), the nitrogen concentrations in Pareja Limno-reservoir indicates oligotrophic waters except during those winters when the Ompólveda River has a high flow volume. Dodds *et al.* (1998) suggest that the upper limit of total nitrogen for eutrophic temperate lakes is 1.26 mg/l, whereas Camargo & Alonso (2006) state that total nitrogen levels lower than 0.5- 1.0 mg/l may prevent aquatic ecosystems from developing eutrophication.

The total phosphorus (TP) concentrations ranged from the detection level (0.010 mg/l) to 0.035 mg/l, with a peak of 0.110 mg/l during winter 2010. During this season, the Ompólveda River had its highest flow volume. The water transparency was always higher in the dam zone than in the inflow zone (Table 4.1.1). The range of CHL *a* concentration was generally 1-4 µg/l and showed higher values during the summer and autumn than during the winter and spring. According to OECD criteria (OECD, 1982), the TP concentrations were in the oligotrophic (<0.01 mg/l) and mesotrophic (0.01-0.035 mg/l) ranges (except for winter 2010). The CHL *a* mean and maximum were 1.9 µg/l and 6.23 µg/l, respectively. Both values were in the oligotrophic range (<2.5 µg/l for mean CHL *a*, <8.0 µg/l for maximum annual peak). However, the mean and minimum values of the Secchi depth in the dam zone were 1.83 m and 1.1 m, respectively. These values were in the eutrophic range (3-1.5 m for the mean Secchi depth and 1.5-0.7 m for the annual minimum). Nevertheless, in lakes and reservoirs receiving high amounts of nonalgal particulate matter, Secchi disk transparency measurements might be expected to produce erroneous values (Carlson, 1977). This caveat applies to Pareja Limno-reservoir. Caramujo & Boavida (2000) and Baião & Boavida (2005) determined that the same caveat applied to the Secchi depth measurements in the Tajo River Basin reservoirs. Carlson's Trophic State Index (TSI) (Carlson, 1977) was calculated for the CHL *a* and TP concentrations. These values varied between 24.2 and 48.5 for CHL *a* and between <37.4 and 55.4 for TP (with the exception of the winter 2009 peak, which gave a TSI value for TP of 72.0). According to the Carlson model, Pareja Limno-Reservoir could be classified as mesotrophic (35-55) or even oligotrophic (25-35).

The results obtained suggest oligo-mesotrophic conditions in Pareja Limno-reservoir. This finding is consistent with the characteristics of the Ompólveda River Basin. The river is at the head of the Tajo River Basin, and eutrophication was not expected in Pareja Limno-reservoir. The phytoplankton community was also studied in Pareja Limno-reservoir. The mean seasonal phytoplankton biomass values are shown in Table 4.1.1. Figure 4.1.3 shows the distribution of the different groups (in percentage of biomass) in the dam and the inflow zones.

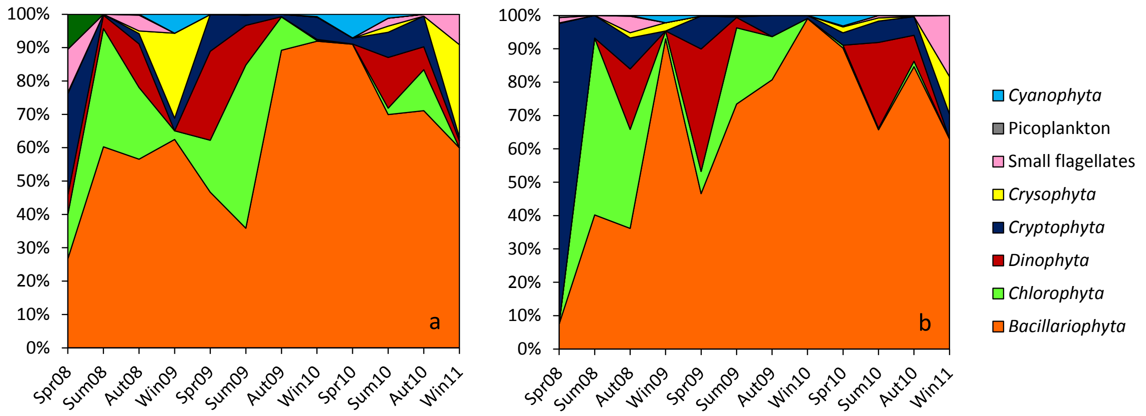

Fig. 4.1.3. The distribution of phytoplankton groups (as a percentage of total biomass) during the study in the dam (a) and inflow (b) zones of the Pareja Limno-reservoir.

The phytoplankton biomass was higher during the summer and autumn than during the spring and winter, in agreement with the higher concentrations of CHL *a*. The biomass values during the summer are a result of higher water temperatures, thermal stability and the enhanced light climate, whereas the values during the autumn respond to the beginning of the mixing period and the subsequent resuspension of nutrients and sunken algae in the limno-reservoir (Margalef, 1978; Reynolds, 1984; Souza *et al.*, 2008; Hoyer *et al.*, 2009). The total phytoplankton biomass and the distribution of groups were similar in the dam and the inflow zones. *Chlorophyta* showed the highest biomass during summer 2008 and 2009. This group was dominant in the inflow zone in 2008 and in the dam zone in 2009. *Cryptophyta* were dominant in both zones in the first sample (spring 2008). *Bacillariophyta* (diatoms) were the most abundant taxonomic category and dominated the remainder of the samples. *Dinophyta* species were abundant in a number of samples but showed no clear temporal pattern. The representative species included *Planctonema lauterbonii* and *Oocystis spp.* for *Chlorophyta*, *Cryptomonas spp.* and *Plagioselmis nannoplanctica* for *Cryptophyta*, *Cyclotella spp.* and *Cyclotella ocellata* for *Bacillariophyta* and *Ceratium hirundinella* for *Dinophyta*.

4.1.3.2. Zooplankton richness and relative abundance

In total, 32 zooplankton species belonging to the three principal zooplankton groups (rotifers, copepods and cladocerans) were found in Pareja Limno-reservoir. These species included 17 rotifers, 13 cladocerans and only 2 copepods (Fig. 4.1.4). The total richness in the dam and inflow zone was the same for rotifers (13 species were found in both zones, but different species compositions were found in the two zones) and copepods (2 species), whereas the total richness of cladocerans was higher in the inflow zone (13 species) than in the dam zone (7 species). However, the average richness in each sample was 8 and 9 species in the dam and inflow zones, respectively. These results showed that the group of species present at each sampling time was variable. These findings are consistent with the statement by Margalef (1983) that zooplankton communities are usually composed of a small number of species. Rarefaction techniques were not used to determine the richness of the zooplankton. However, this methodological choice of rarefaction may not affect the results of the study because all zooplankton individuals found in the settling chamber in each sample were identified to obtain the richness value. The principal species found in Pareja Limno-reservoir are consistent with those described by other studies performed on the Iberian Peninsula (Armengol, 1978; Colomer, 2001; Conde-Porcuna *et al.*, 2002; Baião & Boavida, 2005). This similarity holds even for the species described by Margalef (1983) for a group of reservoirs that includes Entrepeñas Reservoir, which is adjacent to Pareja Limno-reservoir.

Colomer (2001) surveyed 77 Spanish reservoirs. For each reservoir, three sample collections were made at two sampling points, the dam and the inflow. The average number of species per reservoir was 23±6. The relatively small size of the limno-reservoir may tend to produce a decrease in the number of species (Colomer, 2001; Wetzel, 2001). In view of this tendency, the number of zooplankton species in Pareja Limno-reservoir would seem to be relatively high. Moreover, it appears that the zooplankton community was not limited by the nutritional quality of the phytoplankton because diatoms (*Bacillariophyta*), whose nutritional quality is high (Conde-Porcuna *et al.,* 2004), dominate the phytoplankton community. Although Pareja Limno-reservoir resembles a lake more than it resembles a reservoir, the comparison with reservoirs is appropriate. The zooplankton communities are very similar in both systems and studies of Iberian lakes are scarce (Spain has a few lakes and more than 1400 reservoirs) (Margalef, 1983; Colomer, 2001).

The analysis of rotifers showed that certain species, such as *Polyarthra dolichoptera*, *Synchaeta pectinata* and *Asplanchna priodonta*, occurred in most of the samples. *P. dolichoptera* and *S. pectinata*, absent from the dam zone in the first samples, showed the highest values of relative abundance (Fig. 4.1.4). These species are phytophagous and feed primarily on *Cryptophyta*, *Chrysophyta* and central diatoms (Pourriot, 1970, 1977), which dominate the phytoplankton community of Pareja Limno-reservoir. Both species are cold stenotherms and have been found to exhibit maxima at low temperatures (de Manuel, 2000). This pattern can be observed in Pareja Limno-reservoir, especially in the dam zone. In contrast, *A. priodonta* (very frequent in Spain) is eurythermic polyphagous and even predatory (Margalef, 1983; de Manuel, 2000; Wetzel, 2001). This species feeds on diatoms, dinoflagellates and other rotifers, such as *Keratella cochlearis* and *P. dolichoptera* (Guiset, 1977), which showed an important presence in Pareja Limno-reservoir.

Keratella species, which feed on algae, organic detritus and bacteria and tolerate a wide range of conductivities (de Manuel, 2000), were alsopresent. *K. quadrata* was the first of these species to appear. It was subsequently replaced by *K. cochlearis cochlearis* or *K. cochlearis tecta* (the latter species only in the dam zone). This segregation between these two species was previously described by Margalef (1983). Another species found in many samples is *Hexarthra fennica*, described as euryhaline (i.e., tolerant of high conductivity) and seasonal. The highest relative abundances of this species were found during the summer, but a high relative abundance was also found during winter 2010. Other rotifer species occured only sporadically in the Pareja Limno-reservoir. Most of these species were found only in the dam zone or only in the inflow zone (Fig. 4.1.4).

Only two species of copepods, *Copidodiaptomus numidicus* (calanoid) and *Tropocyclops prasinus* (cyclopoid), were found in Pareja Limno-reservoir. However, these species occurred in most of the samples. Their copepodite and naupliar stages were also identified (the naupliar stages of the two species were not differentiated). Zooplankton communities in Spanish reservoirs are generally composed of one diaptomid species (*C. numidicus* is the most abundant) and one or two cyclopoid species, one of which is carnivorous (Margalef, 1983). This finding generally agrees with the results from Pareja Limno-reservoir except for the absence of the carnivorous cyclopoid.

The naupliar stage showed the highest relative abundances in the copepods sampled (Fig. 4.1.4). This stage is favoured if the temperature, dissolved oxygen or food availability decrease. This stage is also favoured during the summer because it allows copepods to avoid fish predation (Wetzel, 2001). A comparison of the two copepod species present showed that *C. numidicus* generally exhibited higher relative abundances than *T. prasinus*. This difference was particularly evident during the second half of the study, when *T. prasinus* was not present in a number of samples. *T. prasinus* is herbivorous (not a filter-feeder), and microfiltering cladocerans have been found to replace herbivorous copepods in Spanish reservoirs (Margalef, 1983).

Cladocerans showed the lowest relative abundances of the three groups of zooplankton. In general, rotifers and cladocerans (especially *Daphnia* species) share the same food resources (Wetzel, 2001; Conde-Porcuna *et al.,* 2004). Therefore, high relative abundances of rotifers produce a decline in of cladoceran populations. Only one or two *Daphnia* species were present in most of the samples, as is usually the case in Spanish reservoirs (Margalef, 1983). *D. longispina* and *D. galeata* were the main representatives of the genus. *Chydorus sphaericus*, a macrofiltering species (as are *Daphnia* species) is also present in a number of samples, especially in the inflow zone.

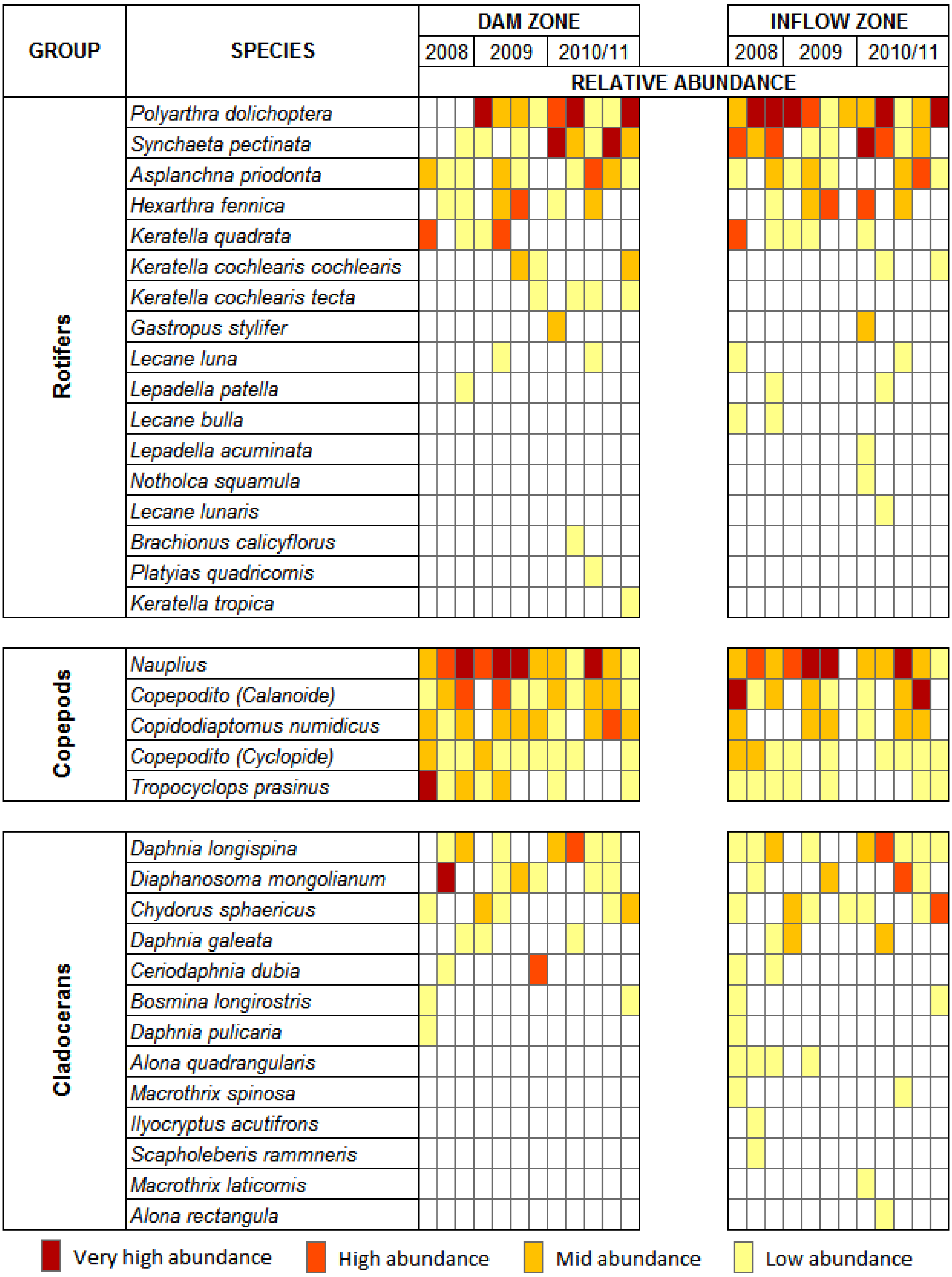

Fig. 4.1.4. Presence and relative abundance of zooplankton species present during the study (spring 2008-winter 2011).

The microfiltering *Diaphanosoma mongolianum* was found particularly during the summer, as Margalef (1983) and Caramujo & Boavida (2000) have previously described. Other microfiltering species present (only in two samples per zone) are *Ceriodaphnia dubia* and *Bosmina longirostris*. The first species is described as sporadically present in Spanish reservoirs, whereas the second is cosmopolitan but is found in more eutrophic conditions (Margalef, 1983; Caramujo & Boavida, 2000). Many other cladoceran species were sporadically present only in the dam zone of the limno-reservoir and primarily in the first samples (Fig.4.1.4).

Finally, although the value of zooplankton as an indicator of the trophic state is lower than the value of phytoplankton (Colomer, 2001), a number of findings about the zooplankton community of the Pareja Limno-reservoir suggest the oligo-mesotrophic state described above. These findings include the following: a high species richness (Colomer, 2001); a higher relative abundance of *Copidodiaptomus numidicus* (calanoid) than *Tropocyclops prasinus* (cyclopoid) (Maier, 1996; Caramujo & Boavida, 2000; Parra *et al.*, 2009); the absence of carnivorous copepod species (Caramujo & Boavida, 2000); and the scarcity of *Bosmina longirostris* (Margalef, 1983; Caramujo & Boavida, 2000). Nevertheless, these findings should be regarded cautiously, and further research should be performed in the Pareja Limno-reservoir to better determine the nature of the relationship between the zooplankton community and the trophic state of the water body.

4.1.4. CONCLUSIONS

The Pareja Limno-reservoir showed a warm monomictic stratification pattern, with one period of vertical mixing starting at the beginning of the autumn and one period of stratification starting at the beginning of the spring. The waters were sulphated-calcic and slightly alkaline. These waters showed conductivity values ranging from 744 to 1464 μS/cm.

The highest nutrient concentrations (nitrogen compounds and total phosphorus) were generally found during the winter, whereas the maximum CHL *a* values occurred during the summer and the autumn. The results of the trophic classification and the TSI index suggested an oligo-mesotrophic state in the Pareja Limno-reservoir. The phytoplankton biomass was greater during the summer and autumn than during the spring and winter. The *Bacillariophyta* represented the dominant taxonomic group in the phytoplankton community, followed by the *Chlorophyta*, *Cryptophyta* and *Dinophyta*.

Thirty two zooplankton species were found in the Pareja Limno-reservoir. This level of species richness is high compared to that in other Spanish reservoirs. The total species richness was higher in the inflow zone than in the dam zone as a result of a higher richness of cladoceran species. The most representative species found are similar to those described by previous studies conducted on the Iberian Peninsula. *Polyarthra dolichoptera*, *Synchaeta pectinata* and *Asplanchna priodonta* showed the highest relative abundances among the rotifers found. These species are well adapted to the Pareja Limno-reservoir because of their feeding requirements. Rotifers and cladocerans generally share the same food resources. A high relative abundance of rotifers may produce a decrease in the cladoceran populations. In our study, cladocerans showed the lowest relative abundances of the groups investigated. Only two copepods, *Copidodiaptomus numidicus* and *Tropocyclops prasinus* were present. The former species generally showed a greater relative abundance.

4.1.5. Acknowledgements

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4.2. Phytoplankton and ecological status assessment

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A., Verdugo-Althöfer, M. and Padisák, J. Phytoplankton and ecological status assessment in accordance with the Water Framework Directive in a new type of waterbody: limno-reservoir. Submitted to *Lake and Reservoir Management* on 11/02/2013 and currently under review (Manuscript ID: ULRM-2013-0004)

Abstract

"Limno-reservoirs" are small waterbodies with a constant water level which are constructed in the riverine zone of large Mediterranean reservoirs to mitigate the undesirable effects of reservoir operation. The Pareja Limno-reservoir was among the first limno-reservoirs built, and its purposes are environmental and recreational. Phytoplankton is one of the compulsory biological indicators used to estimate ecological status in lakes and reservoirs in accordance with the EU Water Framework Directive (WFD). Chlorophyll *a* (Chl- *a*) and phytoplankton biomass in the Pareja limno-reservoir were studied between spring 2008 and winter 2011. Phytoplankton composition was analyzed employing the functional group approach. Biomass (Chl- *a* and biovolume) and composition metrics (contribution of cyanobacteria, IGA -Índex de grups algals- and MedPTI -Mediterranean Phytoplankton Trophic Index-) proposed in the first WFD Intercalibration exercise were applied to assess the ecological status of the limno-reservoir, as well as the Assemblage (Q) Index. Phytoplankton composition was dominated by centric diatoms from functional group **B**, although they were replaced by other groups in some periods, responding to environmental changes. Biomass metrics and contribution of cyanobacteria suggested mainly a *Good* -or better- ecological status, while the other composition metrics suggested mainly a *High* ecological status. Checking the response of the composition metrics to a trophic gradient, none of them showed high accuracy. This fact may have relevant management implications for small Mediterranean lakes and reservoirs, since the determination of their ecological status may be imprecise. Consequently, we suggest the need for a new Intercalibration exercise for phytoplankton which includes these waterbodies.

Key words: ecological status, limno-reservoir, Mediterranean, phytoplankton, Water Framework Directive.

Resumen

En los sectores de cola de grandes embalses mediterráneos, la construcción de limnoembalses (pequeñas masas de agua diseñadas para mantener un nivel constante) pretende mitigar los efectos negativos de la gestión de aquellos. El Limnoembalse de Pareja fue uno de los primeros en construirse, con una doble funcionalidad ambiental y recreativa. En otro orden de cosas, el fitoplancton es uno de los indicadores biológicos obligatorios para estimar el estado ecológico en lagos y embalses según la Directiva Marco del Agua (DMA). Se ha analizado la clorofila *a* (Chl- *a*) y la biomasa de fitoplancton en el Limnoembalse de Pareja entre primavera de 2008 e invierno de 2011. La composición de la comunidad fitoplanctónica fue analizada siguiendo la aproximación de los grupos funcionales. Los índices relativos a la biomasa (Chl- *a* y biovolumen) y a la composición (el porcentaje de cianobacterias, el IGA -*Índex de grups algals*- y el MedPTI -*Mediterranean Phytoplankton Trophic Index*-) propuestos en el primer ejercicio de Intercalibración de la DMA fueron aplicados para evaluar el estado ecológico del limnoembalse, así como el *Assemblage (Q) Index*. Las diatomeas centrales del grupo funcional **B** dominan la comunidad fitoplanctónica, aunque son reemplazadas por otros grupos en ciertos periodos, respondiendo a cambios ambientales. Los índices de biomasa y el porcentaje de cianobacterias sugieren un estado ecológico *Bueno* -o superior-, mientras que los índices de composición denotan mayormente un estado ecológico *Muy Bueno.* Comprobando la respuesta de los índices de composición a un gradiente trófico, ninguno mostró una alta precisión. Este hecho puede tener importantes implicaciones en la gestión de pequeños lagos y embalses mediterráneos, pues la determinación de su estado ecológico podría ser imprecisa. Por ello, sugerimos la necesidad de llevar a cabo un nuevo ejercicio de Intercalibración para el fitoplancton que incluya esta tipología de masas de agua.

Palabras clave: Directiva Marco del Agua, estado ecológico, fitoplancton, limnoembalse, mediterráneo.

4.2.1. INTRODUCTION

The construction of large reservoirs has resulted in a number of undesirable effects caused by these structures in the Mediterranean region, including the “arid band” phenomenon in the drawdown zone of the reservoir (MMA and CNEGP 1996, Molina-Navarro et al. 2010, MMAMRM 2011). One of the actions taken in Spain to mitigate these impacts has been the construction of small dams in the riverine zone of these large reservoirs (MMA and CNEGP 1996). These dams are known as “riverine dams” or “flood dams” and are aimed at keeping a small waterbody with a constant level, independent of the management of the main reservoir. These water bodies are more analogous to lakes than reservoirs due to their constant level and the absence of human operations associated with the dam (Molina-Navarro et al. 2010).

In Spain, the first limno-reservoir initiatives were proposed in the late 1980s and the early 1990s, with the primary goal of creating a suitable habitat for birds (Rodríguez Cabellos 1995; MMA and CNEGP 1996). The Pareja limno-reservoir (central Spain, upper Tagus River Basin) was built in 2006 and it was the first limno-reservoir with a two-fold purpose, since it holds recreational and environmental uses. It is located in the riverine zone of a sidearm of the Entrepeñas Reservoir, which has a capacity of 835×10^6 m^3 and a maximum inundation area of 32.13 km^2 (Molina-Navarro et al. 2010).

Limno-reservoirs are innovative water management initiatives of unquestionable interest. Nevertheless, their construction has raised some issues about its feasibility (Molina-Navarro et al.

2010). We set up an environmental observatory at the Pareja limno-reservoir to study its environmental feasibility from a multidisciplinary perspective. The project started in 2008, and includes the study of hydrologic feasibility and the risk of siltation (Molina-Navarro et al. 2010, in press). In addition, the evolution of the waterbody is being monitored through analyses of physical, chemical, limnological and microbiological conditions (Molina-Navarro et al. 2011, 2012). Limnological analyses are of particular importance to check the degree of fulfilment of the EU Water Framework Directive (WFD) requirements (OJEU num. 327 2000).

The analysis of five biological indicators is compulsory under the WFD, and one of these is phytoplankton, which has been widely used for decades as an indicator of water quality. Different methods have been developed for using phytoplankton to assess water quality, ranging from simple chlorophyll *a* (Chl- *a*) concentration (e.g., Carlson 1977, OECD 1982) to phytoplankton biovolume (e.g., Willén 2000) and from indicator species (e.g., Rosén 1981, Tremel 1996) to phytoplankton community structures (e.g., Padisák et al. 2006). The first Lake Intercalibration exercise coordinated by the EU was aimed at ensuring that good ecological status represents the same level of ecological quality everywhere in Europe (EC 2009, Poikane et al. 2011). This exercise included two types of metrics for phytoplankton: biomass metrics and composition metrics.

The Geographical Intercalibration Group for the Mediterranean region (Med GIG) proposed the use of two phytoplankton biomass metrics, Chl- *a* values and phytoplankton biovolume. Three phytoplankton composition metrics were proposed: the contribution of cyanobacteria to total phytoplankton biovolume, the IGA (*Índex de grups algals*, also known as the Catalan Index -Catalan et al. 2003-) and the Mediterranean Phytoplankton Trophic Index (MedPTI, Marchetto et al. 2009). These metrics have only been intercalibrated for deep and large reservoirs (mean depth > 15 m; lake size > 0.5 km^2) with siliceous or calcareous alkalinity, setting the reference conditions and the *Good/Moderate* ecological status (*G/M*) boundaries just for summer mean values. However, in the development of the IGA and the MedPTI, small lakes and reservoirs were also considered. Marchetto et al. (2009) recommended the use of the MedPTI index only for reservoirs with a mean depth greater than 15 m, but they have proved the reliability of the index in a number of Sardinian reservoirs shallower 15 m. They suggested that the effect of reservoir management on the phytoplankton assemblages should be evaluated before applying the index in shallower reservoirs. However, there is no active management in limno-reservoirs. Although the Lake Intercalibration exercise did not include metrics for small and shallow lakes and reservoirs in Mediterranean areas, the aforementioned metrics seem to be among the most suitable for assessing the ecological status of the Pareja Limno-reservoir under the WFD requirements.

The functional group approach (Reynolds et al. 2002) is an additional methodology concerning phytoplankton ecology that has been successfully applied in Mediterranean reservoirs. It has marked a turning point in phytoplankton studies and it has been increasingly applied in the latest phytoplankton studies (Padisák et al. 2009). The approach has a phytosociological basis and describes phytoplankton assemblages that can be understood as functional groups of species with defined demands for different combinations of physical, chemical and biological properties (Padisák et al. 2006). Therefore, examining phytoplankton functional groups is extremely useful and provides additional information on the ecology of phytoplankton assemblages (Salmaso and

Padisák 2007, Richtecký and Znachor 2011). Several studies of phytoplankton in Mediterranean lakes and reservoirs were conducted using this approach (e.g., Moustaka-Gouni et al. 2007, Katsiapi et al. 2011), although they are less numerous than those in tropical and subtropical reservoirs (e.g., Crossetti and Bicudo 2008, Souza et al. 2008, Becker et al. 2009). In the Iberian Peninsula, some studies have been carried out in the Tablas de Daimiel and Xeresa wetlands (Lionard et al. 2005, Romo and Villena 2005), in the El Gergal Reservoir (Hoyer et al. 2009) and in the Sau Reservoir (Becker et al. 2010). However, all these study areas are quite different from the surroundings of the Pareja limno-reservoir, being very shallow wetlands or canyon-shaped and medium to large reservoirs and subject to inflows from agricultural or urban catchments and/or large volume fluctuations.

Based on this functional group approach, Padisák et al. (2006) developed the Assemblage Index (Q Index) to assess the ecological status of the different lake types established by the WFD. Even though the index was developed for Hungarian lakes, it can also be applied in reservoirs, regardless of the geographic region (Padisák et al. 2006, Crossetti and Bicudo 2008, Becker et al. 2009, Pasztaleniec and Poniewozik 2010, Cellamare et al. 2012). In the Mediterranean context, Becker et al. (2010) applied it successfully in a deep, canyon-shaped reservoir in Spain, being the first application of the index to a European water-supply reservoir. Since both the functional group approach and the Assemblage Index have been applied successfully in Mediterranean locations, this index could represent another possibility for assessing the ecological status of the Pareja Limno-reservoir.

Previous studies on the Pareja Limno-reservoir have included a global limnological study and an initial assessment of its trophic state. An overall oligo-mesotrophic state was suggested on the basis of OECD (Organisation for Economic Co-operation and Development) criteria (OECD 1982) and Carlson's Trophic State Index (Carlson 1977); however, Chl- *a* values suggested a lower trophic state than Total Phosphorous (TP) concentrations (Molina-Navarro et al. 2012).

The main objectives of the present study are:

- The analysis of phytoplankton composition in the Pareja Limno-reservoir using the functional group approach.

- The assessment of its ecological status applying the phytoplankton biomass and composition metrics previously mentioned.

- The verification of the suitability of the phytoplankton composition metrics for assessing the ecological status of Mediterranean limno-reservoirs in accordance with the WFD requirements, checking the response of the indices to a trophic gradient (Chl- *a* and TP concentrations and their classification in the OECD model; OECD, 1982).

4.2.2. STUDY SITE

The Pareja Limno-reservoir is located in southern Guadalajara (central Spain) and at the upper Tagus River basin. It is situated the riverine zone of a sidearm of the Entrepeñas Reservoir, which has developed an arid band (Fig. 4.2.1). The limno-reservoir had a capacity of 9.4×10^5 m^3, a maximum inundation area of 0.26 km^2 and a mean depth around 4 m. Its maximum depth was approximately 13 m near the dam, becoming progressively shallower towards the inflow zone. The average retention time of the limno-reservoir was around 70 d., although this may vary considerably as annual discharges of the Ompólveda River at the E-3270-Pareja gauging station show a high variability, ranging from 1.13×10^6 m^3 (1992–1993) to 13.66×10^6 m^3 (1987–1988) (CEH-CEDEX 2008).

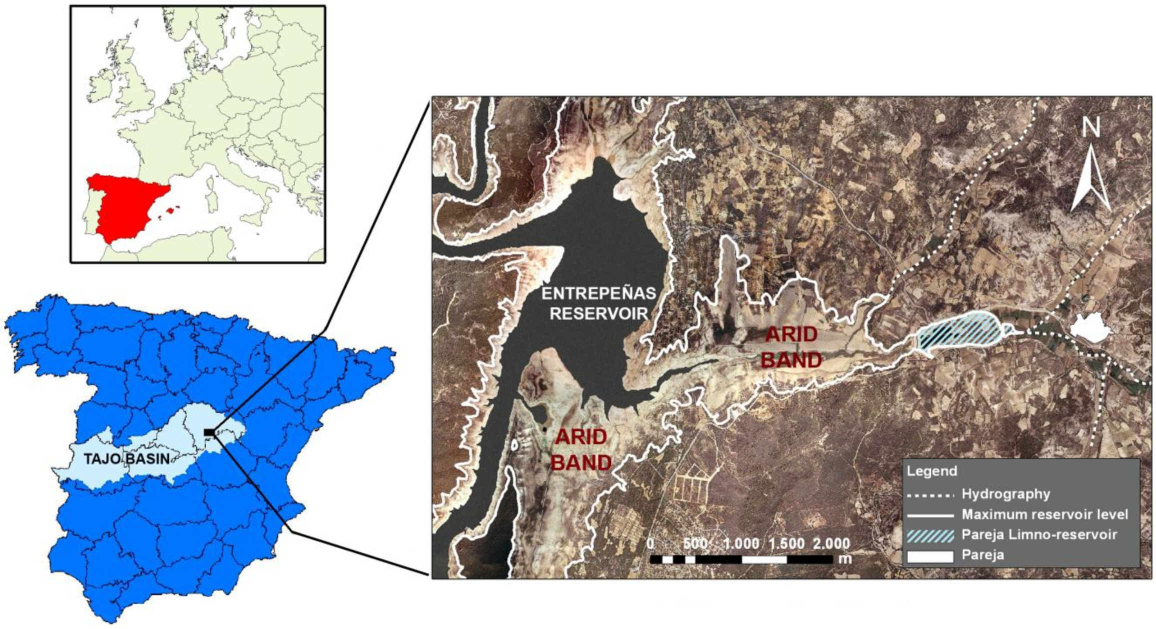

Fig. 4.2.1. The location of the Pareja Limno-reservoir and a comparison of the volume of water stored in the Entrepeñas Reservoir in 2006 with its maximum capacity (modified from Molina Navarro et al. 2010).

The Pareja Limno-reservoir was the first to have a dual function: environmental and recreational. It is open for swimming or for walking, it has a quay for motorless craft, a sunbathing area, two man-made islands that serve as bird refuges and a fish ladder (Fig. 4.2.2).

The Ompólveda River has an 88 km^2 basin (approximately) which flows into the limno-reservoir. Its main tributary is the Valdetrigo stream, merging from the northeast (Molina-Navarro et al. 2011). The upper basin is dominated by a limestone plateau, giving calcareous alkalinity to the water. The small size of the basin, together with its low population (≈300 inhabitants, quadrupling in summer) and low percentage of agricultural surface area (25%), may contribute to a good ecological status in the Pareja limno-reservoir.

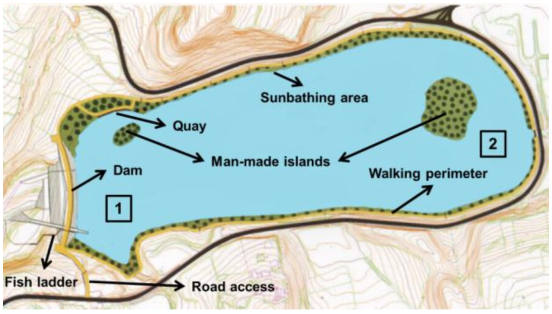

Fig. 4.2.2. Pareja Limno-reservoir sketch, modified from MMA (2002). Numbers "1" and "2" indicate the location of the sampling points.

The limnological characteristics of the Pareja limno-reservoir, studied between spring 2008 and winter 2011, are described in detail in Molina-Navarro et al. (2012). The Pareja limno-reservoir had a warm monomictic stratification regime. Similar results were obtained in the dam and the inflow zones of the limno-reservoir, and the main environmental background data were summarised (Table 4.2.1). The water was slightly alkaline. Its ionic composition was dominated by sulphate and calcium, showing conductivity values ranging from 744 to 1464 µS/cm. Nutrient concentrations (nitrogen compounds and total phosphorous) were also analysed, showing generally low values in most of the sampling surveys except for those conducted during winter periods when the Ompólveda River had its highest discharge volume, increasing the nutrient load in the limno-reservoir. Nevertheless, nutrient depletion caused by the presence of a lentic habitat (Dobson and Frid 1998) occurred in the Pareja limno-reservoir (Molina-Navarro et al. 2011), being especially noticeable in the dam zone.

Table 4.2.1. Average seasonal values for the main physico-chemical and biological parameters in the Pareja limno-reservoir (2008-2011, Molina-Navarro et al. 2012).

	Dam Zone				Inflow Zone			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
Temperature (ºC)	17.3	24.6	10.4	7.1	17.0	24.6	10.4	7.7
Dissolved O_2 (mg/l)	10.5	9.4	10.7	12.5	10.9	8.9	10.6	12.3
pH	8.0	7.5	7.7	7.7	8.1	7.7	7.9	7.9
Conductivity (µS/cm)	1183	1317	1405	1096	1181	1320	1408	1024
Ionic composition type	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca
N-NO_3^-	<0.31	<0.23	<0.23	1.220	<0.31	<0.23	<0.23	<0.64
N-NO_2^-	<0.015	<0.015	<0.015	<0.024	<0.017	<0.018	<0.016	<0.015
N-NH_4^+	0.070	0.072	0.111	0.027	0.065	0.079	0.113	0.290
TP (mg/l)	<0.015	<0.015	<0.010	<0.017	<0.013	<0.023	<0.013*	<0.052
Secchi depth (m)	2.57	1.23	1.87	1.66	1.38	0.71	1.03	1.03
Chlorophyll a (µg l^{-1})	1.30	1.93	2.28	1.16	1.20	3.52	2.38	1.73
Phytoplankton biomass (mg/l)	0.24	0.79	0.63	0.16	0.38	0.81	0.53	0.12

* It was not possible to detect TP in autumn 2009 because of the interference of another chemical compound in the analytic method.

4.2.3. MATERIALS AND METHODS

4.2.3.1. Sampling strategy

Sampling and laboratory analyses were carried out in collaboration with the Centre for Hydrographic Studies (Spanish Ministries of the Environment and Public Works) team. Twelve sampling surveys were performed seasonally, starting in spring 2008 and ending in winter 2011. Two sampling sites were selected: one next to the limno-reservoir dam and another in the inflow zone (“1” and “2” in Fig. 4.2.2). All sampling surveys were conducted from 10:00 to11:30 a.m.

Phytoplankton samples were collected in 250 ml dark glass bottles from the surface layer. Samples were fixed with acid Lugol’s iodine. Sampling for TP and Chl- *a* was performed as described by Molina-Navarro et al. (2012).

4.2.3.2. Sample analysis

Phytoplankton samples were analysed using the Utermöhl technique (Utermöhl 1958) with a Leica DMRIB microscope, settling 25 or 50 ml of sample. The largest species were counted at 100×, 200× or 400×, depending on their size and density, and the smallest were counted at 1000×. For those species counted at 100×, the entire chamber surface was scanned. For 200× or more, species were counted in transects or per field, reaching at least 100 individuals for the most frequent species whenever possible. TP and Chl- *a* concentrations were analysed by photometry as described by Molina-Navarro et al. (2012). A value of 0.010 mg/L was considered for TP concentration when it was below than the limit of detection.

To calculate the algal biovolume, the dimensions of at least 20 individuals per species (cells, filaments or colonies) were measured at 400× or 1000× magnification. Once a geometric shape has been assigned to each species, the appropriate dimensions (length, width, diameter) were measured and the cell volume was calculated. Phytoplankton biomass was calculated considering a cell density of 1 g/cm^3. The measurements were performed by image analysis using the LAS program (Leica Application Suite). Geometric shapes in Rott (1981) and Edler (1979) were used as a reference.

4.2.3.3. Data analysis

Ecological status of the Pareja Limno-reservoir was assessed comparing summer values for Chl- *a* and phytoplankton biovolume with the *G/M* boundaries reported for calcareous reservoirs (EC 2009, Poikane et al. 2011; Table 4.2.2). The same assessment was carried out for the contribution of cyanobacteria to total phytoplankton biovolume. The other phytoplankton composition metrics included in the WFD Lake Intercalibration exercise were calculated. The IGA index was calculated according to Catalan et al. (2003), sorting the phytoplankton species in 10 different algal groups. The MedPTI index was calculated according to Marchetto et al. (2009). MedPTI is based on the trophic and indicator values of 44 taxa, and the biovolume of the listed species shall be at least 70% of the annual average biovolume. Data from 2008 and 2011 in the Pareja limno-reservoir did not fulfil this condition, consequently the MedPTI was only calculated for years 2009 and 2010. The same premise (70%) was followed in the IGA calculation, and only 3 out of 24 samples did not fulfil the condition. As the WFD Intercalibration exercise (EC 2009) only gives the reference values and the *G/M* boundary for summer mean values (Table 4.2.2), the ecological status thresholds for IGA and MedPTI included in the original publications were also considered (Table 4.2.3).

Phytoplankton species were also sorted into assemblages following the criteria of Reynolds (2002) and Padisák et al. (2003, 2006, 2009). The Assemblage Index (Q index) was calculated taking into account the methodology from Padisák et al. (2006). The factor *F* weights assigned to each functional group were those corresponding to lake type 7 in Padisák et al. (2006), since it was the most similar type to the Pareja limno-reservoir (calcareous, average depth < 4 m, persistent). This index assigns a score between 0 and 5, classifying the ecological status of the aquatic ecosystems in accordance with the WFD (Table 4.2.3).

Table 4.2.2. Reference values and Good/Moderate ecological status class boundaries for the phytoplankton metrics included in the WFD first Lake Intercalibration exercise for Mediterranean calcareous reservoirs.

	Reference value	**G/M boundary**
Chl- *a* (µg/L)	1.8 - 2.6	4.2 - 6.0
Total Biovolume (mm^3/L)	0.76	2.1
% Cyanobacteria	0	28.5
IGA (Índex de grups algals)	0.61	7.7
MedPTI (Mediterranean Phytoplankton Trophic Index)	3.09	2.38

Table 4.2.3. IGA (Índex de grups algals), MedPTI (Mediterranean Phytoplankton Trophic Index) and Assemblage (Q) Index ecological status class boundaries.

	High	**Good**	**Moderate**	**Poor**	**Bad**
IGA (Catalan *et al.* 2003)	<10	10-100	100-200	200-300	>300
MedPTI (Marchetto *et al.* 2009)	>2.77	2.77-2.45	2.45-2.13	2.13-1.81	<1.81
Assemblage Index (Padisák *et al.* 2006)	4-5	3-4	2-3	1-2	0-1

We evaluated the response of the different phytoplankton composition metrics to a trophic gradient. The results of these indices were plotted against TP and Chl- *a* values, as in Marchetto et al. (2009) for TP. Metrics results were also compared with the trophic classification from the OECD model (OECD 1982), as in Kaiblinger et al. (2009). Simple regression analyses between these metrics and trophic state indicator values were also performed, as well as for each pair of metrics (as in Pasztaleniec and Poniewozik 2009). Analyses were performed for the dam zone, the inflow zone and the whole set of samples.

4.2.4. RESULTS

4.2.4.1. Phytoplankton composition

We identified 77 phytoplankton species in the Pareja Limno-reservoir. We sorted the phytoplankton species into 17 groups applying the functional group approach. Only 20 of the total number of species were descriptor (> 5% of total biovolume) at least in one of the sampling surveys, belonging to 10 functional groups (Table 4.2.4).

Table 4. 2.4. Main phytoplankton species with their taxonomic and functional groups according to Reynolds (2002) and Padisák et al. (2003, 2006, 2009) for the Pareja limno-reservoir (2008-2011).

Functional Group	Descriptor Species	Taxonomic Group
B	*Aulacoseira* spp., *Cyclotella ocellata*, *Cyclotella radiosa*, *Cyclotella* sp.	Bacillariophyta
D	*Nitzschia* sp.	Bacillariophyta
P	*Fragilaria* sp.	Bacillariophyta
	Amphora sp., *Campylodiscus* sp., *Surirella* spp.	Bacillariophyta
MP	*Pseudoanabaena catenata*	Cyanobacteria
	Cosmarium spp.	Chlorophyta
T	*Planctonema lauterbornii*	Chlorophyta
X2	*Kephyrion litorale, Pseudokephyrion cf. poculum*	Crysophyta
	Plagioselmis nannoplanctica	Cryptophyta
Y	*Cryptomonas* spp.	Cryptophyta
F	*Oocystis* sp.	Chlorophyta
J	*Coelastrum* spp., *Scenedesmus planctonicus*	Chlorophyta
L_o	*Ceratium hirundinella*	Dinophyta

Despite the contribution of many functional groups, assemblage **B** was the predominant in the phytoplankton community throughout the whole period (49% average biovolume, Table 4.2.5), especially in the dam zone. Codon **B** is mainly composed of centric diatoms. *Cyclotella* species such as *Cyclotella ocellata* or *Cyclotella radiosa* were abundant in the Pareja Limno-reservoir.

Table 4.2.5. Percentage of phytoplankton functional group biovolume in the dam (a) and inflow (b) zones of the Pareja limno-reservoir (2008-2011).

a)

Group	Spr'08	Sum'08	Aut'08	Win'09	Spr'09	Sum'09	Aut'09	Win'10	Spr'10	Sum'10	Aut'10	Win'11
B	26.7	**60.3**	**56.4**	**56.5**	**47.4**	35.9	**88.6**	**86.9**	**64.3**	**64.7**	**70.8**	**39.3**
D							0.8				0.3	2.4
P				6.0				2.2	26.3	0.1		18.2
MP	1.1		0.2	5.7				2.6	1.5	6.4	0.0	
T		35.4	7.3	2.3	5.2	**47.6**		0.3		0.6		
X2	**43.7**	0.1	7.5	25.5	9.1	3.2	1.2	2.6	0.5	6.1	10.1	37.2
Y	3.4	0.3	1.1	3.8	2.6	1.2	0.3	4.2	1.3	6.8		0.8
F			5.3		4.1		6.1	0.0	0.1		0.1	
J	20.0	0.0	9.2		3.5	0.1	2.8				11.8	
L_o	5.1	4.0	13.1		27.1	11.9	0.1	0.3	2.2	15.2	6.9	2.1
Others	0.0	0.0	0.0	0.3	1.0	0.2	0.1	0.8	3.8	0.2	0.0	0.0

b)

Group	Spr'08	Sum'08	Aut'08	Win'09	Spr'09	Sum'09	Aut'09	Win'10	Spr'10	Sum'10	Aut'10	Win'11
B	7.4	39.4	**36.2**	**61.7**	**47.4**		**69.1**	2.1	**64.3**	**47.3**	**39.8**	**51.2**
D	0.0					1.9	3.6				4.6	10.9
P		0.1		28.4		3.5		**57.9**	22.7	14.5	34.2	
MP	0.1	0.8		5.2		**90.4**	8.1	39.0	6.1	3.9	5.6	0.8
T		**52.9**	6.0		3.0	0.3	0.0			0.3		
X2	12.5	0.9	8.4	2.5	7.0	0.2	3.5	0.9	1.9	3.6	7.2	29.7
Y	**79.1**	5.8	7.4		3.0		3.5	0.0	3.7	4.6	0.2	7.4
F			7.5	0.2	1.1			0.1	0.4	0.0	0.0	0.1
J	0.6	0.1	16.4	0.8	0.7	0.1	12.1		0.4		0.5	
L_o	0.1		18.1	0.0	37.4	3.1			0.2	25.7	7.7	
Others	0.0	0.0	0.0	1.3	0.4	0.4	0.1	0.0	0.2	0.2	0.1	0.0

Other functional groups were abundant or dominant in some sampling surveys. In the first sampling survey (spring 2008), species belonging to **X2** (dam zone) and **Y** (inflow zone) were dominant due to an abundance of *Cryptophyta* species (*Plagioselmis nannoplanctica* and *Cryptomonas* spp., respectively) (Table 4.2.5). Assemblage **J** contribution to biovolume displayed a maximum in the dam zone during this first sampling survey (Table 4.2.5).

Group **X2** (*Kephyrion litoralle*) also showed high biovolume percentages in winter 2009 in the dam zone and in winter 2011 in the dam and the inflow zones of the limno-reservoir (*Pseudokephyrion cf. poculum* and *P. nannoplanctica*, respectively). Other functional groups abundant in winter included **P**, **MP** and **D**. Assemblage **P** dominated the phytoplankton community in the inflow zone in winter 2010. It was also very abundant in the other winter periods and even in spring. Group **MP** was also very abundant in the inflow zone in winter 2010. Group **D** (*Nitzschia sp.*) showed the highest biovolume percentage in winter 2011, in the inflow zone (Table 4.2.5).

Regarding summer periods, assemblage **T** (*Planctonema lauterbornii*) increased its contribution, replacing group **B** dominance in the inflow zone in 2008 and in the dam zone in 2009. However, in summer 2009, group **B** was massively replaced in the inflow zone by the **MP** functional group (*Campylodiscus sp.*, *Surirella* spp.) (Table 4.2.5). The metaphytic desmid *Cosmarium* spp., also part of the **MP** group, was similarly abundant.

Other groups that showed high biovolume percentages in some surveys were assemblages **F** and $\mathbf{L_o}$ (Table 4.2.5). *Oocystis* spp. was the main species of the **F** functional group, and reached the highest biovolume percentages in autumn. *Ceratium hirundinella* was the main species of group $\mathbf{L_o}$, with the highest biovolume percentage in both limno-reservoir zones in spring 2009, but also showing high percentages in other samplings, especially in summer 2010.

4.2.4.2. Ecological status assessment

We have calculated metrics values and their ecological status classifications (Table 4.2.6). For IGA and MedPTI, ecological status classification is based on the original publications, since the Lake Intercalibration exercise only provides the *G/M* boundary for summer mean values. TP concentrations and TP and Chl- *a* trophic state classification according to the OECD (1982) were also obtained (Table 4.2.6).

Chl- *a* values were higher in the inflow zone than in the dam zone (mean values are 1.67 µg/L and 2.21 µg/L, respectively), while phytoplankton biovolume showed similar values (averages of 0.45 mm^3/L and 0.46 mm^3/L in the dam and inflow zones, respectively). They were generally low values, below the *G/M* boundary for calcareous reservoirs in summer samples, except for Chl- *a* in summer 2009 in the inflow zone.

The contribution of cyanobacteria to total phytoplankton biovolume showed two peaks in winter 2009 and spring 2010, with higher percentages in the dam zone. Despite those peaks, all the values seem low, being all those in summer below the *G/M* boundary for calcareous reservoirs (28.5%).

The IGA index, which increases as the ecological status deteriorates, showed very low values, especially in the dam zone, suggesting a *High* ecological status for all the sampling surveys and in both zones of the limno-reservoir.

Table 4.2.6. Trophic state suggested by total phosphorous (TP) and chlorophyll a (Chl- a) concentrations and ecological status obtained from the phytoplankton metrics used in the Pareja limno-reservoir in the dam (a) and the inflow (b) zones (Biov. = Total phytoplankton biovolume, IGA = Índex de grups algals, MedPTI = Mediterranean Phytoplankton Trophic Index, Q Index = Assemblage Index, UO = Ultra-oligotrophic, ≥ O = Oligotrophic or better, O = Oligotrophic, O/M = Oligo-mesotrophic, M = Mesotrophic, M/E = Meso-eutrophic, HE = Hyper-eutrophic, H = High, G = Good, ≥ G = Good or better, ≤ Mo = Moderate or worse)

a)

	Spr'08	Sum'08	Aut'08	Win'09	Spr'09	Sum'09	Aut'09	Win'10	Spr'10	Sum'10	Aut'10	Win'11
						NUMERICAL VALUES						
TP (mg/L)	0.025	0.020	0.010	<0.010	<0.010	0.015	<0.010	<0.010	<0.010	<0.010	<0.010	0.030
Chl- *a* (μg/L)	1.50	2.90	2.10	1.14	1.56	2.13	3.35	1.64	0.84	0.77	1.39	0.69
Biov. (mm^3/L)	0.08	1.67	0.31	0.02	0.27	0.44	1.50	0.38	0.37	0.25	0.08	0.07
% Cyanobacteria	0.00	0.00	0.00	5.68	0.06	0.22	0.00	0.70	7.06	1.17	0.03	0.00
IGA	0.62		0.34	0.88	0.14		0.14	0.09	1.26	0.09	0.03	0.37
MedPTI				2.98	3.16	3.31	3.41	2.64	3.04	2.57	2.58	
Q Index	3.87	4.99	4.58	4.44	4.65	4.92	4.78	4.81	4.76	4.68	4.60	4.38
						TROPHIC STATE						
TP	**M**	**M**	**O/M**	**≥ O**	**≥ O**	**M**	**≥ O**	**≥ O**	**≥ O**	**≥ O**	**≥ O**	**M**
Chl- *a*	**O**	**M**	**O**	**O**	**O**	**O**	**M**	**O**	**UO**	**UO**	**O**	**UO**
						ECOLOGICAL STATUS						
Chl- *a*	-	**≥ G**	-	-	-	**≥ G**	-	-	-	**≥ G**	-	-
Biov.	-	**≥ G**	-	-	-	**≥ G**	-	-	-	**≥ G**	-	-
% Cyanobacteria	-	**≥ G**	-	-	-	**≥ G**	-	-	-	**≥ G**	-	-
IGA	**H**	-	**H**	**H**	**H**	-	**H**	**H**	**H**	**H**	**H**	**H**
MedPTI	-	-	-	**H**	**H**	**H**	**H**	**G**	**H**	**G**	**G**	-
Q Index	**G**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**

b)

	Spr'08	Sum'08	Aut'08	Win'09	Spr'09	Sum'09	Aut'09	Win'10	Spr'10	Sum'10	Aut'10	Win'11
						NUMERICAL VALUES						
TP (mg/L)	0.015	0.025	0.015	<0.010	0.015	0.035	-[1]	0.110	<0.010	<0.010	<0.010	0.035
Chl- *a* (μg/L)	1.7	3.3	2.3	2.27	1.38	6.23	3.4	1.87	0.52	1.02	1.44	1.05
Biov. (mm^3/L)	0.62	1.86	0.38	0.01	0.39	0.06	1.06	0.32	0.12	0.51	0.14	0.03
% Cyanobacteria	0.00	0.00	0.00	2.18	0.17	0.17	0.00	0.01	3.14	0.01	0.09	0.00
IGA	1.03		0.64	1.01	0.04	0.12	0.04	2.81	0.84	0.29	1.07	0.05
MedPTI				3.43	3.15	2.92	3.46	3.34	3.00	2.86	3.13	
Q Index	3.61	4.88	4.28	4.81	4.80	3.14	4.42	4.20	4.78	4.79	4.67	4.21
						TROPHIC STATE						
TP	**M**	**M**	**M**	**≥ O**	**M**	**M**	-*	**HE**	**≥ O**	**≥ O**	**≥ O**	**M/E**
Chl- *a*	**O**	**M**	**O**	**O**	**O**	**M**	**M**	**O**	**UO**	**O**	**O**	**O**
						ECOLOGICAL STATUS						
Chl- *a*	-	**≥ G**	-	-	-	**≤ Mo**	-	-	-	**≥ G**	-	-
Biov.	-	**≥ G**	-	-	-	**≥ G**	-	-	-	**≥ G**	-	-
% Cyanobacteria	-	**≥ G**	-	-	-	**≥ G**	-	-	-	**≥ G**	-	-
IGA	**H**	-	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**
MedPTI	-	-	-	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	-
Q Index	**G**	**H**	**H**	**H**	**H**	**G**	**H**	**H**	**H**	**H**	**H**	**H**

*It was not possible to detect TP in autumn 2009 due to interference of another chemical compound in the analytic method.

The MedPTI index, applied only for 2009 and 2010, increases as the ecological status improves. The lowest values were found in winter, summer and autumn 2010 in the dam zone, suggesting a *Good* ecological status. A *High* ecological status was suggested for the remaining sampling surveys, including all of the surveys conducted in the inflow zone.

The Assemblage Index (Q Index) also increases as the ecological status improves. The status suggested was mainly *High* ($4 < Q < 5$), only descending into the *Good* category ($3 < Q < 4$) in spring 2008 (both zones) and summer 2009 (inflow zone).

Trophic state categories derived from application Chl- *a* values suggested an oligotrophic state in most of the samplings, even ultra-oligotrophic. Mesotrophic state was found in some summer and autumn sampling surveys in both zones of the limno-reservoir. TP yielded a slightly worse trophic state than Chl- *a*, especially in winter 2010 and 2011 in the inflow zone.

We have plotted phytoplankton composition metrics vs. TP and Chl- *a* concentrations (Fig. 4.2.3). Simple regression analyses between phytoplankton composition metrics and trophic state indicators revealed significant correlations between IGA and TP in the inflow zone ($R^2 = 0.51$, $P = 0.020$) and in the whole set of samples ($R^2 = 0.44$, $P = 0.001$). Correlation between Chl- *a* and Assemblage (Q) Index in the inflow zone was statistically significant too ($R^2 = 0.35$, P =0 .041). Other regression analyses were not significant. Regarding correlations between indices, the only significant correlation found was between IGA and cyanobacteria contribution in the dam zone ($R^2 = 0.74$, $P = 0.002$).

4.2.5. DISCUSSION

4.2.5.1. Phytoplankton composition

Group **B** was the predominant assemblage throughout the study. The habitat template for this group has been described as mesotrophic small- and medium- sized lakes (Reynolds et al. 2002; Padisák et al. 2009), which matches up with the characteristics of the Pareja limno-reservoir (Molina-Navarro et al. 2012). Group **B** has also been described as dominant in other Spanish reservoirs, but only during the mixing period (Moreno-Ostos 2008, Hoyer et al. 2009). As a consequence of thermal stratification, non-buoyant and non-motile phytoplankton species such as group **B** diatoms are thought to sink into the hypolimnion (Hoyer et al. 2009). However, functional group **B** showed a high percentage of the total biovolume in the Pareja limno-reservoir in spring and summer, especially in the dam zone (Table 4.2.5).

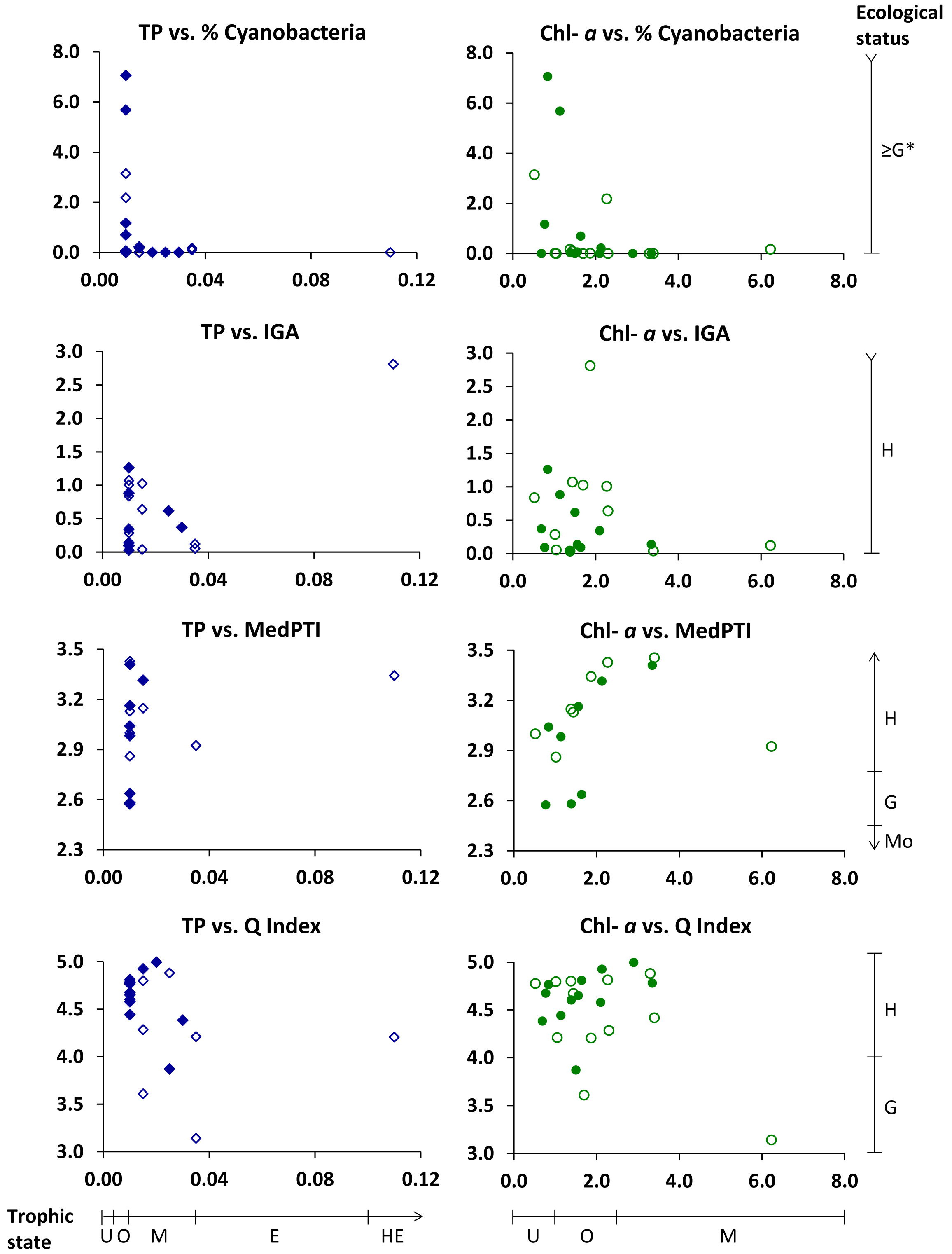

Figure 4.2.3. Phytoplankton composition metrics vs. total phosphorous (TP, mg/L) and chlorophyll a (Chl-a, µg/L) (IGA = Índex de grups algals, MedPTI = Mediterranean Phytoplankton Trophic Index, Q Index = Assemblage index). Black and white points represent dam zone and inflow section values, respectively. Secondary axis shows trophic state and ecological status thresholds (U = Ultra-oligotrophic, O = Oligotrophic, M = Mesotrophic, E = Eutrophic, HE = Hyper-eutrophic, Mo = Moderate, G = Good, ≥G = Good or better, H = High) *% Cyanobacteria ecological status boundaries were defined for summer values.

The presence of group **B** species in epilimnetic water during thermal stratification may be due to the existence of atelomixis in the Pareja limno-reservoir, which could act synergistically with low limno-reservoir depth. Atelomixis is a mixing pattern driven by a marked difference in day/night water temperatures, consisting in one robust water movement occurring once a day (at night), affecting the entire water column or the epilimnion (partial atelomixis) (Barbosa and Padisák 2002, Souza et al. 2008). It was originally described by Lewis (1978) in tropical and subtropical lakes, although it has also been observed in Mediterranean lakes and reservoirs (Naselli-Flores 2003, Katsiapi et al. 2011). Thus, atelomixis can play a role in preventing these relatively heavy and non-motile algae from sinking to the hypolimnion, but further research is required to confirm this.

Groups **Y** and **X2** were dominant in the first sampling (spring 2008) in the inflow and dam zones, respectively. **Y** group has been described as well adapted to a wide range of habitats but vulnerable to zooplankton grazing pressure (Reynolds et al. 2002, Padisák et al. 2009). According to Reynolds (1984), *Cryptophyta* (group **Y**) rarely dominate the phytoplankton community. Their opportunistic behaviour (Rychtecký and Znachor 2011) and the low abundance of phytophagous zooplankton species (Molina-Navarro et al. 2012) may explain the abundance of group **Y** in this newly created habitat at the beginning of the research.

On the other hand, group **X2** has been described in shallow lakes with a meso-eutrophic state (Reynolds et al. 2002, Padisák et al. 2009), and thus its presence could imply a deterioration of the ecological status. The high percentage of group **J** found in the first sampling survey reinforces this inference, since its habitat template comprises shallow, mixed and highly enriched systems (Reynolds et al. 2002, Padisák et al. 2009). These results match up with the TP concentration found in the dam zone in the first sampling, the second highest throughout the sampling period (Table 4.2.6).

High biovolume percentages of group **X2** in winter 2009 and 2011 also reveal a deterioration of trophic conditions, probably related to high flow volumes in the Ompólveda River and the consequent influx of a higher nutrient load into the Pareja limno-reservoir (Molina-Navarro et al. 2011, 2012). Groups **P**, **MP** and **D** abundances found in winter may also be related to high discharges from the Ompólveda River. Assemblage **P** (*Fragilaria* sp.) has been described as dwelling in eutrophic mixed layers 2–3 m thick (Reynolds et al. 2002, Padisák et al. 2009) and the group **D** (*Nitzschia sp.*) habitat template consists of shallow turbid waters including rivers (Reynolds et al. 2002, Padisák et al. 2009). Group **MP** is mainly composed of diatoms which live in littoral habitats in inorganically turbid shallow lakes (Padisák et al. 2009). This group was very abundant in the inflow zone in winter 2010, when the Ompólveda River flow volume was the highest, producing a lot of turbidity in the limno-reservoir (0.3 m Secchi depth and the highest TP concentration, Table 4.2.6). These results are in accordance with the observations reported by Rychtecký and Znachor (2011), who demonstrated that flood events deteriorate water quality in reservoirs due to a marked increase in suspended solids, nutrient availability and organic matter enrichment.

The replacement of group **B** dominance by assemblage **T** in some summer surveys was not surprising, since this group has been described in persistent mixed layers, including well-mixed epilimnia of lakes in summer (Reynolds et al. 2002, Padisák et al. 2009). The 2008-2009 hydrologic year was the driest recorded during the research, registering a long period without water surplus (and consequently increasing water residence time) in the Pareja limno-reservoir during summer–autumn (Molina-Navarro et al. in press(a)). Positive relationships between residence time and phytoplankton growth have been widely described (e.g., Lucas et al. 2009), and they have been observed in the Pareja Limno-reservoir (Molina-Navarro et al. in press(b)). This fact may have played a role in the dominance of group **MP** in summer 2009, as higher residence time favours phytoplankton growth (maximum Chl- *a* found, Table 4.2.6) and consequently turbidity, making the habitat template of group **MP** up.

Group **F** showed the highest percentages in autumn, when the water column of the Pareja limno-reservoir showed the best mixing, consistent with the habitat template described for this functional group: clear, deeply mixed meso-eutrophic lakes (Reynolds et al. 2002, Padisák et al. 2009). Finally, the habitat template for group $\mathbf{L_o}$ was originally described by Reynolds *et al.* (2002) as being summer epilimnia in mesotrophic lakes, while Padisák et al. (2009) expanded the habitat description to deep and shallow, oligo to eutrophic, medium to large lakes, without temporal constraints. The latter description matches up better with behaviour of the $\mathbf{L_o}$ group at the Pareja limno-reservoir, as the group did not show a clear temporal pattern.

The occurrence of different phytoplankton assemblages responds to changes in the Pareja Limno-reservoir environment as described by Reynolds et al. (2002) and Padisák et al. (2009). Habitat templates described by Padisák et al. (2009) matched up with those found for the different functional groups in the limno-reservoir. Consequently, the functional group approach seems useful to describe the phytoplankton community in the Pareja Limno-reservoir on an ecological basis.

4.2.5.2. Ecological status assessment

Chl- *a* and phytoplankton biovolume seemed consistent metrics when assessing ecological status in summer, being below the *G/M* boundary in most of the summer samples (Table 4.2.6), except Chl- *a* for summer 2009 in the inflow zone. A good response of phytoplankton biovolume to Chl- *a* values was generally observed, although higher biovolume would have been expected in the inflow section, according to the worse trophic state observed. Nevertheless, the assessment of ecological status of the Pareja Limno-reservoir according to the first Lake Intercalibration exercise must be done carefully, as the reference conditions and *G/M* boundaries were defined for summer in deep and large Mediterranean reservoirs (EC 2009, Poikane et al. 2011).

At first glance, the results obtained with all the phytoplankton composition metrics (cyanobacteria contribution to total phytoplankton biovolume, IGA, MedPTI and Assemblage –Q-Index) seem consistent, as all of them suggested a *high* ecological status for most of the samplings (*Good* or better for cyanobacteria contribution in summer samplings). However, some differences were found in the behaviour of these metrics (Table 4.2.6). In fact, no statistically significant relationships were found between them, but for cyanobacteria contribution and IGA in the dam zone (consequence of the higher cyanobacteria contributions found in this zone and the relevance of this algal group in the IGA calculations). Differences in the response of the metrics to the trophic state were also found (Table 4.2.6, Fig. 4.2.3).

Cyanobacteria contribution percentages were low, and peak values (winter 2009 and spring 2010), higher in the dam zone, did not seem to respond to variations in trophic state (Table 4.2.6).

The IGA index, which was the first based on phytoplankton composition developed for Mediterranean sites (Catalan et al. 2003), showed values possibly too low, as they were quite far from the *High/Good* ecological status boundary (10, Table 4.2.6). Regarding the trophic state classifications obtained, apparently, IGA in the original form was not a reliable metric for assessing ecological status in the Pareja limno-reservoir. Nevertheless, the index yielded higher values in the inflow zone, a logical value since this zone received the nutrient discharge from the Ompólveda River. Furthermore, the highest IGA value matched up with the highest TP concentration, although this high TP level probably was a transitory situation since the Ompólveda River was discharging an extraordinarily high volume of water (28.8 mm of rainfall in the previous 48 h., including 9.6 mm the night before the sampling survey). Regardless, comparison of trophic state and ecological status suggested that values could be too low to be considered fully reliable.

Marianni (2007) also found that IGA did not evaluate the ecological quality of Mediterranean Italian lakes correctly. Probably, one of the reasons is that the index was developed for application in Catalonia, where most of the lakes are Alpine (Pyrenees mountains) rather than Mediterranean (338 Alpine and 3 karstic lakes were chosen to develop the index, Catalan et al. 2003). In fact, the WFD Intercalibration exercise (EC 2009) changed the *Good/Moderate* IGA boundary from the original value of 100 to 7.7 for the summer mean in deep and large calcareous Mediterranean reservoirs, apparently more suitable considering the results obtained for the Pareja limno-reservoir.

For our data, MedPTI suggested a poorer ecological status than IGA. However, contrary to the IGA, higher MedPTI values (better ecological status) were obtained in the inflow zone. Furthermore, the lowest values were obtained in sampling surveys which were among those showing better trophic state according the OECD classification (OECD 1982). Apparently, the MedPTI was not an appropriate metric for assessing the ecological status of the Pareja limno-reservoir either. The existence of different species in the same algal group which have been shown to have different trophic preferences in Spanish and in Sardinian reservoirs (Marchetto et al. 2009) may be the reason behind this misfit of the index. Moreover, the species commonly found in Sardinian reservoirs do not usually account for more than 70% of the total annual biovolume in most Spanish reservoirs (Marchetto et al. 2009). This fact may complicate the application of the index not only in the Pareja limno-reservoir (as happened in 2008 and 2011), but in Spanish waterbodies as a whole.

Since the functional group approach seemed useful to describe the phytoplankton community in the Pareja Limno-reservoir, the Assemblage (Q) Index was also applied. It yielded lower values (worse ecological status) in the inflow zone than in the dam zone. Besides, the index suggested a *Good* ecological status in sampling surveys with trophic state conditions among the worst obtained (Table 4.2.6). Therefore, Assemblage (Q) index seems to be the most reliable phytoplankton composition metric of the three studied for assessing the ecological status of the Pareja limno-reservoir based on the phytoplankton composition. This is not surprising, since the assemblage approach has been successfully applied in other Mediterranean lakes and reservoirs (e.g., Moustaka-Gouni et al. 2007, Hoyer et al. 2009, Katsiapi et al. 2011). Our results suggest that the application of the assemblage approach could be also possible in the Pareja Limno-reservoir, whose surroundings are quite different from the cited waterbodies.

The simple regression analysis performed between the phytoplankton composition metrics and the trophic state indicators revealed the absence of statistical signification in most of the cases, even the tendency was opposite than expected in some of them (cyanobacteria contribution vs. TP and Chl- *a* and MedPTI vs. Chl- *a*, Fig. 4.2.3). Regressions versus TP were conditioned to the extreme TP value obtained in winter 2010 in the inflow zone. The TP vs. IGA relationship was statistically significant for the inflow zone samples and for the whole set. Aside from the extreme TP value, the tendency of the relationship was the opposite than expected. Q Index vs. Chl- *a* relationship was statistically significant in the inflow zone and, dismissing the extreme TP value, Q Index vs. TP was also statistically significant for the whole set of samples ($R^2 = 0.32$, $P = 0.006$). The Q Index would seem again to be the most reliable phytoplankton composition metric among the studied, although none of them showed a high level of accuracy. The fact of having many TP samples below the limit of detection, especially in the dam zone (Table 4.2.6), may reduce credibility from the analyses. A more precise method to quantify TP would be convenient in further research.

Our results suggested a *High* ecological status in the Pareja limno-reservoir according to the phytoplankton composition for most of the sampling surveys. This is consistent with the original expectation of a good ecological status favoured by the small size of the Ompólveda River basin, its low population and the low percentage of agricultural surface area. Results seem to confirm the fulfilment of the requirements of the WFD regarding phytoplankton (OJEU num. 327 2000), which would mean that the ecological status of the Pareja limno-reservoir provides a suitable environment for its original recreational purpose.

Nevertheless, we observed a lack of accuracy for all the phytoplankton composition metrics used in this research, which may have relevant implications in the management of the waterbody. The absence of fully reliable metrics may yield uncertainties when assessing the ecological status of the Pareja Limno-reservoir to check the fulfilment of the WFD, whose objective is to achieve a “good ecological status” in every aquatic ecosystem by 2015 (OJEU num. 327 2000). It led us to conclude that a new WFD Intercalibration exercise suitable for small Mediterranean lakes and reservoirs, including limno-reservoirs, is required. Metrics proposed in the first WFD Intercalibration exercise for Mediterranean deep and large reservoirs (EC 2009, Poikane et al. 2011) shall be updated to perform a proper determination of the ecological status of these smaller waterbodies. The incorporation of the other four biological elements suggested by the WFD in further works may be appropriate for a complete ecological status assessment, since phytoplankton indices may not be sensitive enough to track the changes that occur within a lake (Kaiblinger et al. 2009).

The new Intercalibration exercise for phytoplankton metrics could also include indices initially created for other areas but proven to work in the Mediterranean context, such as the Assemblage (Q) index. This index was created with the aim of being a robust and flexible tool for monitoring ecological status within the WFD regardless the geographic region (Padisák et al. 2006), and so it has been considered by other authors (e.g., Becker et al. 2010, Cellamare et al. 2012). The Assemblage Index showed a slightly better performance assessing the ecological status of the Pareja Limno-reservoir than the other metrics used. The incorporation of small and shallow Mediterranean lakes and reservoirs into WFD intercalibration gains relevance considering the threat that climate change may suppose to them. Several reports have predicted significant reductions in water resources by the end of the 21st century (between 20% and 40% in Central Spain, IPCC 2007, Domínguez-Padilla et al. 2009), and water quantity and water quality are closely linked (EEA 2012). The new Intercalibration exercise would be important for limno-reservoirs, since their number is increasing and they are constructed to mitigate the negative environmental impacts of large reservoirs in a Mediterranean climate (Molina-Navarro et al. 2010).

4.2.6. CONCLUSIONS

The phytoplankton community composition was studied in the Pareja limno-reservoir using the functional group approach. 77 species were identified, comprising 17 groups and 20 descriptor species belonging to 10 of these groups. Assemblage **B** dominated the phytoplankton community: its habitat template matches up with the limno-reservoir characteristics. Nevertheless, changes in the limno-reservoir environment, including deterioration of trophic state, driven shifts in the functional groups occurrence: groups **X2**, **J** and **Y** predominated when filling of the limno-reservoir was achieved and assemblage **B** dominance was occasionally shared or even surpassed by groups **MP** and **T** in summer, **P** and **X2** in winter and $\mathbf{L_o}$ in spring. The response of the phytoplankton assemblages to environmental changes suggested the usefulness of the functional group approach in the Pareja Limno-reservoir.

The ecological status of the limno-reservoir was studied in accordance with the WFD, considering phytoplankton biomass and composition metrics. Biomass metrics (Chl- *a* and phytoplankton biovolume) and contribution of cyanobacteria to total biovolume suggested a *Good* (or better) ecological status in summer for most of the samples. IGA, MedPTI and the Assemblage (Q) index suggested a *High* ecological status for most of the samplings or even in all of them (depending on the index). These results may indicate that the objectives of the WFD for ecological quality were fulfilled regarding phytoplankton at the Pareja limno-reservoir during the research.

However, after checking the response of the phytoplankton composition metrics to variations in trophic state, highly accurate results were never reached. It may have relevant implications in the limno-reservoir management since the ecological status assessment may be imprecise. We conclude that a new WFD Intercalibration exercise for phytoplankton in small and shallow Mediterranean lakes and reservoirs, including limno-reservoirs, is required. This exercise could also include other metrics proven to work in the Mediterranean context, such as the Assemblage (Q) index. Apparently, this index was the most reliable metric for ecological status assessment in the Pareja Limno-reservoir via phytoplankton composition data, despite having been originally developed for Hungarian lakes.

4.2.7. Acknowledgements

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4.2.8. References

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4.3. Microbiological water quality and its relation to nutrients

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A., Soliveri, J., Fernández-Monistrol, I., Copa-Patiño, J.L. Microbiological water quality and its relation to nitrogen and phosphorus at the Pareja Limno-reservoir (Guadalajara, Spain). Published in *Journal of Environmental Management* 92(3) (2011), 773-779.

Abstract

Bordering on the edge of the Entrepeñas reservoir (Guadalajara, Spain), next to the village of Pareja, a small dam that allows a body of water to develop with a constant level has been built. Initiatives like this (which we have termed "limno-reservoirs") are innovative in Spain and around the world. Earlier reservoirs such as this one were constructed to create a habitat for birds, but the Pareja limno-reservoir is the first to promote socio-economic development.

In order to study this limno-reservoir, this research group set up an environmental observatory, analyzing, among other variables, microbiological water quality and nutrient content. After a year and a half of research, it was observed that the concentration of microorganisms is lower in the limno-reservoir than in the river that feeds it, possibly due to the nutrient depletion in the lentic ecosystem. In the limno-reservoir, the total coliforms and enterococci concentrations fall within the European Bathing Water Directive limits, but in the river these concentrations are sometimes higher. The nutrient load in the limno-reservoir is low, with nutrient variations influencing native microorganisms, but not for total coliforms and enterococci. However, the development of special conditions in the bottom has been observed in winter, facilitating coliforms and enterococci survival.

This research is very interesting since the creation of limno-reservoirs is rising in Spain and no research is being done on their behaviour.

Keywords: enterococci, limno-reservoir, native microorganisms, nutrients, Pareja, total coliforms

Resumen

En una zona de cola del embalse de Entrepeñas (Guadalajara, España), junto al pueblo de Pareja, se ha construido una pequeña presa con la finalidad de dar lugar a una masa de agua de nivel constante. Este tipo de iniciativas, a las que hemos denominado "limnoembalses" son innovadoras en España y en el mundo. Los limnoembalses anteriores éste se construyeron con el fin de crear un hábitat para aves acuáticas, pero el Limnoembalse de Pareja es el primero en promover también el desarrollo económico.

Nuestro grupo de investigación ha puesto a punto un observatorio ambiental para estudiar este limnoembalse. Entre otras variables, se viene analizando la calidad microbiológica del agua y el contenido en nutrientes. Después de un año y medio de investigación, se ha observado que la concentración de microorganismos en el limnoembalse es menor que en el río que lo alimenta, posiblemente debido a la depleción de nutrientes en el ecosistema léntico. En el limnoembalse, las concentraciones de coliformes totales y enterococos se situaron por debajo de los límites de la Directiva Europea de Aguas de Baño, mientras que en el río superaron dichos niveles ocasionalmente. Las aguas del limnoembalse han mostrado una baja concentración de nutrientes, cuya variación parece influir a los microorganismos nativos pero no a los coliformes totales y enterococos. Sin embargo, en invierno se ha observado el desarrollo de condiciones especiales en el fondo del limnoembalse que podrían facilitar la supervivencia de coliformes y enterococos.

Esta investigación resulta muy interesante ya que la creación de limnoembalses tiene una tendencia creciente en España y actualmente no se está realizando ninguna investigación sobre su comportamiento.

Palabras clave: coliformes totales, enterococos, limnoembalse, microorganismos nativos, nutrientes, Pareja.

4.3.1. INTRODUCTION

The water levels of large reservoirs in areas with the Mediterranean climate vary widely due to exploitation and climatic conditions, causing undesirable effects on the environment, the landscape (including the “arid band” phenomenon), and even on the socioeconomic development of their surroundings. The Entrepeñas reservoir, located in the south of the province of Guadalajara (central Spain), with a capacity of 835 10^6 m^3 and 3213 10^4 m^2 of potential inundation area, is one of these reservoirs, its situation aggravated by the transfer of important volumes of water to southeast Spain. The inhabitants of the region began to demand corrective and/or compensatory actions for these environmental effects some years ago. In 2006, their protests led to the construction of a small dam on the edge of the Entrepeñas reservoir, next to the village of Pareja, which allows a small body of water with a constant level to develop. Dams like these are known as “edge dams” or “flood dams” and cause the resulting body of water to be independent of the management of the main reservoir. We have termed these bodies of water “limno-reservoirs” since they act more like a lake than a reservoir (Molina-Navarro et al., 2010).

The first initiatives of this kind in Spain were proposed in the late 80s and the early 90s, with the primary aim being the creation of a suitable habitat for birds (Rodríguez Cabellos, 1995; Ministerio de Medio Ambiente y Comité Nacional Español de Grandes Presas, 1996). Nevertheless, the Pareja limno-reservoir is the first to have a dual function: environmental and recreational. It is open for bathing or for taking a walk, it has a jetty for motorless craft, two artificial islands that act as bird refuges, and a fish ladder. No data have been found in the literature on this kind of initiative throughout the world.

Because of the innovative nature of this water management initiative and coinciding with the end of the process of filling the reservoir, we have set up an environmental observatory at the

Pareja limno-reservoir whose main aim is to study its viability through a multidisciplinary perspective. This project started in 2008 and is scheduled to last three years. Among other studies, the behaviour of the body of water is being monitored, including physicochemical, limnological, and microbiological aspects.

The only prior data related to microbiology available for the study area are the water quality analyses done by the Tajo River Basin Council from 2004 to 2009 (Confederación Hidrográfica del Tajo, 2009). In these reports, two points that supply drinking water to the village of Pareja were analyzed: one very near the village, next to the Valdetrigo stream, and a second one 5 km away at the head of the Ompólveda River. The total nitrogen and phosphate concentrations in every analysis were low. However, total coliforms and enterococci concentrations fluctuated, with higher values recorded in summer and early autumn and lower in winter. Total coliforms reached a maximum of 1900 and a minimum of 2 CFU 100 ml^{-1} (Colony-Forming Units per 100 ml), while the values for total enterococci ranging from 164 to 0 CFU 100 ml^{-1}. Otherwise, in every analysis but one, the microorganism concentrations were below the European Union Bathing Water Directive limits (900 and 330 CFU 100 ml^{-1} for Escherichia coli and enterococci, respectively).

The main activities in the Pareja limno-reservoir are bathing, aquatic sports, and motorless boating. For this reason, its water quality must be analyzed. We have evaluated the microbiological quality of the water according to the bathing water legislation in Spain e RD 1341-2007 (BOE, 2007, num. 257), which incorporates the European Union Bathing Water Directive (OJEU, 2006, num. 64) into national law. We have also studied the "good ecological status" of the limno-reservoir from a microbiological point of view, following the European Union Water Framework Directive (OJEU, 2000, num. 327).

The objective of this paper is to study the evolution of the microbiological quality of the water of a new type of reservoir, called a limno-reservoir, located in Pareja (Spain). It has an environmental and recreational function, being the first reservoir of its kind in Spain.

Different groups of microorganisms and nutrients (nitrogen compounds and total phosphorus) were analyzed over a period of 18 months, recording the concentration of microorganisms and the presence of the nutrients cited above. The evolution of the microbiological quality of the water during the study period will be established by comparing the results obtained with European Union Water Directives standards (OJEU, 2000, 2006).

4.3.2. MATERIAL AND METHODS

4.3.2.1. Study site

The Pareja limno-reservoir is located next to the village of the same name, in the south of the province of Guadalajara (Spain) and at the head of the Tajo River basin (Fig. 4.3.1). It has a capacity of 0.94 10^6 m^3, with a potential inundation area of 26 10^4 m^2. Its maximum depth is approximately 9 m near the dam[6], becoming progressively shallower towards its edge, where it measures 1.5 m. It is fed by the Ompólveda River, which has an 85.5 km^2 basin[7], and by its main tributary, the Valdetrigo stream, merging from the northeast. About 300 inhabitants live in the basin area, most of them in Pareja (whose population quadruples in summer). Pareja's wastewater is sent downstream past the limno-reservoir after a primary treatment in order to preserve its water quality. This fact, a priori, favours good quality river and limno-reservoir water.

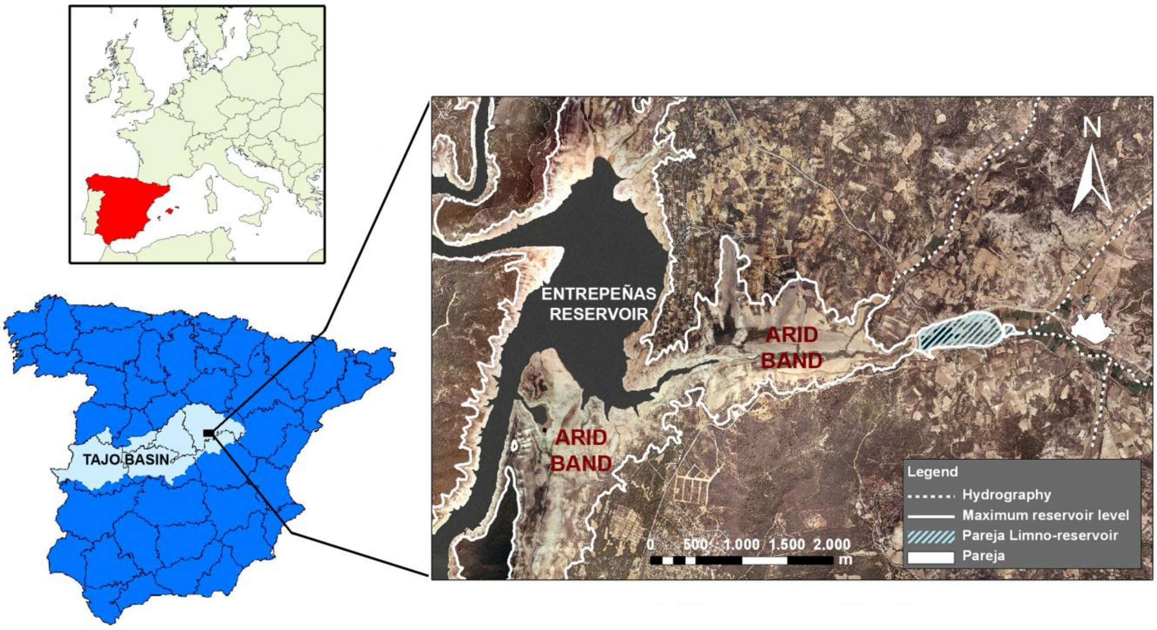

Fig. 4.3.1. The location of the Pareja limno-reservoir and the comparison of the volume of water stored in the Entrepeñas reservoir in 2006 with its maximum capacity (modified from Molina-Navarro et al., 2010).

4.3.2.2. Sampling strategies

Seven sampling campaigns were performed seasonally since the beginning of the study: spring, summer, and autumn 2008; winter, spring, summer and autumn 2009. Six sampling points were designed along the body of water (Fig. 4.3.2): four creating a vertical profile next to the limno-reservoir dam (M1-M4, at depths of 0, 2, 5, and 8 m, respectively), one on the surface of the limno-reservoir edge (M5), and one more in the Ompólveda River,

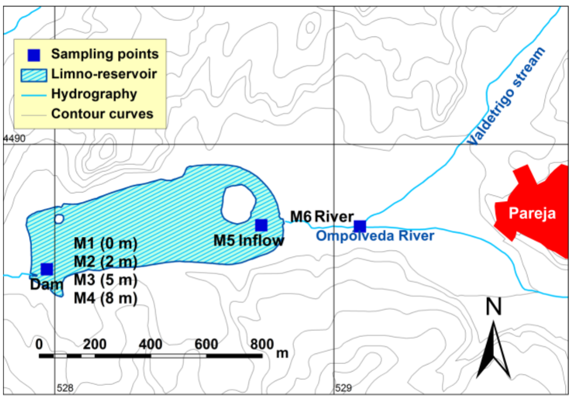

Fig. 4.3.2. Sampling stations at the Pareja limno-reservoir (modified from Molina-Navarro et al., 2009).

[6] A further more accurate study showed that the maximum depth is around 12.5 m
[7] A further more accurate study showed that the basin area is around 88 km^2

just after the mouth of Valdetrigo stream (M6). All of the samplings were conducted from 10:00-11:30 am. In addition, a few samples were taken randomly upstream in the Ompólveda River to look for possible sources of pollution.

4.3.2.3. Microbiological analyses

1.5 l sterile plastic bottles were used to collect samples to analyze the concentration of different groups of microorganisms: aerobic mesophiles, oligotrophs, total coliforms, enterococci, sulphite reducing bacteria, and the presence of faecal *E. coli*. Aerobic mesophiles, oligotrophs, and sulphite-reducing bacteria were determined at the laboratory by spreading 0.2ml of sample in Petri dishes containing 20 ml of PCA (Microkit S.L.), R2 (Microkit S.L.), or SPS (Liofilchem srl) media, respectively. All analyses were duplicated, incubating the dishes at 37 ºC for 24 h (48 h for SPS medium). Oligotrophs were also incubated at 22 ºC for 72 h. Once the culture process had finished, colony counting was performed. Total coliforms and enterococci were counted using the Most Probable Number method (MPN, Guinea et al., 1979) with MacConkey broth (Scharlau) and Kanamycin Esculin Azide broth (Scharlau) media, respectively. For tubes with coliform growth, new tubes were prepared to be incubated at 44 ºC for 24 h to confirm the faecal character of the microorganisms. Petri dishes with Levine medium (Scharlau) were also inoculated using those tubes with the streak-plate technique and either incubated at 37 ºC or 44 ºC (faecal) for 24 h. The dishes were then checked for the presence of *E. coli*.

4.3.2.4. Total phosphorus and nitrogen compound analyses

Sterile containers were used to collect 250 ml and 100 ml samples to analyze nitrogen compound concentrations and total phosphorus (TP) concentrations, respectively. Nitrogen compounds (nitrate, nitrite, and ammonia) were analyzed *in-situ* with a LASA 100 portable photometer. TP was determined in the laboratory using a LASA DR 2800 photometer, but only for the samples obtained from the surface (samples M1, M5, and M6). Beside this, physicochemical characteristics (conductivity, pH, temperature, oxygen and total suspended solids) were analyzed *in-situ* with an YSI 6920 Multi-Parameter Water Quality Sonde. Samplings and analyses were done in collaboration with a specialized team from the Centre for Hydrographic Studies (CEH-CEDEX, Spanish Ministry of the Environment).

4.3.3. RESULTS AND DISCUSSION

4.3.3.1. Concentration of microorganisms

a) Native microorganisms

Results showed that concentrations of aerobic mesophiles and oligotroph microorganisms were lower in the limo-reservoir samples (M1-M5) than in the Ompólveda River (M6) (Fig. 4.3.3).

It can be observed that the concentration of microorganisms in the limno-reservoir samples (M1-M5) was highest in spring 2008, possibly because the limno-reservoir had just been filled for the first time and a lake dynamic had not yet been established. Over the entire study period, the mean values in the limno-reservoir in all the samples taken were 651 CFU ml^{-1} for aerobic mesophiles, 754 CFU ml^{-1} for oligotrophs incubated at 37 ºC, and 1676 CFU ml^{-1} for oligotrophs incubated at 22 ºC. However, in the river (sample M6), mean concentrations of 3458 CFU ml^{-1} for aerobic mesophiles and 8316 CFU ml^{-1} for oligotrophs at 37 ºC were found. Oligotrophs incubated at 22 ºC always showed massive growth (except in the autumn of 2008), as occurred with all of the cultures in the summer of 2009. The depletion of nutrients concentrations caused by the presence of a new lentic habitat (Dobson and Frid, 1998) could explain the decrease in the concentration of native microorganisms in the limno-reservoir. Moreover, nutrient retention in sediments is a well-known process of lakes and reservoirs (Margalef, 1983).

It was observed that both aerobic mesophiles and oligotrophs had the same tendency over time in every sample (Fig. 4.3.3), which is logical since they are native populations. The number of oligotrophs incubated at 22 ºC was higher because the incubation temperature used was similar to the temperature of their natural environment (from 6 ºC to 21 ºC), so it appears that oligotroph microorganisms are the best adapted to their environmental conditions.

b) Total coliforms, enterococci, and sulphite-reducing bacteria

Table 4.3.1 shows the concentration of total coliforms and enterococci in the Ompólveda River (M6) and in the limno-reservoir (M1-M5) over the study period. Growth of sulphite-reducing bacteria was never detected.

The concentrations of these microorganisms are higher in the Ompólveda River, sometimes going beyond the limits of the directive. Flocks of sheep graze in the Ompólveda basin which could be one of the reasons for the presence of total coliforms and enterococci in the river. In addition, it has been demonstrated that small streams flowing through pastures are systematically more contaminated than those draining only forests or farmlands (Garcia-Armisen and Servais, 2007; Servais et al., 2007). Maximum values in the river for total coliforms and enterococci concentrations were more than 2400 CFU 100 ml^{-1} for both groups in the summer of 2009. Concentrations may have reached their highest level because of the increase in the number of inhabitants during the summer season, which implies a significant increase in Pareja's water supply needs coming from the head of the Ompólveda River basin. Consequently, this adds to natural summer drought and brings the flow volume of the river to its lowest, greatly diminishing the dilution capacity for all kinds of pollution.

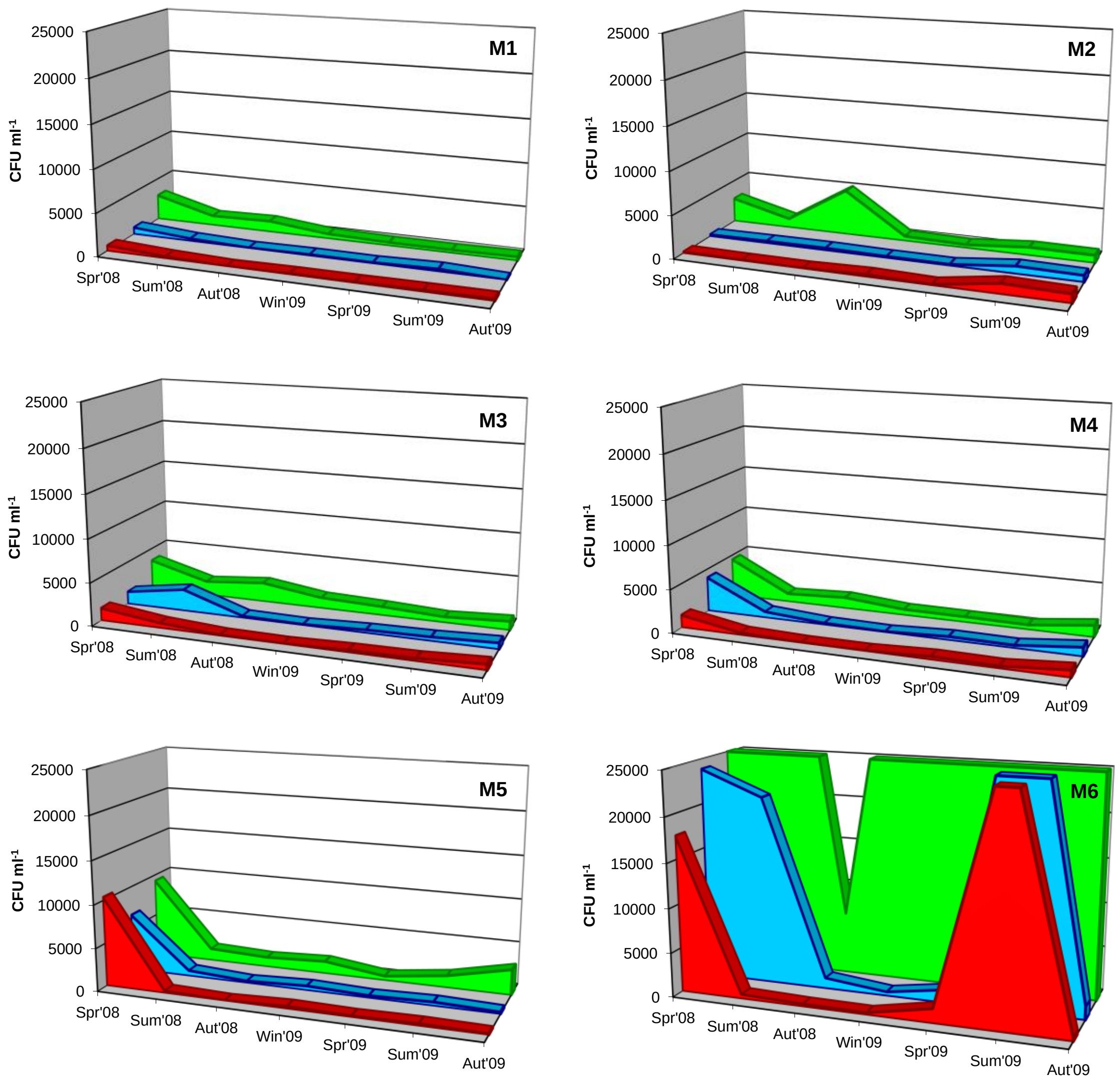

Fig. 4.3.3. Concentrations of aerobic mesophiles (red), oligotrophs at 37 ºC (blue), and oligotrophs at 22 ºC (green) in the Pareja Limno-reservoir (M1-M5) and in the Ompólveda River (M6).

The results obtained from random samples taken upstream in the Ompólveda River basin (Table 4.3.1) confirmed the presence of total coliforms and enterococci (even upstream from the point where Pareja receives its drinking water supply). This fact suggests that these microorganisms most likely come from a diffuse origin (like flocks of sheep) more than from a specific source. Additionally, the values obtained in the river (M6 and upstream) were congruent with the water quality analyses done by the Tajo River Basin Council (Confederación Hidrográfica del Tajo, 2009).

The concentration of total coliforms and enterococci was lower in the limno-reservoir samples (M1-M5) than in the sample taken from the Ompólveda River (M6). Besides nutrient depletion, sedimentation and die-off within reservoirs have been described as processes that decrease the number of total coliforms and enterococci in these bodies of water (Kay et al., 2010). The values obtained in the limno-reservoir samples (M1-M5) were always within the "excellent quality" level of the European Union Bathing Water Directive (500 and 200 CFU 100 ml^{-1} for *E. coli* and enterococci, respectively) (OJEU, 2006, num. 64), thus allowing the activities the infrastructure was designed for to be enjoyed: swimming and recreation. Nevertheless, the highest values of these microorganisms in the limno-reservoir were obtained in autumn 2008 and winter 2009, when rain events were more abundant. This is congruent with the affirmations of some authors who have said that levels of total coliforms and enterococci often peak after rain events (Haggarty et al., 2010; Hong et al., 2010).

The faecal character of coliforms was evaluated by the presence of E. coli, as described in the methods section. Faecal *E. coli* was detected throughout the study in different samples from every sampling campaign except the first (spring 2008) in which no faecal contamination was detected in any sample. In the autumn 2008 campaign, faecal contamination was detected in all of the samples (Table 4.3.1). This phenomenon may be due to some very intensive storms that happened few days before sampling, causing Pareja's water treatment system to collapse, with the overflow reaching the river.

Table 4.3.1. Concentrations of total coliforms and enterococci in the Pareja Limno-reservoir and in the Ompólveda River expressed in CFU per 100 ml. The + and – symbols in the total coliforms column represent the presence or absence of faecal *Escherichia coli.*

	Total Coliforms (Faecal *E. coli*)							**Enterococci**						
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**Upstream**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**Upstream**
Spring 08	15 (-)	9 (-)	9 (-)	9 (-)	43 (-)	1,100 (-)		0	0	0	0	4	43	
Summer 08	0	4 (+)	0	4 (+)	0	93 (+)		0	0	0	0	23	460	
Autumn 08	15 (+)	9 (+)	23 (+)	9 (+)	4 (+)	93 (+)		4	4	0	0	0	150	
Winter 09	4 (+)	0	9 (+)	15 (-)	4 (-)	460 (+)	15 (+)	0	0	4	9	43	150	240
Spring 09	0	0	3 (+)	0	0	75 (+)	93 (+)	0	0	43	3	0	460	93
Summer 09	0	0	0	0	4 (-)	>2,400 (+)	4 (+)	0	0	0	0	0	>2,400	3
Autumn 09	3 (-)	0	4 (+)	0	0	460 (+)	1,100 (+)	0	0	4	0	9	150	43

4.3.3.2. Nutrient load and influence on microorganisms

a) Nitrogen compounds and total phosphorus concentrations

During the course of our research, nitrogen compound concentrations (represented as mg of nitrogen per litre in the nitrate, nitrite or ammonium form) were very low in the limno-reservoir samples (M1-M5). Nitrate concentrations were most often below the limit of detection (LOD), 0.230 mg N l^{-1} (the exceptions were March and June 2009, with average concentrations of 0.640 and 0.420 mg N l^{-1}). Nitrite was also below LOD (0.015 mg N l^{-1}), except in June 2009, with an average concentration of 0.073 mg N l^{-1}. Ammonia concentrations were between 0.040 and 0.430 mg N l^{-1}, reaching their highest values in the summer months at the bottom of the limno-reservoir due to the denitrification of nitrate in the lower hypolimnion during stratification (Wetzel, 2001). Once again, the behaviour in March 2009 was different, with a peak of 2.707 mg N l^{-1} at M3. Highest values for nitrogen compounds that month seemed to come from the resuspension of sediments in the limno-reservoir caused by strong storms prior to sampling.

In the Ompólveda River sample, the values of nitrites and ammonia were similar to those found in samples from the limno-reservoir, but nitrate concentration was higher, 0.530 mg N l^{-1} on average. The nutrient depletion in the limno-reservoir described above (Dobson and Frid, 1998) is clearly observed here, in addition to the retention of nitrate caused by the abundant presence of *Phragmites australis* on the banks of the limno-reservoir (Tian et al., 2009). Apart from that maximum in March 2009, the nitrogen compound values were within the total nitrogen values that Camargo and Alonso (2006) considered to be the eutrophication limits for temperate lakes and rivers (1.260 and 1.500 mg N l^{-1}, respectively), far from the limno-reservoir sample values.

The total phosphorus (TP) load was low in the limno-reservoir (M1-M5) and slightly higher in M6 (Ompólveda River). Concentrations oscillated between 0.025 mg P l^{-1} and LOD (0.010 mg P l^{-1}) at M1, between 0.035 mg P l^{-1} and LOD at M5, and between 0.015 and 0.070 mg P l^{-1} at M6. Nutrient depletion in the lentic ecosystem was observed (Dobson and Frid, 1998). According to the criteria of the OECD (1982) applied by the Spanish Ministry of the Environment (Ministerio de Medio Ambiente, 2000), TP values fall into the “mesotrophic” and “oligotrophic” categories in the limno-reservoir (0.010-0.035 and <0.010 mg P l^{-1}, respectively), while river values are sometimes in the “eutrophic” level (0.035-0.100 mg P l^{-1}). They also belong to Bratli’s (2000) top suitability class (“well suitable”) for water quality for bathing and recreation (<0.070 mg P/l).

Therefore, the nutrient load was not a limitation for microbiological activity in the Ompólveda River. However, nutrient depletion, which was previously pointed out as a possible reason for the decrease in microorganism concentration in the limno-reservoir, actually occurs. The possible influence of differential nitrogen compounds and TP loads inside the limno-reservoir, which could play an important role in microorganism’s populations, was also studied.

b) Influence of nitrogen and phosphorus on native microorganisms

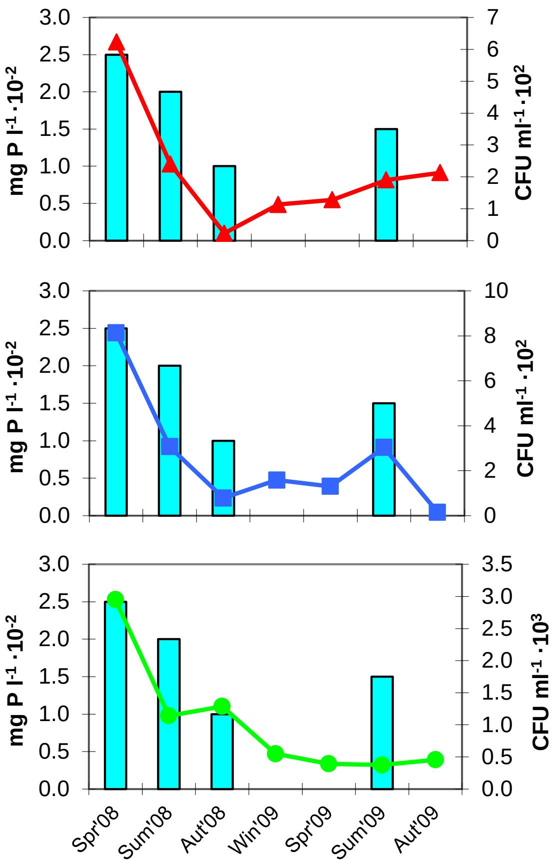

Fig. 4.3.4. Total phosphorus (TP) and aerobic mesophiles (a), oligotrophs at 37 ºC (b) and oligotrophs at 22 ºC (c) concentrations in the surface of the dam zone (M1). The absence of bars indicates TP concentration is below the limit of detection (0.01 mg l^{-1}).

The results showed no relationship between nitrogen compound concentrations and the recount of aerobic mesophiles and oligotroph microorganisms (data not shown). This suggests that the concentration of nitrogen compounds does not limit native micro-organisms populations. Other environmental factors may control the mesophile and oligotrophs populations.

Total phosphorous seems to be directly related to the concentration of native microorganisms in the dam zone (M1) (Fig. 4.3.4). Phosphorus is usually reported as the limiting nutrient in freshwater (Wetzel, 2001), and small increases in low concentrations in the dam zone of the limno-reservoir may actually stimulate microorganism populations.

c) Influence of nitrogen and phosphorus on total coliforms and enterococci

Inside the limno-reservoir, no apparent relationship can be found between total coliforms and enterococci and the nutrient load.

In the winter of 2009, when the highest concentrations of nitrogen compounds were recorded, an increase in both groups of microorganisms was also found at the bottom of the dam zone (M4). However, looking at Fig. 4.3.5[8], this increase cannot be related to nitrogen, as it shows high concentrations throughout the entire water column. Temperature, oxygen and conductivity profiles suggest that special conditions were taking place at a depth of 7-9 m, probably due to the flow of a cool and silt laden runoff from the Ompólveda River into the hypolimnion. The decomposition of the organic matter in the suspended solids by microorganims may explain the diminishing of oxygen and nitrogen compounds concentrations from 5 m depth (M3). At this depth, suspended solids may facilitate coliform survival or growth by adsorbing coliform and by protecting them from adverse factors (Hong et al., 2010). The same behaviour could also be applied to enterococci since both enterococci and total coliforms are part of the natural microorganism populations (Garcia-

[8] Total suspended solids profile in the original figure has been deleted as it actually represented an estimation of total dissolved solids.

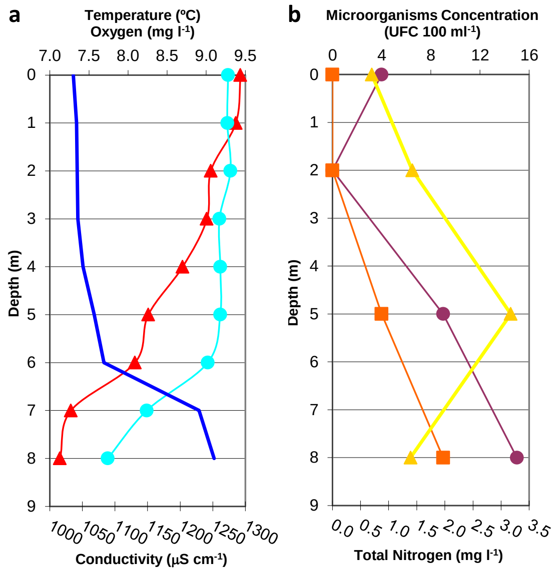

Fig. 4.3.5. Depth profiles for a) temperature (▲), oxygen (●), conductivity (▬) and b) total nitrogen (▲), total coliforms (●) and enterococci (■) in winter 2009 in the dam zone.

Armisen and Servais, 2007; Servais et al., 2007). Further research will be done in order to study the possible occurrence of similar episodes in the future.

Our research group is continuing its investigation in order to obtain more accurate results and to determine how to maintain the microbiological and ecological status of the Pareja limno-reservoir. This research is pioneering and of significant interest as a means of guaranteeing the viability of these new infrastructures because of the rising tendency to build them (every new large reservoir to be built in Spain has projected the construction of a limno-reservoir, in addition to the ones that are being created in old reservoirs) and because studies similar to the one presented in this paper have not been found in the literature.

4.3.4. CONCLUSIONS

After 18 months of research, the microbiological water quality of the Pareja limno-reservoir appears to be fine, with a predomination of oligotrophic microorganisms and with total coliform and enterococci concentrations below the limits of the European Union Bathing Water Directive. Signs of faecal contamination were detected in the Ompólveda River making further investigation necessary.

A remarkable influence of nutrient depletion (from the river to the limno-reservoir) on the microorganisms of the limno-reservoir was observed which controls its populations. Thus, increases in nutrient load may worsen the ecological status of the body of water, which would go against the Water Framework Directive. Regarding the differential nutrient load inside the limno-reservoir, a positive relation between TP and native microorganisms was detected in the dam zone.

Coliforms and enterococci, however, did not show a relationship with differential nutrient load inside the limno-reservoir. However, in winter 2009, higher suspended solids concentration created by silt-laden runoff have been seen to facilitate coliforms and enterococci survival at the bottom of the limno-reservoir.

4.3.5. Acknowledgements

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4.3.7. Annex

This manuscript covers a period of 18 months (spring 2008-autumn 2009). However, to give uniformity to Chapter 4, this appendix expands the published content up to three years, adding data from five seasonal samplings (from winter 2010 to winter 2011). The methodology followed was exactly the same as described above. New results obtained are described and discussed, comparing them with those previously obtained.

4.3.7.1. Updated results and discussion

a) Native microorganisms concentration

Figure 4.3.6 shows the new data on native microorganisms concentration. The highest native microorganisms concentration were found again in the Ompólveda River (M6). However, oligotroph microorganisms incubated at 22 ºC showed massive growth in four limno-reservoir samples (spring 2010 in M1 and winter 2010, autumn 2011 and winter 2011 in M5). In the Ompólveda River, oligotrophs at 37 ºC were massive in winter 2010 too.

The second half of the research was more humid than the first one. Total precipitation between spring 2008 and autumn 2009 sampling surveys (18 months) was 613 mm, while total precipitation between autumn 2009 and winter 2011 sampling surveys (15 months) was 1149 mm, almost double. The Ompólveda River runoff volume increases proportionally much more than the rainfall (Molina-Navarro et al., 2010). High microorganisms concentrations observed in the limno-reservoir during the second half of the research may be associated with higher runoff inputs from the Ompólveda River (Trevisan et al., 2010; Droppo et al., 2011). Actually, the highest Ompólveda River discharges of the research period were recorded in winter and spring 2010 (1128 and 530 l s^{-1}, respectively).

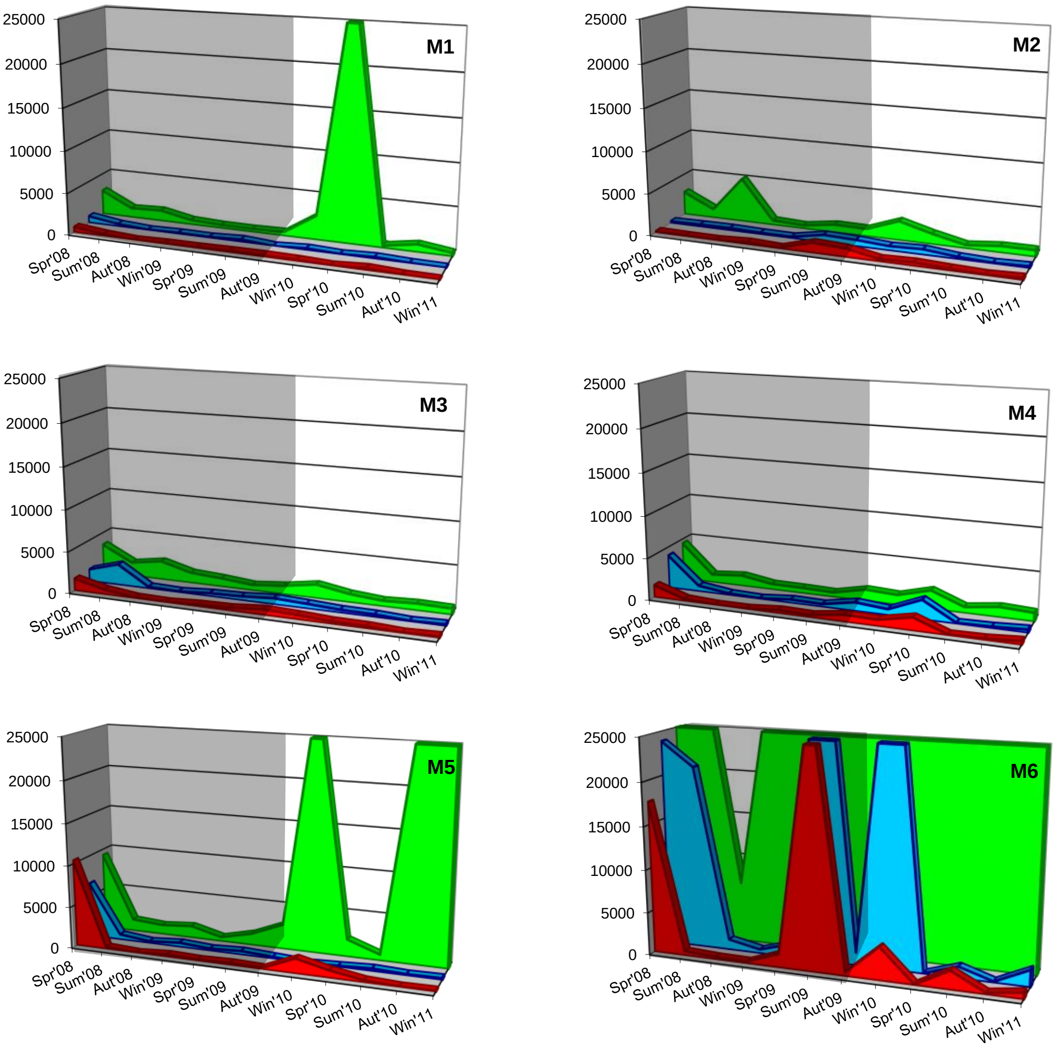

Fig. 4.3.6. Concentrations of aerobic mesophiles (red), oligotrophs at 37 ºC (blue), and oligotrophs at 22 ºC (green) in the Pareja Limno-reservoir (M1-M5) and in the Ompólveda River (M6). Shaded areas correspond to published data.

b) Total coliforms, enterococci and sulphite-reducing bacteria concentrations

The concentration of total coliforms, enterococci and sulphite-reducing bacteria did not show significant differences with the period previously studied (Table 4.3.2). Growth of sulphite-reducing bacteria was never detected again. Total coliforms and enterococci values in the limno-reservoir (M1-M5) remained within the "excellent quality" level of the EU Bathing Water Directive (500 and 200 CFU 100 ml^{-1} for E. coli and enterococci, respectively) (OJEU, num. 64, 2006). Microorganisms are not among the compulsory biological indicators defined in the EU Water Framework Directive (OJEU num. 327, 2000). However, recreational waters are defined as protected areas in this Directive, and these areas shall be supplemented by those specifications contained in other Community legislation (i.e. the Bathing Water Directive). Thus, the fulfilment of the Bathing Water Directive requirements also involves the compliance with the Water Framework directive regarding microorganisms.

Table 4.3.2. Concentrations of total coliforms and enterococci in the Pareja Limno-reservoir and in the Ompólveda River expressed in CFU per 100 ml. The + and – symbols in the total coliforms column represent the presence or absence of faecal *Escherichia coli*. Shaded cells correspond to published data.

	Total Coliforms (Faecal *E. coli*)							Enterococci						
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**Upstream**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**Upstream**
Spring 08	15 (-)	9 (-)	9 (-)	9 (-)	43 (-)	1,100 (-)		0	0	0	0	4	43	
Summer 08	0	4 (+)	0	4 (+)	0	93 (+)		0	0	0	0	23	460	
Autumn 08	15 (+)	9 (+)	23 (+)	9 (+)	4 (+)	93 (+)		4	4	0	0	0	150	
Winter 09	4 (+)	0	9 (+)	15 (-)	4 (-)	460 (+)	15 (+)	0	0	4	9	43	150	240
Spring 09	0	0	3 (+)	0	0	75 (+)	93 (+)	0	0	43	3	0	460	93
Summer 09	0	0	0	0	4 (-)	>2,400 (+)	4 (+)	0	0	0	0	0	>2,400	3
Autumn 09	3 (-)	0	4 (+)	0	0	460 (+)	1,100 (+)	0	0	4	0	9	150	43
Winter 10	0	0	0	0	23 (+)	150 (+)		0	0	0	0	150	150	
Spring 10	4 (+)	9 (-)	4 (-)	0	9 (+)	43 (+)		0	0	3	3	0	43	
Summer 10	4 (-)	0	9 (-)	0	4 (-)	240 (+)		0	4	0	0	0	1,100	
Autumn 10	9 (-)	0	0	4 (-)	93 (+)	240 (+)		4	0	4	4	9	93	
Winter 11	0	0	0	4 (-)	0	4 (+)		0	0	0	0	4	9	

c) Influence of nitrogen and phosphorus on native microorganisms

The massive growth of native microorganisms populations observed the limno-reservoir during winter 2010 and 2011 (Fig. 4.3.7) matched up with the highest nutrients concentrations. In winter 2010, nitrate concentration was 2.21 mg N l^{-1} in the surface of the dam zone (M1) and total phosphorus concentration was 0.11 mg P l^{-1} in the inflow zone (M5). In winter 2011, nitrate and total phosphorus (TP) values were 0.78 mg N l^{-1} and 0.030 mg P l^{-1} in M1 and 0.88 mg N l^{-1} and 0.035 mg P l^{-1} in M5. High rainfall and consequent high runoff in winter favours both microorganisms concentration (Trevisan et al., 2010; Droppo et al., 2011) and nutrients concentration (Álvarez-Cobelas et al., 2008; Buda et al., 2009), but also high nutrients may enhance microorganisms reproduction.

During the first half of the research, TP seemed to be directly related with the concentration of native microorganisms in the dam zone (M1, Fig. 4.3.4). In fact, no statistics were applied, but simple regression analyses corroborate a significant relationship (R^2=0.76 and P=0.010 for aerobic mesophiles; R^2=0.86 and P=0.003 for oligotrophs at 37ºC; R^2=0.63 and P=0.033 for oligotrophs at 22ºC; TP limit of detection, 0.010 mg P l^{-1}, was assigned for those samples below it). However, this relationship was not observed in the second half of the research (Fig. 4.3.7), when TP in M1 was below the limit of detection in all the samples except winter 2011. Climate was much wetter during the second half of the research. It may imply that native microorganisms population during wet seasons are governed by other factors (e.g. lower retention time or higher organic matter inputs due to high river discharges) rather than internal TP concentration.

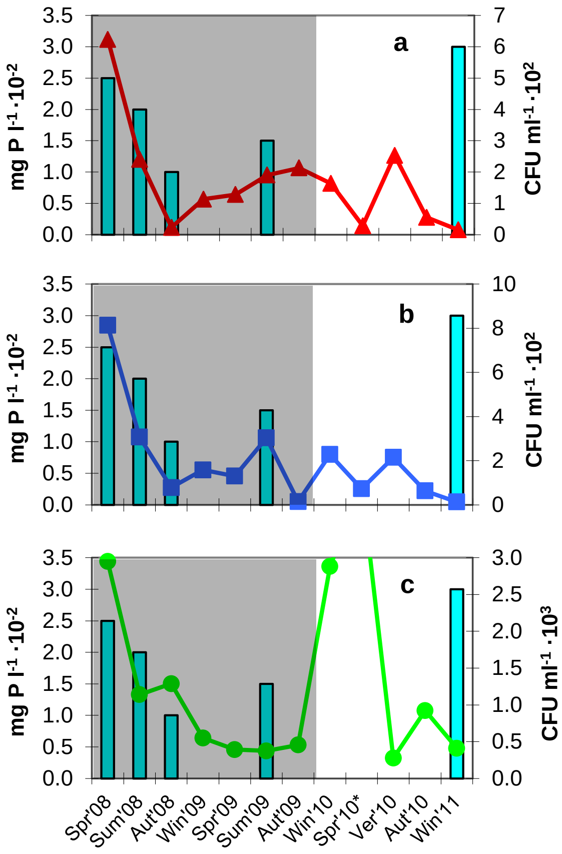

Fig. 4.3.7. Total phosphorus (TP) -bars- and aerobic mesophiles (a), oligotrophs at 37 ºC (b) and oligotrophs at 22 ºC (c) concentrations -lines- in the surface of the dam zone (M1). The absence of bars indicates TP concentration is below the limit of detection (0.01 mg l^{-1}). Shaded areas corresponds to published data. *Massive growth of oligotrophs at 22ºC in spring 2010.

d) Influence of nitrogen and phosphorus in total coliforms and enterococci

Nutrients peaks in this new period (described in the previous section -*c*-) also matched up with some of the highest coliforms and enterococci concentrations (Table 4.3.2) in the limno-reservoir, especially in M5. According to Gao et al. (2011) and Droppo et al. (2011), the fate and transport of faecal bacteria is highly related to the sediment transport, which increases under high river discharge conditions and leads to a rise nutrients as well. Actually, sediment load is one of the main sources of TP in Mediterranean environments (Panagopoulos et al., 2011).

In the published paper, we hypothesized that during winter the cool and sediment laden runoff from the Ompólveda River could flow into the hypolimnion with associated coliforms and enterococci. This phenomenon has been described by various authors (Wetzel, 2001; Hobson et al., 2010). We also suggested that the diminishing of oxygen and nitrogen from 5 m depth may be related to the decomposition of the organic matter in the sediments by microorganisms. In winter 2010 and 2011, decreasing of dissolved oxygen in the bottom of the limno-reservoir was observed again, even more noticeable (see Chapter 4.1, Fig. 4.1.2), but a significant increase of coliforms and enterococci was not observed. Further research would be needed for a deeper study of this kind of episodes.

4.3.7.2. Annex conclusions

Wetter climate and higher Ompólveda River discharges during the second half of the research favoured both microorganisms and nutrients concentrations. High runoff volume involves high sediment transport, which is strongly related with bacteria and nutrient transport. It led to massive growth of native microorganisms at certain moments in the Pareja Limno-reservoir, showing also higher concentrations of total coliforms and enterococci. Nevertheless, they remained within the “excellent quality” level of the EU Bathing Water Directive.

4.3.7.3. Annex references

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5. Catchment erosion and limno-reservoir sedimentation

5. Catchment erosion and limo-reservoir sedimentation risk

This chapter reproduces the text of the following manuscript:

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A. and Bienes-Allas, R. Catchment erosion, sediment delivery and sedimentation risk assessment in a limno-reservoir using a simple methodology. Submitted to *Water Resources Management* on 31/12/2012 and currently under review (Manuscript ID: WARM-D-13-00008)

Abstract

Soil erosion and sediment yield pose significant environmental conservation threats. These processes have been studied in a small catchment in order to assess the sedimentation risk in the Pareja Limno-reservoir (Central Spain). This hydraulic infrastructure was built in 2006 in the riverine zone of a large reservoir with environmental and recreational purposes.

Sedimentation risk is an issue of concern regarding limno-reservoirs environmental feasibility. Thus, the study of the soil erosion at a catchment scale and the sediment yield into the Pareja Limno-reservoir seemed of the utmost importance. In this paper we establish an affordable and simple methodology to address it. A soil erosion and deposition monitoring network was installed in the Ompólveda River basin (≈88 km^2), which flows into the Pareja Limno-reservoir. Sedimentation in the limno-reservoir was studied taking sediment cores.

Gross hillslope erosion in the catchment was 5.97 T ha^{-1} $year^{-1}$, which is in agreement with values reported for Mediterranean areas. After subtraction of the deposition measured, a soil loss of 1.17 T ha^{-1} $year^{-1}$ was found in the catchment. Specific sediment yield (SSY) was estimated to be 0.23 T ha^{-1} $year^{-1}$ in the catchment, being sediment delivery ratio (SDR) around 3.9%. SDR is low as a result of the low connectivity between the stream network and the limno-reservoir. Some local characteristics may also have a secondary influence in the low SDR value. The limno-reservoir is filled up at an approximate rate of 0.29% per year.

Results obtained support the environmental feasibility of the Pareja Limno-reservoir from the sedimentation risk perspective. They also demonstrate that the methodology followed allows the assessment of soil loss and sediment delivery at a catchment scale, and the identification of areas where the erosion problems are most severe.

Keywords: Catchment scale; environmental feasibility; limno-reservoir; sediment yield; sedimentation risk; soil erosion.

Resumen

La erosión del suelo y la producción de sedimentos constituyen significantes amenazas para la conservación ambiental. Se han estudiado dichos procesos en una pequeña cuenca para evaluar el riesgo de aterramiento del Limnoembalse de Pareja (España central). Esta infraestructura hidráulica fue construida en 2006 con fines ambientales y recreativos en la zona de cola de un gran embalse.

El riesgo de aterramiento constituye un asunto de interés en lo relativo a la viabilidad ambiental de los limnoembalses. Es por esto por lo que el estudio de la erosión del suelo a escala de cueca y la descarga de sedimentos hacia el limnoembalse parece primordial. En este artículo se establece una metodología económica y sencilla para abordarlo. Se ha instalado una red de medida de la erosión y la sedimentación en la cuenca del río Ompólveda (≈88 km^2), el cual alimenta al Limnoembalse de Pareja. El aterramiento en el embalse se estudió mediante la toma de testigos.

La erosión bruta en la cuenca se ha estimado en 5,97 T ha^{-1} año^{-1}, lo que resulta concordante con los valores obtenidos por otros autores en áreas mediterráneas. Una vez sustraída la sedimentación registrada, se ha obtenido un valor de pérdida de suelo en la cuenca de 1,17 T ha^{-1} año^{-1}. La producción específica de sedimentos en la cuenca fue estimada en 0,23 T ha^{-1} año^{-1}, lo que supone que solo un 3,9% de los sedimentos movilizados en la cuenca alcanzan el limnoembalse. La poca conectividad hidrológica en la cuenca se configura como el principal motivo de este bajo porcentaje, aunque algunos factores locales también pueden ejercer una influencia secundaria. La tasa anual de aterramiento del limnoembalse es aproximadamente de un 0,29%.

Los resultados obtenidos garantizan la viabilidad ambiental del Limnoembalse de Pareja desde el punto de vista del riesgo de aterramiento. También demuestran que la metodología propuesta permite la evaluación de la pérdida de suelo y el suministro de sedimentos a escala de cuenca, así como la identificación de áreas donde el riesgo de erosión es más severo.

Palabras clave: escala de cuenca; erosión del suelo, limnoembalse, producción de sedimentos, riesgo de aterramiento, viabilidad ambiental.

5.1. INTRODUCTION

Large reservoirs under Mediterranean climate are the origin of a variety of negative impacts (MMAMRM 2011). Consequently, water Administrations in Spain have promoted some mitigation actions during the last decades. The construction of small dams in the riverine zone of large reservoirs has been one of these actions (MMA and CNEGP 1996). They generate a body of water with a constant level, independent from the management of the main reservoir. Because of these specific characteristics, we have termed these bodies of water “limno-reservoirs”, as they resemble a lake more than a reservoir (Molina-Navarro et al. 2010, 2012a). The Pareja Limno-reservoir (central Spain, upper Tagus River Basin) was built in 2006 as a response to the claims of the inhabitants of the Entrepeñas Reservoir area, who have been enduring the environmental and socio-economic effects derived from the construction and exploitation of this large reservoir (835 hm3, 3213 ha of potential inundation). This exploitation includes large water volumes diverted to

Southeast Spain (Molina Navarro et al. 2010). Moreover, the Pareja Limno-reservoir is the first one having a dual function: environmental and recreational (Molina-Navarro et al. 2010, 2011).

The interest and convenience of this kind of initiatives are unquestionable. Nevertheless, limno-reservoirs are not cheap infrastructures and their construction has raised some issues about its environmental feasibility. Considering these facts, their novelty and the rising trend to build them, acquiring knowledge about their behaviour seems convenient. With this aim, in 2008 we started a research project in the Pareja Limno-reservoir considering a multidisciplinary perspective. The research team has been working on microbiological water quality (Molina-Navarro et al. 2011), limnological characteristics (Molina-Navarro et al. 2012a) and hydrologic feasibility (Molina-Navarro et al. 2010, 2012b), among other topics.

Sedimentation risk is another issue of concern regarding limno-reservoirs environmental feasibility and it has been also studied in the Pareja Limno-reservoir project. Soil erosion and sediment yield are processes which pose significant environmental conservation threats. Moreover, they can be strongly accelerated by land use and climate change, and represent an important hazard to the long term sustainability of ecosystems (Alatorre et al. 2010). Spain is one of the countries most severely affected by soil erosion in the European Mediterranean region (Solé Benet 2006). Besides, estimation of sediment discharge is of the utmost importance to assess and design hydraulic systems (de Vente et al. 2005; Zarris et al. 2011). Reservoirs worldwide are currently filled up with sediments at a rate of approximately 1% per year (WDC 2000), but for many reservoirs, annual storage capacity loss can go up to 4% or 5%, losing the majority of their capacity after only 25-30 years (de Vente et al. 2005; Zarris et al. 2011). Considering its low volume, the Pareja Limno-reservoir could lose its capacity in only a few years in case of high sedimentation rates were found. Thus, the study of soil erosion in the Pareja Limno-reservoir catchment and sediment yield into the limno-reservoir seem very important.

Carrying out soil erosion and sediment yield studies at a catchment scale is not an easy task. According to Zarris et al. (2011), the prediction of sediment yield at catchment scale is one of the most crucial challenges in sediment yield research. Moreover, the study of the relations between soil erosion and total sediment yield at the outlet of a catchment involves some difficulties. Not all eroded sediments reaches the outlet of a drainage basin as a significant proportion is generally deposited at intermediate sites depending on multiple factors (Alatorre et al. 2010). Many methodologies have been used to study soil erosion and sediment yield in the last decades, but most of them are not appropriate to work at catchment scale. De Vente et al. (2005) pointed out that most erosion research was basically limited to relatively small scales and to water erosion estimates. Models have been also used for assessments of soil erosion and sediment yield, but they require large and detailed data, and its operational application at the catchment scale is often problematic (de Vente et al. 2005, 2011). USLE and RUSLE models (Wischmeier and Smith 1965, 1978) or adapted versions are among the most popular (Young et al. 1989; Jain and Kothyari 2000; Kinnell 2000; Brath et al. 2002; Zarris et al. 2011), but USLE was originally developed for small agricultural plots and not for prediction of sediment yield at the basin scale.

Recently, de Vente et al. (2011) tested the performance of newly developed regression equations applied to Spanish reservoirs. They found that semi-quantitative approaches such as the

FSM and ART models (Syvitski et al. 2003, 2005; de Vente et al. 2005) performed better. However, these methodologies do not allow identifying where the sediments are originated or where the erosion problems are most severe, which would need the application of spatially distributed approaches (de Vente et al. 2011). Besides, FSM model (de Vente et al. 2005), which was found to estimate specific sediment yields (SSY) in Spain accurately, has been applied to reservoirs with an average draining surface area of 1000 km2. Then, its applicability to small basins like the Ompólveda River one (≈88 km2, flowing into the Pareja Limno-reservoir) may not be very reliable. ART model (Syvitski et al. 2003) was calibrated mostly for large basins of major rivers worldwide, therefore it seems inappropriate for our study. All these factors seemed to indicate that some other approaches should be followed to study the soil erosion in the Ompólveda River basin and the sediment yield into the limno-reservoir.

Prior to this study, Arévalo (2008) applied the RUSLE equation and a modification of the USLE model to study the soil erosion in the Ompólveda River basin. An average soil erosion between 9 and 11 $T \cdot ha^{-1} \cdot year^{-1}$ was found, with a high erosion risk in a 25% of the catchment area. Several tasks were carried out in order to improve this estimate. Real soil erosion and deposition rates were obtained applying an in-situ methodology focused on hillslope erosion (rill and interrill) and eventual deposition. Although other erosion processes, such as the gully erosion, landslides and riverbank erosion, have been detected to be important in Mediterranean areas (Vanmaercke et al. 2012), in our study area they have been rarely observed. Consequently, hillslope erosion is expected to be the predominant process according to the study area characteristics. Hillslope erosion has also been considered the most important type of erosion in the elaboration of the National Inventory of Soil Erosion, which was launched by the Spanish Ministry of the Environment in 2001, and whose first results have been recently published (Martín-Fernández and Martínez-Núñez 2011). Porta i Casanellas et al. (1994) also reported this type of erosion as the most relevant in Spain.

Sediment yield was studied through the taking of sediment cores in the Pareja Limno-reservoir. Sediment delivery ratio (henceforth SDR) is expected to be low, as the characteristics of the basin may yield a low connectivity with the stream network. Eroded sediments may be mostly deposited at parcel boundaries, footslopes as colluvium, floodplains or perched flat areas, rather than being delivered to the river system and the limno-reservoir (de Vente et al. 2005; Alatorre et al. 2010; Vanmaercke et al. 2012). Nevertheless, a comparison with other SDR values in the literature has been performed to check the reliability of the results obtained.

The main aim of this study is to perform a sedimentation risk assessment of the Pareja Limno-reservoir at a catchment scale. This objective has been fulfilled through the estimation of soil erosion and deposition rates with a simple and affordable in-situ methodology, finding their relationship with the sediment yield in the Pareja Limno-reservoir to assess the sediment delivery, and locating the areas with the most significant erosion problems.

5. 2. MATERIAL AND METHODS

5.2.1. Study area

The Pareja Limno-reservoir is located in the riverine zone of a sidearm of the Entrepeñas Reservoir (south of the Guadalajara Province, upper Tagus River Basin, Central Spain). It is adjacent to the village of the same name (Fig. 5.1). It has a capacity of 0.94 hm3 and a potential inundation area of 26 ha. Its maximum water depth reaches 12.5 m in the dam zone, becoming progressively shallower towards the inflow section. It is fed by the Ompólveda River, whose main tributary is the Valdetrigo stream, flowing from the Northeast. The limno-reservoir is surrounded by the National Road N-204.

The Ompólveda River basin covers an approximate area of 88 km2 within a Mediterranean climate region, being the annual average temperature around 13.0ºC. However, cold temperatures prevail in winter (daily average ≈ 5.0ºC) becoming warmer in summer (daily average ≈ 23.0ºC). Average annual precipitation recorded in the Escamilla station (in the upper catchment) is around 600 mm, showing high intra- and inter-annual variability. Periods with maximum amount of rainfall do not follow a precise pattern and can be found in winter, spring or even in both seasons (Molina-Navarro et al. 2010). Storms are not as frequent and intense as in other Mediterranean areas, but may happen in summer or early autumn.

Altitude in the basin ranges from 718 to 1137 m.a.s.l. in a rather small catchment, which means that the existing valleys have hillsides with high slopes (Fig. 5.1). The upper basin is dominated by a high limestone plateau. A more erodible and older sedimentary lithology surfaces in the hillsides of the Ompólveda River and its tributaries (intercalations of clay, marls, silt, sand, sandstone, conglomerates, limestone and gypsum, until the Late Cretaceous) (Fig. 5.2). Quaternary sediments can be mainly found in the alluvial plains of the largest valleys. Soils in the Ompólveda River basin were initially studied by Arévalo (2008) and subsequently categorized and mapped by Molina-Navarro et al. (2012b). 61.5% of the catchment is covered by entisols and 38.5% by alfisols. Detailed information about basin soils can be found in Molina-Navarro et al. (2012b).

The Ompólveda River basin has rural features. There are about 300 inhabitants in the area, most of them in the village of Pareja. Water supply to this village comes from a small pond in the mid reach of the Ompólveda River. Natural vegetation is the main land use in the catchment. 37% of the catchment is covered by forests, mainly combinations of pine and holm oak. Most of the pine forests in the catchment came from a reforestation program, and some of them were planted in terraces. 36% of the catchment is covered by scrubland, occasionally combined with pasture. Just the 25% of the catchment is covered by agricultural uses, mainly unirrigated cereal crops (17%) and olives (7%). Other land uses are minority (Fig. 5.3). These described characteristics make the Ompólveda River basin representative of the small catchments of central Spain.

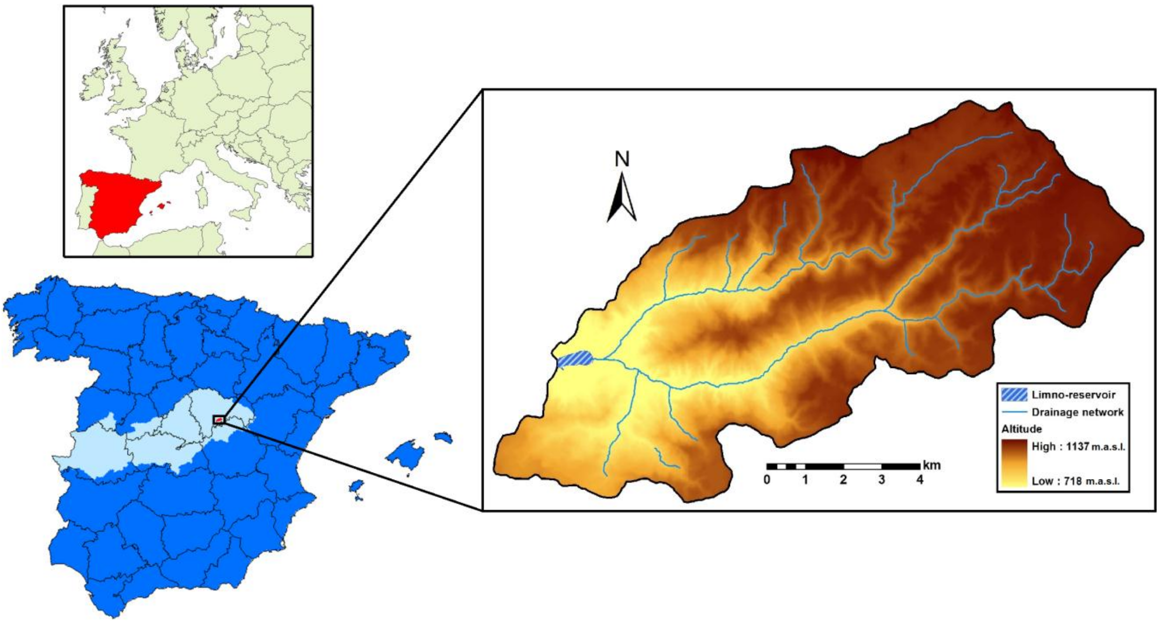

Fig. 5.1. Location of the Ompólveda River basin and Digital Elevation Model

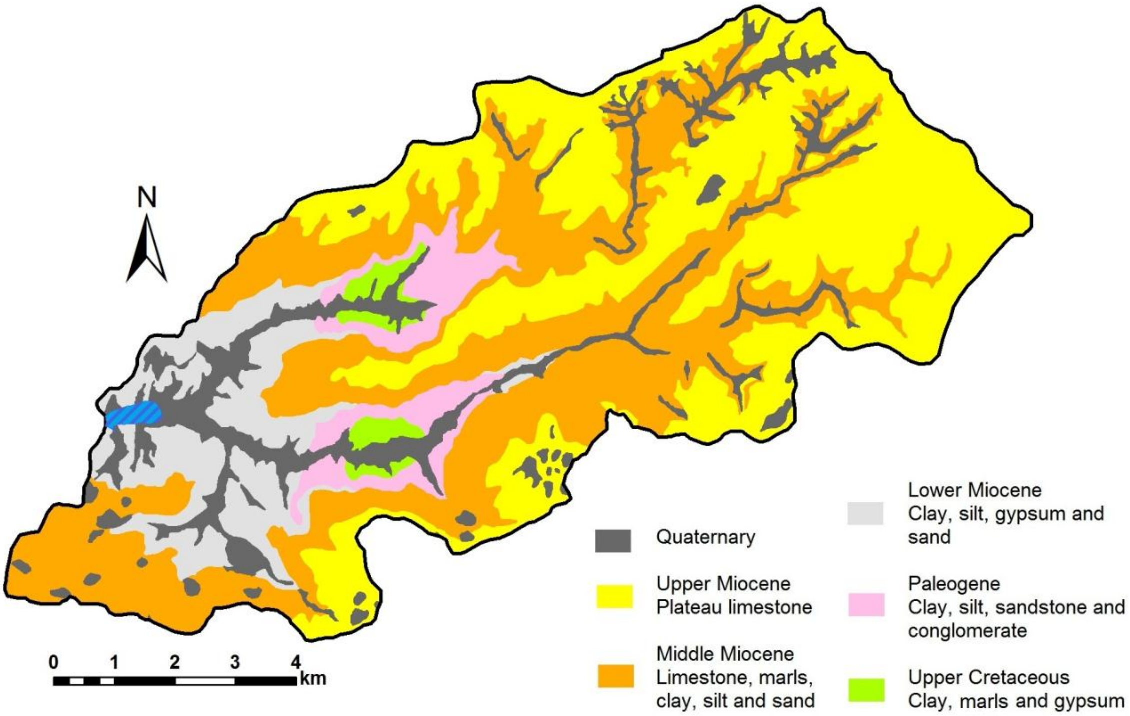

Fig. 5.2. Geologic scheme of the Ompólveda River basin

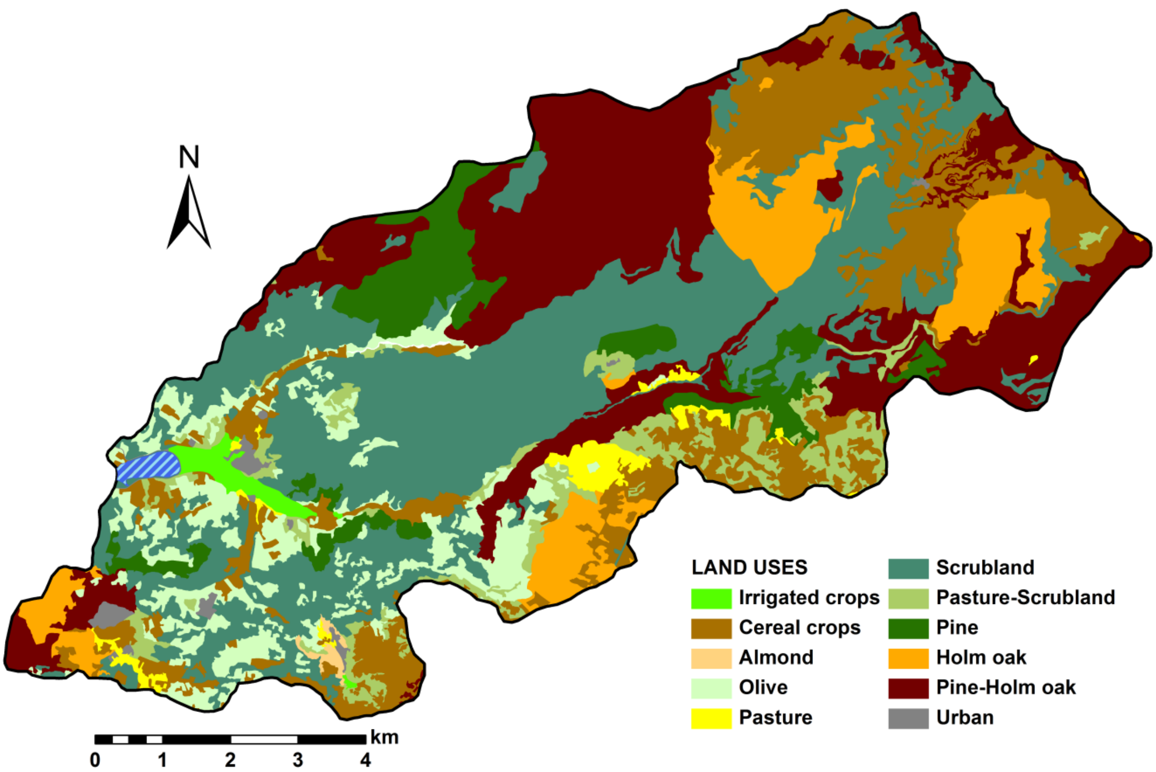

Fig. 5.3. Land uses in the Ompólveda River basin

5.2.2. Soil loss monitoring network

A soil loss monitoring network was installed in order to determine hillslope erosion and deposition rates. Two methodologies were optimized. First, a network of sampling plots was installed in order to quantify interrill erosion and deposition, depending on the topography. Each plot covered a 1x1 m area and was composed by 16 erosion pins, drawing a 4x4 square with a 25 cm distance between them. Iron erosion pins (30 cm length x 1.2 cm width) were used. 15 sampling plots were installed in erosion sites and 7 in deposition sites (Fig. 5.4).

Rill erosion was also measured. Soil erosion in the rill was determined with a needle micro-profiler, while the soil deposition in the terminal zone of each rill was quantified with pins. 2 to 4 profile sites were selected in each rill, depending on its length and heterogeneity, and small landmarks were fixed. Between 7 and 11 pins were installed in the terminal zones of each rill, following the shape of the small deposition cone. 8 rill erosion sites were monitored (Fig. 5.4). More information about erosion pins and micro-profilers can be found in Sancho et al. (1991).

These control points were located in places where the lithology, land use (vegetation cover) and slope are representative of the catchment, in order to extrapolate the results to similar areas (Fig. 5.4). Along with rainfall, these factors have been described as the most important affecting the soil erosion (Wischmeier and Smith 1978; Butt et al. 2010; Marín and Desir 2010; de Vente et al. 2011). Monitoring was performed for three years (starting in 2009) and every three months.

Soil erosion and deposition with the pins were measured following Sancho et al. (1991) using a precision ruler. Rill erosion was determined drawing the rill section in a sheet of paper, calculating the rill area afterwards. Soil samples from each site were taken with cylinders of known volume (100 ml) to obtain bulk density values and calculate deposition and soil erosion rates.

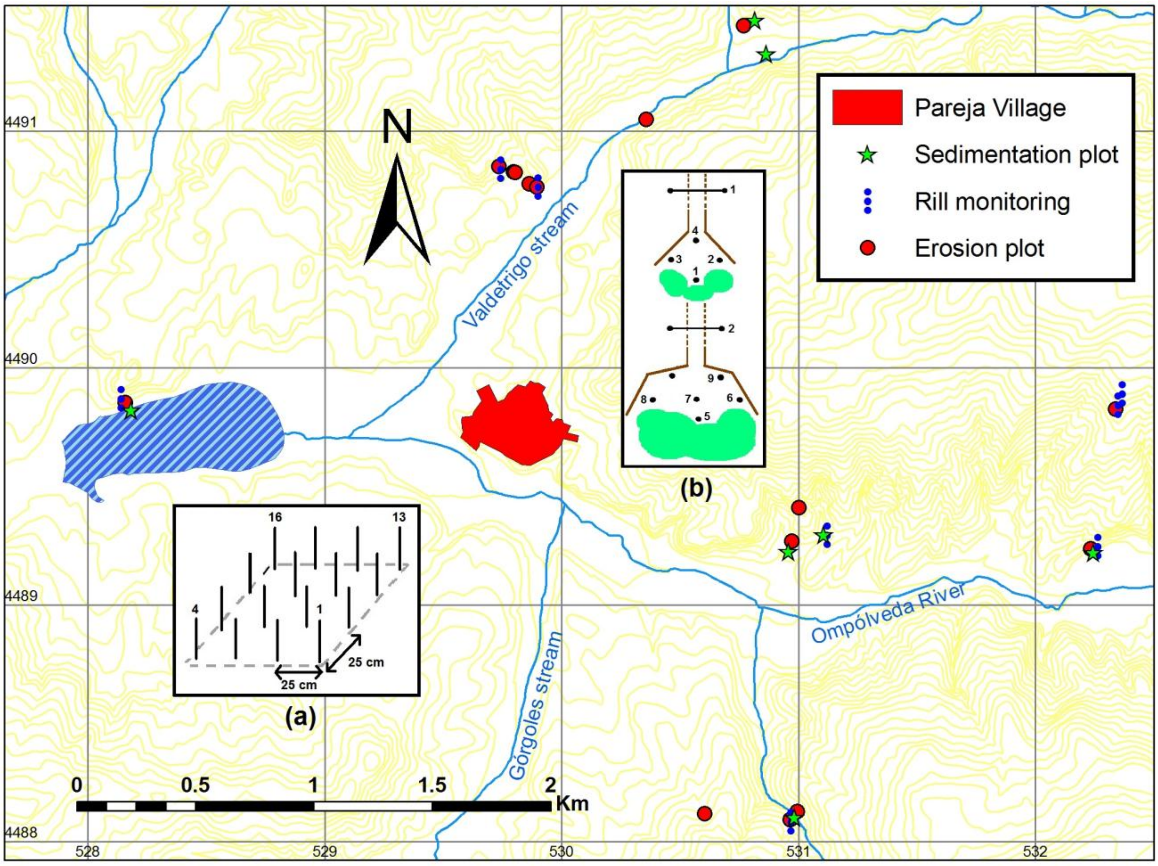

Fig. 5.4. Soil loss monitoring network installed. Design of the deposition and erosion plots (a) and rill monitoring (b) (modified from Molina-Navarro et al., 2010)

5.2.3. Erosion and deposition data analysis

Soil erosion and deposition rates were calculated from the measurements described in 2.2. Due to several circumstances such as the soil distortion during the pins installation, Sancho et al. (1991) recommend to carry out the first measurement after three months. Haigh (1977) estimates a pin height difference of 2 mm over the real values for the first 3 months. Thus, values in the first sampling were dismissed. Moreover, in the pins measurements, outlying values per plot and sampling survey were removed (values separated from a central value more than three times the length of the interquartile range were considered as outliers). Soil erosion and deposition rates in $T \cdot ha^{-1} \cdot year^{-1}$ were calculated after every sampling, and a final average value was obtained in each monitored plot or rill.

A global value of hillslope erosion integrating rill and interrill components was obtained for each monitored zone, in which the percentage of the area corresponding to interrill erosion, rill erosion and rill deposition was determined.

The whole catchment was divided into polygons of homogeneous response to erosion, in the delineation of which vegetation cover, lithology and slope were the factors considered. Using ArcGIS software (v. 9.3.1., ESRITM) and highly detailed scale, visual inspection of the images from the PNOA flight aerial photography (0.5x0.5 m resolution, raster format, Instituto de Desarrollo Regional 2008) was used for vegetation cover. Lithology information came from the vector format version lithology map published by the IGME (Instituto Geológico y Minero de España, scale 1:50000). The vector format version of the National Topographic Map published by the IGN (Instituto Geográfico Nacional, scale 1:25000) and the Digital Elevation Model published by the Castilla-La Mancha Government (5.0x5.0 m resolution, raster format, Instituto de Desarrollo Regional 2008) were used for slope.

Following this process, 315 polygons were obtained. A value of soil loss or deposition rate was assigned to each polygon considering the most similar area among those monitored in terms of slope, vegetation cover and lithology. A null value for erosion was assigned in urban areas and alluvial plains. Soil loss monitoring network did not reach the high limestone plateau. Although the expected erosion rates were very low compared to the other areas in the catchment, a soil loss value was assigned to this area using the SWAT model, as applied in Molina-Navarro et al. (2012b). SWAT model gives hillslope erosion outputs calculated with USLE equation (Neitsch et al. 2005). Deposition in the floodplain could not be measured in this work.

It has been reported that extrapolation of measured soil erosion rates without considering the actual hillslope conditions may overestimate the actual rates (Boardman 1998; Cerdán et al. 2010; Quinton et al. 2010). Thus, in order to obtain the final rates of soil erosion, two adjustments were applied in those polygons where the soil erosion values were extrapolated.

Firstly, areas with terraces were detected by visual inspection of PNOA images and field work, and soil loss rate was multiplied there by 0.14 (P factor), following Wischmeier and Smith (1978).

Secondly, a vegetation cover adjustment based on the C factor from the USLE methodology (Wischmeier and Smith 1965) was applied. Like in other recent research works (e.g. Alatorre et al. 2010; Zarris et al. 2011), tabulated values of USLE C factor were used, in particular those in Wischmeier and Smith (1978) in combination with values obtained by Arévalo (2008) for the main land uses of the study area after detailed field work. By visual inspection of the aerial photography, a vegetation cover factor from Table 5.1 was assigned to each polygon. A mathematical adjustment of the soil erosion rate was applied, multiplying the measured soil erosion rate by the quotient between the C factor in the extrapolated site and the C factor in the monitored site.

Table 5.1: USLE C cover factors used in the study. a) Cover management C factors, modified from Wischmeier and Smith (1978). b) C factors obtained after field work in the study area by Arévalo (2008)

a)

Vegetal Canopy		Cover that contacts the surface (percent ground cover)						
Type and height of raised canopy[1]	Canopy covers[2] %	Type[3]	0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.012	0.003
		W	0.45	0.24	0.15	0.090	0.043	0.011
Canopy of tall weeds or short brush, 0.5 m fall ht.	25	G	0.36	0.17	0.09	0.038	0.013	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.17	0.10	0.06	0.032	0.011	0.003
		W	0.17	0.12	0.09	0.068	0.038	0.011
Appreciable brush or bushes, 2 m fall ht.	25	G	0.40	0.18	0.09	0.040	0.013	0.003
		W	0.40	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.040	0.011
Trees but no appreciable, low brush, 4 m fall ht.	25	G	0.42	0.19	0.10	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.013	0.003
		W	0.36	0.20	0.13	0.084	0.042	0.011

[1]Average fall height of waterdrops from canopy to soil surface.
[2]Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a birds's-eye view).
[3]G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 inches deep. W: Cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near the surface, and/or undecayed residue).

b)

Vegetal canopy	**C factor**
Pine forest	0.018
Holm oak forest	0.017
Olive grove (cultivated)	0.293
Olive grove (abandoned)	0.083
Dispersed scrubland (sunny hillside)	0.270
Dispersed scrubland (shady hillside)	0.106
Dense scrubland (sunny hillside)	0.217
Dense scrubland (shady hillside)	0.025
Pasture	0.012
Cereal crops	0.270

5.2.4. Sediment yield, sediment delivery and sedimentation risk assessment

Three sediment cores were taken from the Pareja Limno-reservoir in order to obtain an estimation of the sediment yield: one corresponding to the shallowest section (1.5 m depth), another in the central part of the limno-reservoir (5.0 m depth) and the last in the deepest zone (9.0 m. depth) (Fig. 5.5). Samples from the cores were used to determine its bulk density in the laboratory.

The cores were taken in November 2010 and the definitive filling of the limno-reservoir started in July 2007. The thickness of the accumulated sediments was measured. According to Wetzel (2001), deposition of sediments decreases exponentially with the depth of the reservoir. Taking into account this fact, limno-reservoir area was divided into three polygons with the output of a 0.5 m resolution bathymetry that was carried out in autumn 2010 (Fig. 5.5). The area of these polygons was assigned to each sedimentation record for calculations, and an approximate value of the sedimentation rate was determined. This sedimentation rate was compared to the gross erosion value obtained with the soil loss monitoring network. Then a final value of SDR was calculated (100% trap efficiency of the limno-reservoir was considered, following Verstraeten and Poesen (2000)). SDR was compared to values obtained in similar catchments, checking the reliability of the obtained results.

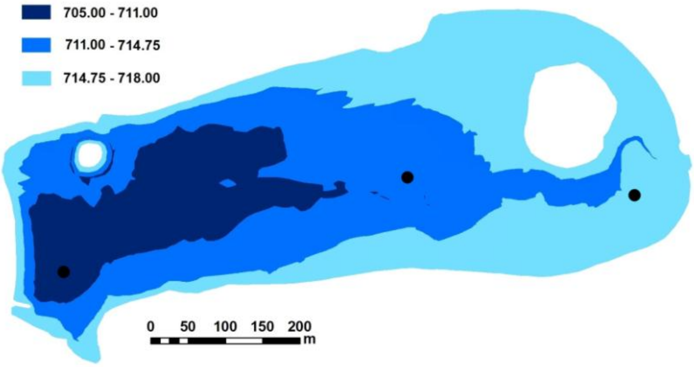

Fig. 5.5. Areas corresponding to the shallow, central and deep sediment cores. Black dots indicate the location where the cores were taken

An in-detail study was also carried out to test the influence of the National Road N-204 in the sediment delivery to the Pareja Limno-reservoir from the adjoining hillslopes. Soil loss was monitored in the northern hillslope of the limno-reservoir (fig. 5.4). Two tunnels connect the ditch of the road with the limno-reservoir under the road, evacuating the sediments. Four pins were installed to measure the amount of sediments intercepted by the ditch. Sediment samples were taken, dried and weighted yearly in the terminal part of the tunnels, in order to know the amount of sediments that did not reach the limno-reservoir.

5.3. RESULTS

5.3.1. Soil erosion and deposition in the catchment

The value obtained for gross hillslope erosion was 9.07 T ha^{-1} $year^{-1}$. Taking into account the deposition rates measured at intermediate locations, a soil loss average value of 4.27 T ha^{-1} $year^{-1}$ was obtained for the Ompólveda River basin.

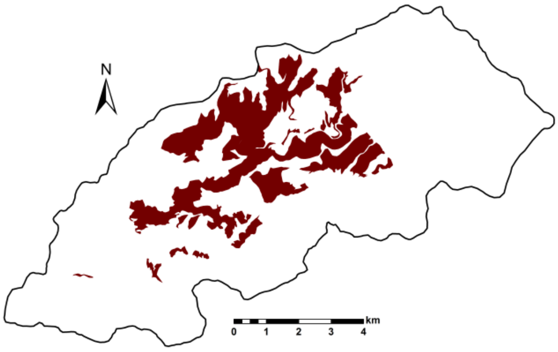

Fig. 5.6. Location of terrace practices in the Ompólveda River basin.

Once this value was obtained, erosion adjustment was applied. 21% of the scrubland area and 29% of the pine (or pine combined with holm oak) forest area were found to have terraces, and the appropriate factor was applied as described in 2.3. Their location in the catchment is showed in the Fig. 5.6. Vegetation cover factor was assigned for each polygon as mentioned in 2.3. Its value varied from 0.012 in the most densely forested areas to 0.45 in those locations with scarce vegetation coverage, located in the hillsides of the valleys. Values of C factor assigned to the 315 polygons delineated are showed in Fig. 5.7.

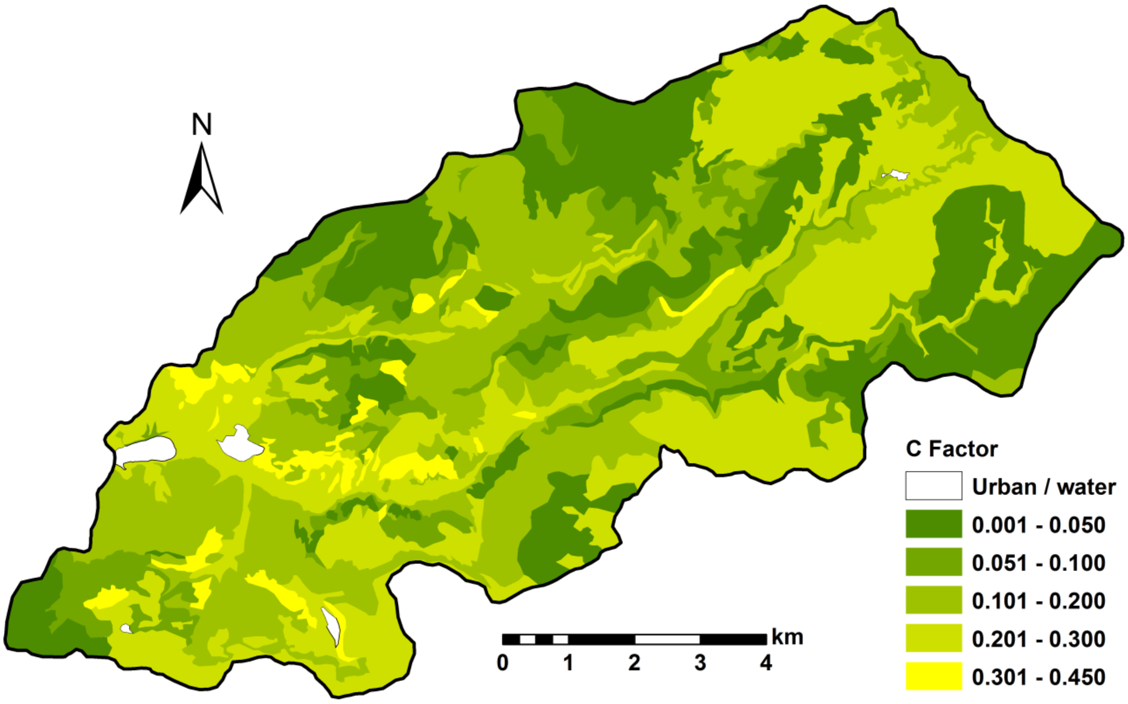

Fig. 5.7. C Factor values obtained in the Ompólveda River basin.

After applying the proper adjustments, a final map of soil erosion and deposition of the basin was obtained (Fig. 5.8).

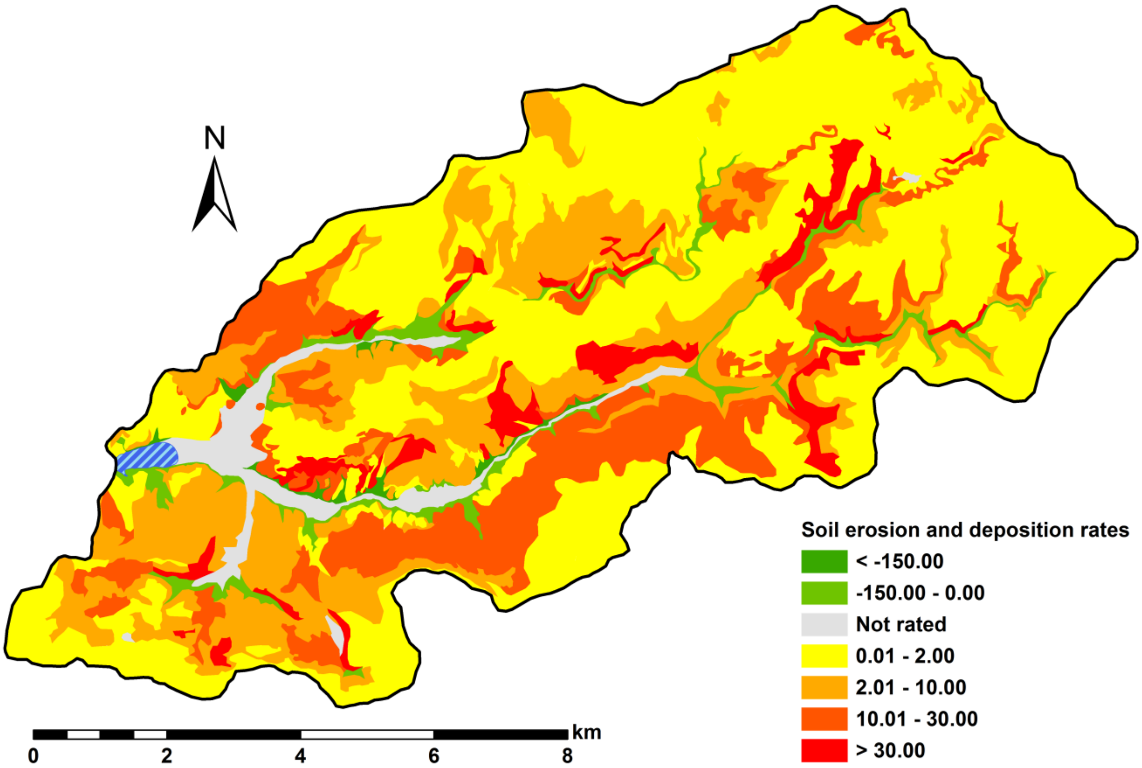

Fig. 5.8. Soil erosion and deposition rates in the Ompólveda River basin

Gross hillslope erosion obtained in the catchment after applying adjustments was 5.97 T ha^{-1} $year^{-1}$. The final average value of soil loss obtained in the basin after considering deposition was 1.17 T ha^{-1} $year^{-1}$. Soil erosion rates obtained ranged from 0.03 T ha^{-1} $year^{-1}$ to 64.37 T ha^{-1} $year^{-1}$, while soil deposition rates went up to 166.27 T ha^{-1} $year^{-1}$.

5.3.2. Sedimentation in limno-reservoir and sediment delivery

The average sediment thicknesses were 4.50 cm in the shallowest section, 3.63 cm in the central part and 1.94 in the deepest zone. Bulk densities were determined in laboratory afterwards, and values obtained were 0.82, 0.73 and 0.49 g cm^{-3}, respectively. After assignation of the corresponding area to each core, the estimated weight of sediments accumulated in the Pareja Limno-reservoir was 6909 T (2032 T per year). Converted into SSY, the corresponding value is 0.23 T ha^{-1} $year^{-1}$. The annual volume of sediments expected to be accumulated in the limno-reservoir is around 2690 m^3. According to these results, in 3.4 years (July 2007 – November 2010), approximately 1.0% of the limno-reservoir volume has been lost due to sedimentation.

Gross soil erosion calculated in the catchment was 5.97 T ha^{-1} year^{-1}. As SSY estimated was 0.23 T ha^{-1} year^{-1}, SDR in the Ompólveda River basin is around 3.9 %.

1.21 T year^{-1} of sediments were intercepted by the ditch of the National Road N-204 and by the terminal part of the tubes that connect the ditch with the limno-reservoir. It represents around 7.2% of the gross erosion in the adjacent hillslope.

5.4. DISCUSSION

5.4.1. Soil erosion and deposition in the catchment

The soil erosion measurements performed in the Ompólveda River basin gave an average gross erosion rate of 5.97 T ha^{-1} year^{-1}. Soil loss was equal to 1.17 T ha^{-1} year^{-1} after considering measured soil deposition. Before application of P factor and adjustment of C factor, gross erosion obtained was 9.07 T ha^{-1} year^{-1} and soil loss was 4.28 T ha^{-1} year^{-1}. These values demonstrate that simple extrapolation may overestimate the actual erosion rates as has been already reported by Boardman (1998), Cerdán et al. (2010) and Quinton et al. (2010).

The higher soil erosion rates obtained in-situ, over 45 T ha^{-1} year^{-1}, were found in scattered patches in the hillsides of the main valleys, in areas with low vegetation cover. They were mainly found in the most erodible levels of the Paleogene, where soils have clay or clay loam textures (Molina-Navarro et al. 2012b). Other authors (e.g. Alatorre et al. 2010; Marín and Desir 2010) have also reported high soil erosion rates in Tertiary clays in other Spanish areas. The lowest soil loss rates were those estimated by the SWAT model for the limestone plateau (0.03 T ha^{-1} year^{-1}). Regarding the values yielded from the in-situ soil monitoring network, the lowest values, around 0.10 T ha^{-1} year^{-1}, were found in forested areas with terraces, mostly in the upper part of the catchment.

Gross hillslope erosion in the catchment obtained in this research was 5.97 T ha^{-1} year^{-1}, a figure that agrees with the mean soil erosion rates reported by Cerdán et al. (2006) for various land uses in Mediterranean areas (0.05-31.62 T·ha^{-1}·year^{-1}, with an overall mean of 7.87 T·ha^{-1}·year^{-1}). The value obtained in the studied basin is lower than the values obtained by Arévalo (2008) with RUSLE and a modified USLE equations (between 9 and 11 T·ha^{-1}·year^{-1}). The difference could be partly attributed to weaknesses in the USLE model application. It was originally developed for small agricultural plots in the USA and not for prediction at the basin scale (Wischmeier and Smith 1965). Moreover, some limitations may be also expected when applying it in zones with different climatic and topographic conditions from those where it was originally developed (Zarris et al. 2011). Besides, although Arévalo (2008) worked with a highly detailed input in most of the variables, a few of them may be somewhat imprecise (e.g. a 100 m resolution DEM was used for topographic factor) and may also cause over-estimation.

5.4.2. Sediment delivery and sedimentation risk assessment

Annual sedimentation estimated in the Pareja Limno-reservoir was low (2032 T, 2690 m3). This means that the limno-reservoir is filled up with sediments at an approximate rate of 0.29% per year. This value is lower than the average obtained for reservoirs worldwide (1%) by WDC (2000), and also lower than the 4% or 5% reported for many reservoirs (de Vente et al. 2005; Zarris et al. 2011). The low sedimentation rate observed in the Pareja Limno-reservoir assures its environmental feasibility from the sedimentation risk perspective.

SSY was estimated as 0.23 T ha^{-1} $year^{-1}$ in the catchment and, as expected, the SDR is low (3.9%). This is a consequence of the low connectivity between the stream network and the limno-reservoir. The abundant vegetation cover and the shape of the basin, elongated and with one main river channel draining to the limno-reservoir, are some of the factors favouring the low sediment delivery (de Vente et al. 2005).

Eroded sediments may be mostly deposited in multiple intermediate locations rather than being delivered to the limno-reservoir (Alatorre et al. 2010; de Vente et al. 2005; Vanmaercke et al. 2012). This fact has been demonstrated with the in-situ measurements of sedimentation, which represent the difference between the gross erosion value (5.97 T ha^{-1} $year^{-1}$) and the average soil loss (1.17 T ha^{-1} $year^{-1}$). The necessary additional sedimentation required to reach the SSY value may be ascribed to sediment deposition in the alluvial floodplain. Floodplains are composed by sediments transported by the river (Strahler 1986), but sedimentation in the floodplain could not be measured in this work.

Studies in other Spanish catchments have reported higher SDR values, generally speaking. Alatorre et al. (2010) found a SDR of 10% in the Barasona Reservoir watershed (Central Spanish Pyrenees), pointing it out as a high value, though not extreme. The same group studied the soil erosion and sediment delivery in a small experimental catchment also located in the Central Spanish Pyrenees (2.84 Km2), finding a SDR of 5% (Alatorre et al. 2012). SDR values of 7-46% were found by Romero Díaz et al. (1992) in the sub-catchments of the Segura River (Spain), while de Vente et al. (2008) predicted SDR values ranging from 0.03% to 55% for 61 Spanish catchments.

Although the main reason for the low SDR seems to be the low connectivity in the catchment, some local characteristics may play a role too. First of all, the National Road N-204 surrounds the majority of the limno-reservoir perimeter. In the hillslope adjoining the northern part, 1.21 T $year^{-1}$ of sediments that would be entirely yielded into the limno-reservoir were trapped by the road infrastructures. This value may be sensibly higher, as under the road there are some sediment traps that could not be sampled. De Vente et al. (2005) pointed out that the areas close to a reservoir or else with a good connectivity to the reservoir are the most important source areas for sediments at the basin outlet. Thus, the existence of the road reduces the relevance of these areas, favouring lower SSY and SDR.

Another local issue of importance may be the existence of a small pond in the mid reach of the Ompólveda River, built to derivate drinking water to the village of Pareja. According to Verstraeten and Poesen (2000), approximate trapping efficiencies for this pond may be 100% for sand, coarse silt and medium silt, 60% for fine and very fine silt and 10% for clay. Trapped sediments could reach the Pareja Limno-reservoir in part if the pond did not exist. Therefore, this small pond may be also contributing to the low sedimentation rate in the limno-reservoir, favouring its environmental feasibility.

The results obtained differ from those found by Vanmaercke et al. (2012), who have recently studied the relationship between measured soil erosion rates due to interrill and rill erosion, predicted soil erosion rates and measured catchment sediment yields in Europe. Vanmaercke et al. (2012) found measured hillslope erosion rates significantly lower than measured sediment yield for the Mediterranean region. The authors attribute the higher sediment yield to the existence of erosion processes other than rill and interrill erosion (e.g. gully erosion or mass movements), which have little impact in the Ompólveda River basin. Moreover, the percentage of erosion plots with favourable conditions to the soil loss used in this study is high (e.g. arable land or bare soil). These conditions increase the SDR because of the much better connectivity between the erosion areas and the stream network (Alatorre et al. 2012) and do not represent the characteristics of the Ompólveda River basin, which drains off into the Pareja Limno-reservoir.

5.4.3. Suitability of the methodology

Determinations done in this work are essential to face the more and more complex range of environmental requirements in the legislation. Such requirements in the European Union include those from the Environmental Impact Assessment Directive (Directive 85/337/EEC, codified with its three amendments by OJEU num.55 2012), the Common Agricultural Policy, the European Water Framework Directive (OJEU num.327 2000) or the proposed European Union directive for soil protection, that forces EU Members to identify areas of risk with substantial evidence (or evidence that it has occurred or is likely to occur in the near future) of soil degradation such as erosion (Martín-Fernández and Martínez-Núñez 2011).

Although the results obtained in this study seem adequate, they must be taken with care, since they come from a number of field observations. It is also important to take into account that just three years of field measurements have been performed and that the climate in the study area is very variable. Moreover, it must be considered that the methodology may be appropriate for basins in the same size range or smaller, but maybe not for larger ones. Firstly, setting up and sampling an in-situ monitoring network in a much larger catchment may be unaffordable in terms of time and manpower. Secondly, the suitability of scaling up from experimental plots to catchments of thousands of kilometres is arguable (Zarris et al. 2011).

The methodology used is simple and affordable, and it has been proved to be useful to provide an estimate of average annual soil erosion and sediment yield in a catchment considered representative of those in central Spain. Basin sediment yield does not necessarily represent the severity of on-site erosion problems (de Vente et al. 2005). In this study, the methodology has also served as a tool to identify where in the catchment the erosion problems are most severe and to assess the sedimentation risk in a reservoir.

5.5. CONCLUSIONS

Gross hillslope erosion found in the Ompólveda River basin was 5.97 T ha^{-1} $year^{-1}$. After considering soil deposition in intermediate locations, average soil loss found was 1.17 T ha^{-1} $year^{-1}$. Estimated SSY was 0.23 T ha^{-1} $year^{-1}$ and consequently the approximate SDR in the catchment of study was 3.9%. Low connectivity between the stream network and the limno-reservoir seems to be the main reason of this low SDR.

The hillslope erosion obtained in the Ompólveda River basin and the SSY calculated for the limno-reservoir fall in line with the findings of other authors. Considering the annual sedimentation rate obtained in the limno-reservoir (0.29%), the environmental feasibility of the Pareja Limno-reservoir seems to be guaranteed from the sedimentation risk perspective.

Soil erosion and sediment yield in the catchment have been studied with a simple methodology, identifying where the erosion problems are most severe. This methodology is useful to address the environmental feasibility assessment of the limno-reservoir, and to decide where to take proper measures against high erosion risk in order to combat the limno-reservoir sedimentation.

Methodologies of this kind are not only useful for the sedimentation risk assessment of a limno-reservoir. They are also quite convenient to policies' implementation, as they require simple, inexpensive and reliable techniques to determine regional soil erosion rates and sediment yields.

5.6. Acknowledgements

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6. Catchment modelling and scenarios simulation

6.1. Hydrological modelling and feasibility

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Martínez-Pérez, S., Sastre-Merlín, A. and Bienes-Allas, R. Hydrologic Modeling in a Small Mediterranean Basin as a Tool to Assess the Feasibility of a Limno-Reservoir. Accepted for publication *Journal of Environmental Quality* (2012). DOI: 10.2134/jeq2011.0360

Abstract

The SWAT model was applied to the Ompólveda River Basin (Guadalajara, central Spain) to assess the hydrologic feasibility of the Pareja Limno-reservoir. A limno-reservoir is a water management infrastructure designed to counteract some negative impacts caused by large reservoirs under Mediterranean climate. Highly detailed inputs were selected to set up the model. Its performance was evaluated by graphical and statistical techniques and compared with the previous knowledge of the basin. An overall good performance was obtained during the calibration and validation periods (monthly and annual NSE values of 0.67 and 0.60, respectively, for calibration and 0.70 and 0.83, respectively, for validation). Total discharge was well simulated, and flow components prediction was acceptable. However, the model is not accurate at predicting evapotranspiration. Once evaluated, the model was used to simulate the water discharge into the Pareja Limno-reservoir during 2008 and 2009, establishing a water balance and assessing its hydrologic feasibility. The water balance predicted the absence of surplus during summer (2008 and 2009) and autumn (2009), matching up with the decrease of water level and demonstrating the usefulness of SWAT as a tool to evaluate the hydrologic feasibility of the Pareja Limno-reservoir. Very low discharges from the Ompólveda River after a sequence of normal and dry years are the main factors responsible of this phenomenon, whereas the effect of the wastewater flow redirection in the Pareja village is negligible. These results question the usefulness of the Pareja Limno-reservoir during summer, the most favorable season for recreational activities.

Keywords: hydrologic feasibility, hydrologic modelling, limno-reservoir, SWAT.

Resumen

El modelo SWAT ha sido aplicado en la cuenca del río Ompólveda (Guadalajara, España central) para evaluar la viabilidad hidrológica del Limnoembalse de Pareja. Un limnoembalse es una infraestructura de gestión hidrológica diseñada para mitigar algunos de los impactos negativos causados por los grandes embalses en clima mediterráneo. El modelo se configuró con información de partida de alto nivel de detalle, su funcionamiento se evaluó mediante técnicas gráficas y estadísticas y los resultados fueron contrastados con el conocimiento adquirido previamente en la cuenca. En general, el modelo ha mostrado un funcionamiento satisfactorio durante los periodos de calibración y validación (los valores mensuales y anuales de NSE fueron 0,67 y 0,60, respectivamente, para la calibración y 0,70 y 0,83, respectivamente, para la validación). La escorrentía total fue correctamente simulada y la predicción de sus distintos componentes resultó aceptable. Sin embargo, el modelo no estimó con precisión la evapotranspiración. Una vez evaluado, el modelo se utilizó para simular la aportación al Limnoembalse de Pareja en 2008 y 2009, estableciendo un balance de agua y evaluando su viabilidad hidrológica. El balance de agua predijo una ausencia de excedente en verano (2008 y 2009) y en otoño (2009), coincidiendo con los descensos de nivel observados y demostrando así la utilidad de SWAT como herramienta para evaluar la viabilidad hidrológica del Limnoembalse de Pareja. El bajo caudal del río Ompólveda tras una serie de años normales y secos parece ser el principal responsable de la mencionada ausencia de excedente, mientras que el efecto la derivación del agua residual del pueblo de Pareja no resulta relevante. Estos resultados podrían cuestionar la utilidad del Limnoembalse de Pareja en verano, la época más favorable para el desempeño de actividades recreativas.

Palabras clave: limnoembalse, modelización hidrológica, SWAT, viabilidad hidrológica

6.1.1. INTRODUCTION

The construction and use of large reservoirs in areas with Mediterranean climate causes a variety of negative effects. The wide variation of the water level due to exploitation and climatic conditions causes some of these undesirable effects, including the “arid band” phenomenon in the drawdown zone of the reservoir, which is a landscape impact. Changes in water level cause other environmental impacts, such as the loss of bank vegetation and nesting places for aquatic birds (Ministerio de Medio Ambiente and Comité Nacional Español de Grandes Presas, 1996; MMAMRM, 2011). Socioeconomic impacts are also relevant because the construction of large reservoirs raises tourist and recreational expectations that may be unmet because of the water level variation (Molina-Navarro et al., 2010). One of the actions taken in Spain to mitigate these impacts has been the construction of small dams in the riverine zone of these reservoirs (Ministerio de Medio Ambiente y Comité Nacional Español de Grandes Presas, 1996). These dams are known as “riverine dams” or “flood dams” and have the goal of maintaining a small body of water with a constant level that is independent of the management of the main reservoir. These bodies of water resemble a lake more than a reservoir because of their constant level and the absence of human operations in the dam, so we have proposed the term “limno-reservoir” for them (Molina-Navarro et al., 2010, 2012).

In Spain, the first initiatives of this kind were proposed in the late 1980s and the early 1990s, with the primary goal being the creation of a suitable habitat for birds (Rodríguez Cabellos, 1995; Ministerio de Medio Ambiente y Comité Nacional Español de Grandes Presas, 1996). There are nine limno-reservoirs in operation, 10 under construction, and six in design. Despite the lack of studies about the feasibility of limno-reservoirs, there is a rising tendency to build them. The Pareja Limno-reservoir (central Spain, upper Tagus River Basin) was built in 2006 and was the first limno-reservoir to serve environmental and recreational goals (Molina-Navarro et al., 2010, 2011). It has a capacity of 0.94 hm^3 and 26 ha of potential inundation. It is located in the riverine zone of a sidearm of the Entrepeñas Reservoir, which has a capacity of 835 hm^3 and 3213 ha of potential inundation and, consequently, has been suffering from the environmental problems mentioned above.

Due to the innovative nature of this water management initiative, at the end of its filling process, we set up an environmental observatory at the Pareja Limno-reservoir. The main aim was to study its feasibility through a multidisciplinary perspective. This project started in 2008 and continues today. It is important to assess the hydrologic feasibility of the Pareja Limno-reservoir, which implies keeping a constant level of water to fulfill its functions as an impact-mitigating action. A streamflow gauging station was located where the Ompólveda River flows into the Pareja Limno-reservoir. However, since 2004, with the construction of the limno-reservoir, the station became inoperative (now it is below the water level), making this assessment difficult. Nevertheless, the existence of water yield data at the outlet of the basin and the presence of nearby meteorological stations open the possibility of developing a hydrologic model. This model could be used to estimate the water yield of the basin in the following years. In this work, the Soil and Water Assessment Tool (SWAT) has been used. SWAT is a physically based, basin-scale, continuous time, semidistributed hydrologic model that uses spatially derived data on topography, land use, soil, and weather for hydrologic modeling and operates on a daily time step (Arnold et al., 1998; Arnold and Fohrer, 2005).

The main objective of this work is to assess the hydrologic feasibility of the Pareja Limno-reservoir. A previous study done by this team (Molina-Navarro et al., 2010) did a first approach to this assessment using the streamflow data available and predicted the maintenance of a constant level of water in the limno-reservoir even during dry years. However, two important facts that may call into question its hydrologic feasibility were not taken into account by the authors. First, Pareja village wastewater discharge, originally computed in the gauging station, was redirected downstream the limno-reservoir after constructing it. This bypass may be significant, especially in the summer months when water consumption rises and the population of Pareja village quadruples. Second, this initial assessment did not consider the possibility of having two or more dry years consecutively. This fact may have an impact in the conservation of a constant level in the limno-reservoir because the groundwater flow plays a significant role. This circumstance is common in the Iberian Peninsula, where drought periods may be relatively long (Font, 1983). Moreover, climate change may cause a higher frequency of dry years in the near future compared with the recent climatology (Iglesias et al., 2005). These two factors were also not considered in the construction project.

The SWAT model was used to predict the water yield into the Pareja Limno-reservoir between 2008 and 2009, assessing its hydrologic feasibility and checking the importance of the facts mentioned above. Nevertheless, modeling the Ompólveda River Basin with SWAT has an interest itself because applications of SWAT in Mediterranean environments are relatively limited. Moreover, the area of study differs from other Mediterranean basins where SWAT has been applied. Apart from the smaller size of the Ompólveda River Basin, SWAT applications in the Mediterranean area have been performed mostly in areas of impervious lithology with important agricultural and urban activities (Varanou et al., 2002; Gikas et al., 2006; Boskidis et al., 2010; Pisinaras et al., 2010; Oeurng et al., 2011; Panagopoulos et al., 2011). Other applications have been performed near the coast (Plus et al., 2006; Cau and Paniconi, 2007; Panagopoulos et al., 2008; Boskidis et al., 2010; Pisinaras et al., 2010; De Girolamo and Lo Porto, 2012). SWAT has been scarcely applied in Spain or under specific contexts, such as acid mine drainage contamination in a basin without relevant aquifers (Galván et al., 2009) or in a large agricultural basin affected by uncontrolled groundwater withdrawals (Conan et al., 2003). In the Tagus River Basin, SWAT modeling has been performed in the lower basin, under humid conditions (Nunes et al., 2008). It has also been applied in the Madrid Region, close to the area studied in this paper, although the purpose has only been to study erosion assessment, not to offer hydrological results (Gómez Jiménez et al., 2007). Unlike all these basins where SWAT has been applied in the Mediterranean area, the Ompólveda River Basin is representative of the inland Spanish basins, with a Continental Mediterranean climate, dominated by a limestone aquifer and located in a rural context that is affected little by human activities.

6.1.2. MATERIALS AND METHODS

6.1.2.1. The study area

a) General characteristics

The Ompólveda River Basin has an area of 87.8 km^2. It is located in the south of the Guadalajara Province, at the head of the Tagus River Basin. The Ompólveda River is a tributary of the Tagus River, flowing to it from a northeast-southwest direction. Its main tributary is the Valdetrigo stream, merging from the northeast. Figure 6.1.1 shows the location of the basin with the drainage network, the digital elevation model (DEM), and the location of the Pareja Limno-reservoir (40°33’17’’ N, 2°40’17’ W, 718 m.a.s.l.).

The climate in the basin has Continental Mediterranean characteristics. The annual average daily temperature in the nearby Entrepeñas Reservoir ranged from -9°C in January to 40°C in August, with an annual mean temperature of 12.5°C. The average annual precipitation at the Escamilla station (in the border of the basin) is 600 mm, although it shows high intra- and interannual variability (Molina-Navarro et al., 2010) (data provided by AEMET, Ministerio de Agricultura, Alimentación y Medio Ambiente). Altitude in the basin ranges between 709 and 1134 m.a.s.l. The upper basin is dominated by a limestone plateau from the Middle-Late Miocene that is permeable and acts as an important shallow aquifer. Older sedimentary lithology (until the Late Cretaceous) surfaces in the hillsides of the Ompólveda River and its tributaries, mainly intercalations of clay, loam, silt, sand, limestone, and gypsum. Quaternary sediments are restricted to the deepest part of the largest stream valleys.

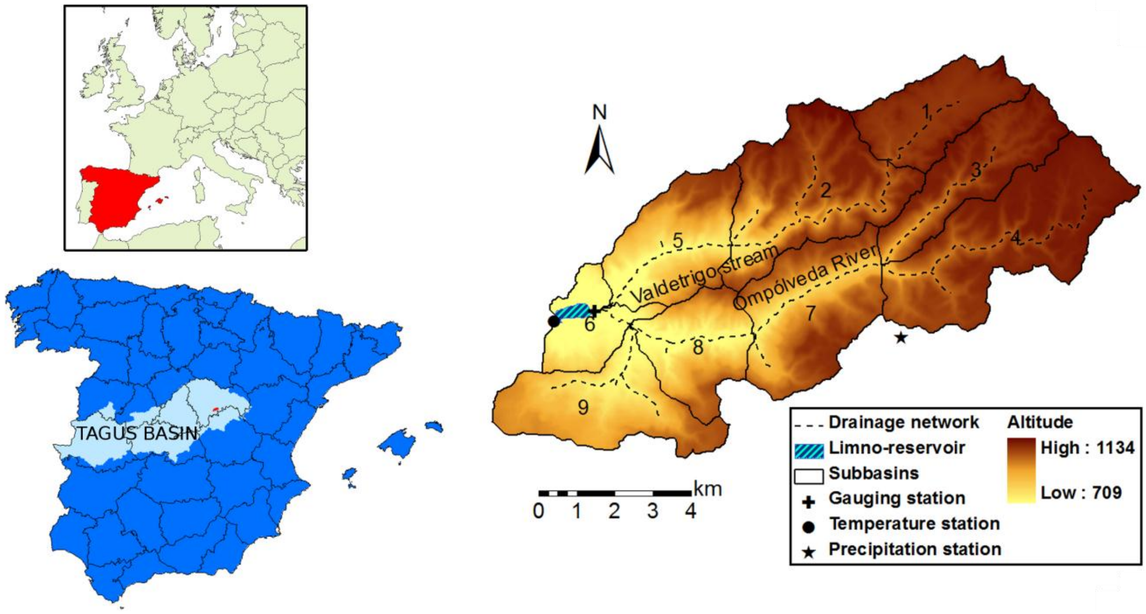

Fig. 6.1.1. Location of the Ompólveda River Basin, current site of the Pareja Limno-reservoir, and digital elevation model. Sub-basin division and location of the temperature, precipitation, and gauging stations.

There are about 300 inhabitants in the basin area, most of them in the village of Pareja. The limno-reservoir tries to provide them and people from the surrounding areas with an infrastructure that favors a hydrologic-environmental recovery in addition to an economical promotion of the area. It is open for swimming or for walking; it has a jetty for motorless craft, two artificial islands that act as bird refuges, and a fish ladder (Molina-Navarro et al., 2010, 2011).

b) Hydrologic parameters

The limno-reservoir hydrologic feasibility supposes the conservation of a constant water level at its maximum capacity (0.94 hm^3 in an area of 26 ha). Thus, it is necessary to know the behavior of the main hydrological parameters in the Ompólveda River Basin.

The installation of a Davis Vantage Pro2 Weather Station next to the limno-reservoir dam provided potential evapotranspiration (PET) values. Calculations of PET in the station are based on the equations provided by CIMIS (Snyder and Pruitt, 1992), which use a modified Penman type equation. Working on basin soils data from Arévalo (unpublished observations), an available water capacity of 62 mm was obtained and considered to calculate actual evapotranspiration (AET). On average, water loss via AET assumes a high percentage (89%) of rainfall, fitting with the average discharge value measured in the basin.

Like rainfall, annual discharges of the Ompólveda River at the E-3270-Pareja gauging station (Fig. 6.1.1) show a high variability, ranging from 1.13×10^6 m^3 (1992–1993) to 13.66×10^6 m^3 (1987–1988) (CEH-CEDEX, 2008). Discharges were generally low from June to November. Peaks of highest discharges did not show a specific pattern, rising in winter or in spring or even in both seasons during the same year. The average annual discharge is around 10% of the rainfall in the basin. Regarding the components of the river discharge, Molina-Navarro et al. (2010) estimated a 70% of average groundwater flow, showing the importance of the limestone aquifer. In the 30% remaining, a high contribution of lateral flow is expected because more than a 70% of the basin area has slopes over 8%, and lateral flow has been seen to increase with slope (Samper et al., 2011).

c) Limno-Reservoir Water Balance

A water balance in the Pareja Limno-reservoir was also done by Molina-Navarro et al. (2010). Balances were done considering dry (rainfall <15% annual average), normal, and wet (rainfall >15% annual average) annual rainfall rates after seeing the high interannual variability of precipitations. Starting with a complete filling situation, the authors predicted a water surplus in the limno-reservoir every month even in dry years (Fig. 6.1.2), which would ensure its hydrologic feasibility. This surplus would flow out the limno-reservoir through the fishway (and eventually through the spillway), resulting in a steady state in the limno-reservoir. However, neither the existence of two or more consecutive dry years nor the Pareja village wastewater redirection were considered by Molina-Navarro et al. (2010).

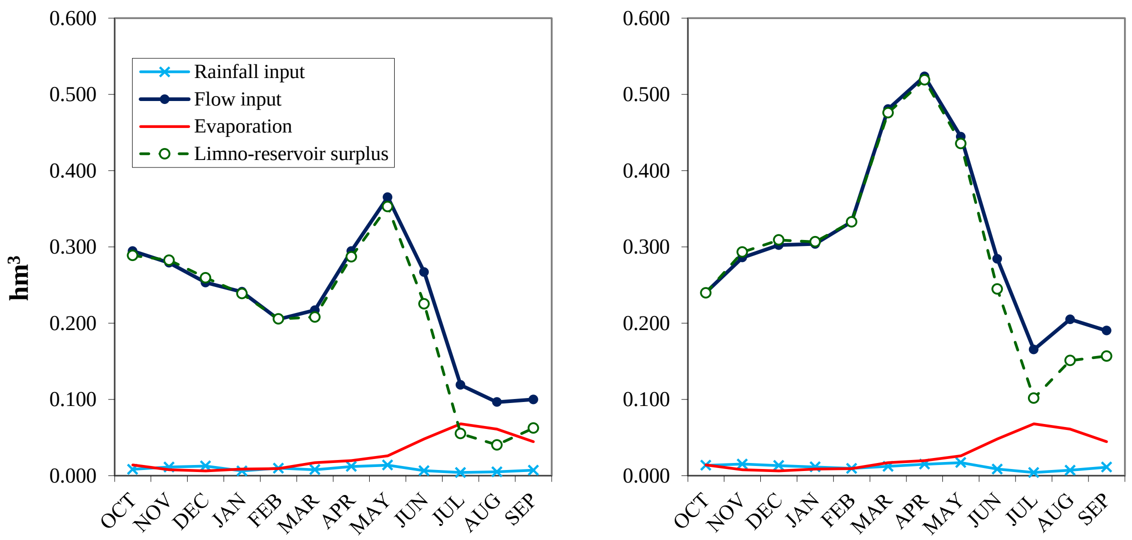

Fig. 6.1.2. Water balance in the limno-reservoir for a typical dry year (a) and a typical normal year* (b). Modified from Molina-Navarro et al. (2010) *Differs from the originally published because of an error amendment.

6.1.2.2. Modeling approach

a) Data inputs

The topography was obtained based on the DEM of the Castilla-La Mancha Regional Government (Instituto de Desarrollo Regional, 2008), with an accuracy of 5 × 5 m (Fig. 6.1.1).

Based on the DEM, the program draws the slope map, defines the drainage network, and delimits the basin and sub-basins. Outlets generated were edited to obtain nine sub-basins, representing somewhat homogeneous areas of the territory (Fig. 6.1.1).

Land use data were obtained from the updated version (1999–2008) of the Ministerio de Medio Ambiente land use map (1:50,000). Land uses in the map were related to those included in the SWAT database. Ten different land uses are found in the Ompólveda River Basin. Scrubland is the main land use, covering a 36% of the basin area; 22% is covered by a combination of pine (50%) and holm oak (50%) forest, and 17% is covered by unirrigated cereal crops. Basin area percentage of other land uses is lower than 10% (Fig. 6.1.3a).

Soils in the Ompólveda River Basin were studied by Arévalo (2008). Applying the soil taxonomy (USDA Soil Survey Staff, 2010) and the results obtained by Arévalo (2008), 17 different soils were identified and mapped in the Ompólveda River Basin. The main characteristics of the basin soils are shown in Table 6.1.1. Of the basin surface, 61.5% was covered by entisols (subgroups Typic Xerorthent [36%], Lithic Xerorthent [15.5%], and Typic Xerofluvent [10%]), and 38.5% was covered by alfisols (subgroups Typic Haploxeralf [29%] and Lithic Haploxeralf [9.5%]) (Fig. 6.1.3b). The SWAT Users Soils Database was modified to include the soils found. The required parameters were filled thanks to the soil sample analysis performed or were inferred following USDA Soil Survey Division Staff (1993), Schoeneberger et al. (2002), Fuentes Yagüe (2003) and Porta Casanellas and López-Acevedo Reguerín (2005).

The slope was divided into three classes, following the FAO criteria for preparation of soil degradation maps. These classes are 0 to 8%, 8 to 30%, and >30%. Slopes lower than 8% lead to rill and interrill erosion, between slopes of 8 and 30% gully erosion takes place, and when slopes are higher than 30% the processes of stream and channel erosion start (FAO, 1980).

Weather data were obtained from the AEMET (Ministerio de Agricultura, Alimentación y Medio Ambiente). Among the available precipitation stations, the Escamilla station (located in the southeast border of the basin; Fig. 6.1.1) is the closest to the centroid of all sub-basins. Rainfall has been recorded at Escamilla station from 1963 to 2010. One pluviometric station may be enough for such a small basin (87.8 km^2): Brath et al. (2004) pointed out that four gauges were appropriate for a 1000 km^2 basin. SWAT has been successfully applied in some locations geographically close to our study area, using five rainfall stations in a 1110 km^2 basin in southwest France (Oeurng et al., 2011) or two weather stations in a 315 km^2 basin in southwest Spain (Galván et al., 2009).

Closer daily maximum and minimum temperatures were taken from Guadalajara station. This station is about 45 km northwest of the Ompólveda River Basin, but temperatures in both locations are nearly the same. A weather station was installed next to the Pareja Limno-reservoir dam in September 2009, and temperature records obtained there were correlated to those at the Guadalajara station. A very good determination coefficient was found ($R^2 = 0.98$ for maximum temperatures; $R^2 = 0.94$ for minimum temperatures), and, applying the regression equation, Guadalajara station records were modified, creating a fictitious temperature station next to the Pareja Limno-reservoir (Fig. 6.1.1). Missing values in Guadalajara station were generated by linear regression equation from the data of Torrejón station located about 30 km southwest of Guadalajara (R^2 = 0.99 for maximum temperatures; R^2 = 0.94 for minimum temperatures). Data were preprocessed into database files with the SWAT required format.

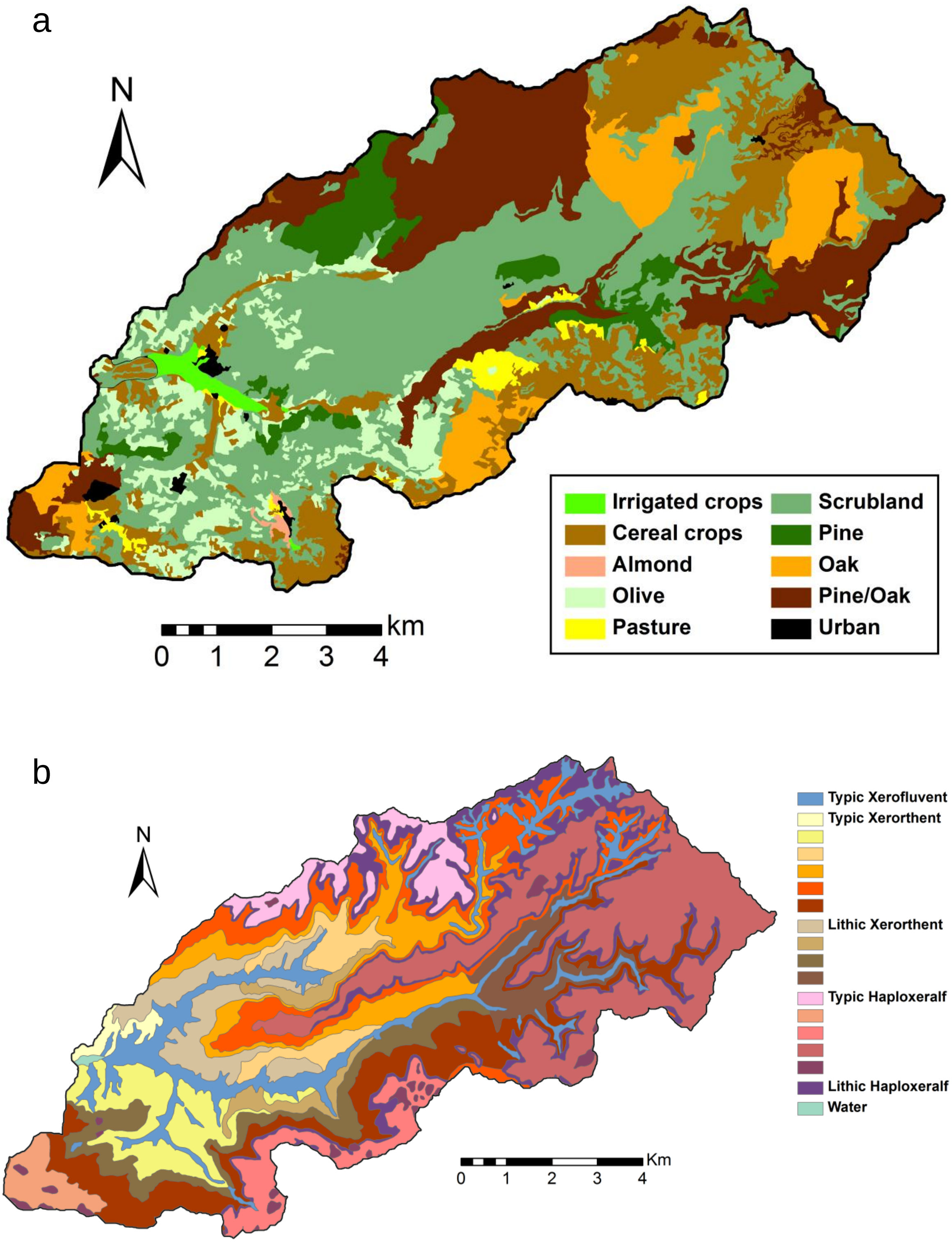

Fig. 6.1.3. Land uses (a) soil types (b) in the Ompólveda River Basin.

Table 6.1.1. Main characteristics of the soils in the Ompólveda River Basin.

	Typic Xerorthent						Lithic Xerorthent			
	1	2	3	4	5	6	1	2	3	4
Basin surface, %	0.84	5.55	2.93	6.89	9.10	10.63	5.09	2.22	5.26	3.07
Depth cm	60	70	70	55	65	70	40	40	40	40
Hydrologic group	C	C	B	B	C	C	C	C	C	C
Texture	SCL	L	L	L	SCL	CL	CL	L	L	SIL
Bulk density, g cm^{-3}	1.53-1.63	1.54-1.74	1.34-1.50	1.05-1.15	1.01-1.11	1.18-1.45	1.16-1.36	1.28-1.43	1.00-1.15	1.19-1.30
AWC,┼ mm mm^{-1}	0.09	0.07	0.09	0.09	0.09	0.12	0.11	0.09	0.10	0.10
OC╪ content, % wt	0.09-0.45	0.09-1.99	0.06-0.94	0.05-1.66	0.05-1.15	0.03-1.22	0.03-0.96	0.03-1.78	0.03-2.55	0.06-1.12
SHC,§ mm h^{-1}	8.0	7.5	7.5	7.5	8.0	5.0	5.0	7.5	7.5	10.0
USLE¶ K factor	0.196-0.205	0.519-0.650	0.417-0.478	0.328-0.438	0.290-0.332	0.265-0.311	0.301-0.311	0.366-0.464	0.265-0.449	0.510-0.573

	Typic Xerofluvent	Typic Haploxeralf 1	2	3	4	5	Lithic Haploxeralf
Basin surface, %	9.76	3.60	1.98	3.62	18.63	1.17	9.52
Depth cm	125	60	60	60	60	90	49
Hydrologic group	B	C	C	C	B	C	B
Texture	SL	L-CL	SICL-C	L-CL	L-CL	CL-C	L
Bulk density, g cm^{-3}	1.28-1.50	0.97-1.15	1.22-1.52	1.35-1.65	1.03-1.33	1.05-1.35	0.98-1.45
AWC,┼ mm mm^{-1}	0.07-0.11	0.09-0.10	0.12-0.14	0.09-0.11	0.09-0.10	0.11-0.12	0.08-0.10
OC╪ content, % wt	0.06-1.69	0.05-4.03	0.05-0.58	0.05-3.90	0.05-1.80	0.05-3.97	0.05-2.72
SHC,§ mm h^{-1}	12.0	5.0-7.5	2.5-7.5	5.0-7.5	5.0-7.5	2.5-5.0	7.5
USLE¶ K factor	0.356-0.470	0.248-0.521	0.262-0.366	0.335-0.607	0.350-0.480	0.130-0.270	0.271-0.382

┼ Available water capacity
╪ Organic carbon
§ Saturated hydraulic conductivity
¶ Universal Soil Loss Equation

b) Model set-up

The subdivision into hydrologic response units (HRUs) was performed with the land use, soil, and slope maps. Threshold levels of 15% for land use and 10% for soils and slope were selected, and the ArcSWAT interface defined 252 HRUs for the model (22–36 HRUs per sub-basin). These threshold values are used by the interface to eliminate minor land uses, soil types, or slopes in each sub-basin.

Before sensitivity analysis and calibration, default SWAT parameter values were manually modified according to the previous knowledge of the basin. Many of the routing, groundwater, and watershed parameter values were assigned considering the observations done by Molina-Navarro et al. (2010) and the field work done in the basin, where discharges in 40 springs have been monitored semiannually over a 3-yr period (2009–2011). The altitude range in the basin was divided into four elevation bands, and precipitation and temperature lapse rates were obtained using the records from the closest AEMET stations and were included in the model (9.9 mm km^{-1} and 9.1°C km^{-1}, respectively). The Hargreaves method (Hargreaves and Samani, 1985), which only needs daily values for minimum and maximum temperatures and geographical location, was used to estimate PET. To calculate the surface runoff, the U.S. Soil Conservation Service curve number procedure was used. This method calculates the surface runoff based on soil type, slope, initial soil moisture state, land use, and management practices (Arnold et al., 1995).

c) Model calibration and validation

Discharge data to perform the model were available from 1 Jan. 1986 to 31 Dec. 2003. The period from 1 Jan. 1986 to 31 Dec. 1988 was used to allow the initial values of the model parameters to reach equilibrium. The remaining period was used for model evaluation (calibration and validation). Building of the Pareja Limno-reservoir had not started by this period, so the E-3270-Pareja gauging station was still active, and model performance could be compared with river discharges obtained there.

SWAT input files were compiled in the ArcSWAT interface for SWAT version 2005 (Winchell et al., 2007), and the model was run. Sensitivity analysis, calibration, and validation processes were performed using the Sequential Uncertainty Fitting, version 2 (SUFI2) procedure of the software SWATCUP (SWAT Calibration and Uncertainty Programs) (Abbaspour, 2008). In SUFI2, parameter uncertainty accounts for all sources of uncertainties, such as uncertainty in driving variables, conceptual model, parameters, and measured data. A more detailed description of SWAT-CUP and SUFI2 can be found in Abbaspour (2008). Sensitivity analysis was performed to identify parameters that are most influential in governing streamflow. In SUFI2, parameter sensitivities are determined by a multiple regression system, which regresses the Latin hypercube-generated parameters against the objective function values. Sensitivities were obtained after 500 runs. The automatic calibration procedure was used to determine best parameter values, based on observed data at Pareja gauging station and using the Nash-Sutcliffe coefficient (NSE; Nash and Sutcliffe, 1970) as the objective function. A total of 1500 simulations were run in three steps of 500 simulations, readjusting the parameters after each step. Calibration was performed monthly from 1 Jan. 1989 to 31 Dec. 1996 because the final objective of modeling is the simulation of future discharges into the Pareja Limno-reservoir to establish a monthly water balance and asses its hydrological feasibility. This period includes wet, average, and dry years, which is desirable to obtain a good model calibration (Gan et al., 1997). Validation of the model was performed following the SUFI2 procedure from 1 Jan. 1997 to 31 Dec. 2003.

d) Model evaluation

The model performance was judged using graphical and statistical evaluation techniques. The coefficient of determination (R^2, along with the p value for the linear regression variance analysis) and the NSE were used for statistical model evaluation because they are the most widely used statistics reported for hydrologic calibration and validation (Gassman et al., 2007), besides the RMSE-observations standard ratio (RSR), developed by Moriasi et al. (2007) and based on the recommendation by Singh et al. (2004). The NSE ranges from ∞ to 1 and measures how well the simulated versus observed data match the 1:1 line. Moriasi et al. (2007) proposed that NSE values should exceed 0.5 in order for model results to be judged as “satisfactory” for hydrologic evaluation, rating the model performance as "good" if NSE is between 0.65 and 0.75 and "very good" if NSE is >0.75. Values for RSR vary from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. Based on Singh et al. (2004) recommendations, Moriasi et al. (2007) suggested a "very good" rating for those models with a RSR value <0.5, "good" for RSR between 0.5 and 0.6, and "satisfactory" between 0.6 and 0.7.

Two graphical techniques were used. The first one was the hydrograph, a time series plot of predicted and measured flow throughout the calibration and validation period. Scattergrams were also used where predicted values are plotted against observed ones. Following Boskidis et al. (2010) and Pisinaras et al. (2010), a regression line in the form $S_i = \gamma O_i$ (where S_i refers to the model simulated values O_i refers to the observed values) was fitted through the data, computing R^2 for this line too. The slope γ can be compared with the 1:1 slope (perfect match) as a measure of overprediction ($\gamma > 1.0$) or underprediction ($\gamma < 1.0$).

e) Limno-reservoir hydrologic feasibility assessment

Once the model was properly calibrated and validated, discharge flow into the Pareja Limno-reservoir was simulated to assess the hydrologic feasibility of the infrastructure. Because the definitive filling process ended in late 2007, a water balance for the limno-reservoir was established for 2008 and 2009 to discover if a constant water level was maintained. The simulated discharge was the input in the water balance subtracted from the water consumption in Pareja village (redirected downstream the limno-reservoir with its construction). Water consumption data were provided by the Pareja City Hall. Annual consumption is approximately 19,000 m^3. In summer, water consumption per capita is higher, and the population quadruples. Monthly consumption is estimated to be 800 m^3 from October to May, 1300 m^3 in June, 4000 m^3 in July and August, and 3500 m^3 in September. The output of the balance was the direct evaporation, using the values measured for this period in the adjacent Entrepeñas Reservoir by the Confederación Hidrográfica del Tajo. Larger input than output throughout the period would indicate a continuous surplus (flowing out the limno-reservoir via the fishway and/or the spillway) and a constant maximum water level. Otherwise, the water level could go under the fishway exit (717.75 m.a.s.l.), and the hydrologic feasibility of the limno-reservoir could be questioned.

To check the usefulness of the SWAT model as a tool to assess the feasibility of the Pareja Limno-reservoir, the water balance performed was compared with the water level variation in the limno-reservoir recorded by the research team since the beginning of the project (spring 2008).

6.1.3. RESULTS AND DISCUSSION

6.1.3.1. Modeling approach

a) Sensitivity analysis and auto-calibration

The sensitivity analysis showed that the most influential parameters were the deep aquifer percolation fraction (RCHRG_DP), the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), the soil evaporation compensation factor (ESCO), the U.S. Soil Conservation Service curve number (CN2), the groundwater “revap” coefficient (GW_REVAP), and the available water capacity of the soils (SOL_AWC). The higher sensitivity of these parameters denotes the importance of the groundwater (RCHRG_DP, GWQMN, and GW_REVAP) and the evaporation (ESCO) in the basin, which was expected due to the Mediterranean climate (high evapotranspiration rates) and the presence of the limestone shallow aquifer. Similar results have been found in other Mediterranean basins. There, ESCO is reported most frequently as an influential parameter and is used in calibration (Galván et al., 2009; Boskidis et al., 2010; Pisinaras et al., 2010; Oeurng et al., 2011; De Girolamo and Lo Porto, 2012). In addition, groundwater parameters were influential in Mediterranean basins where shallow aquifers are relevant (Varanou et al., 2002; Conan et al., 2003; Plus et al., 2006) and even where minor shallow aquifers were playing a role (Gikas et al., 2006; Galván et al., 2009; Oeurng et al., 2011). CN2 and SOL_AWC are also sensitive parameters in most of the cited works, and baseflow depends on them as well (Conan et al., 2003). Arnold et al. (2000) showed that surface runoff is extremely sensitive to CN2 and, consequently, baseflow.

These most sensitive parameters, along with others that may improve the model results (widely included by the authors cited above), were calibrated for years 1989 to 1996 to reproduce discharges at the Pareja gauging station. The list of the SWAT parameters adjusted, showing the initial values and the values obtained after the calibration process (best SUFI2 simulation), is given in Table 6.1.2. Initial values were assigned based on the previous knowledge of the catchment, apart from Manning’s “n” values for tributary channels (CH_N1) and for overland flow (OV_N), which show the SWAT default value.

The parameters values obtained after calibration may reflect the characteristics of the Ompólveda River Basin. Baseflow recession coefficient (ALPHA_BF) is a direct index of groundwater flow response to changes in recharge. Although the value increased with calibration, 0.27 indicates a slow response, according to the limestone aquifer present. Values in other Mediterranean studies are variable but are usually higher when no relevant aquifers are present (Galván et al., 2009; Oeurng et al., 2011; De Girolamo and Lo Porto, 2012). The delay time for aquifer recharge (GW_DELAY) ranged from 1.8 to 4.4 d, being lower in the alluvial lithology but showing a shallow depth of the water table. Deep aquifer percolation fraction (RCHRG_ DP) may also simulate the groundwater recharge (Pisinaras et al., 2010). The value obtained was relatively high (0.33), which could be partially related to the recharge of the limestone aquifer. In other basins with limestone lithology, the percolation fraction is even higher (Varanou et al., 2002). The

GW_REVAP value scarcely changed during calibration. It controls the amount of water that moves from the shallow aquifer to the root zone and varies from 0.02 to 0.2 (lower values indicating a restricted movement of water). However, the threshold water depth in the shallow aquifer needed for this phenomenon (REVAPMN) increased remarkably after calibration. The value for GW_ REVAP obtained for the Ompólveda River Basin is higher than in most of the other Mediterranean SWAT applications (e.g., Varanou et al., 2002; Pisinaras et al., 2010), maybe due to the role played by the abundant forest coverage (Galván et al., 2009).

Table 6.1.2. Initial values for the adjusted parameters and best fitted values after calibration with SUFI2.

Parameter	Description	Initial value	Best value
ALPHA_BNK	baseflow alpha factor for bank storage	0.15	0.13
ALPHA_BF	baseflow recession coefficient	0.01	0.27
CANMX (mm)	maximum canopy storage	4.0	18.3
CH_N1	Manning's "n" value for the tributary channels	0.014	0.137
CH_N2	Manning's "n" value for the main channel	0.30	0.17
CN2	U.S. Soil Conservation Service curve number for soil moisture condition II	38.8–70.0	28.7–51.7
EPCO	plant uptake compensation factor	0.50	0.32
ESCO	soil evaporation compensation factor	1.00	0.89
GW_DELAY (days)	delay time for aquifer recharge	4.4–14.4	1.8–6.0
GW_REVAP	groundwater "revap" coefficient	0.10	0.09
GWQMN (mm)	threshold water depth in the shallow aquifer for base flow	1000	1202
OV_N	Manning's "n" value for overland flow	0.14	0.32
RCHRG_DP	deep aquifer percolation fraction	0.30	0.33
REVAPMN (mm)	threshold water depth in the shallow aquifer for "revap"	60	107
SOL_AWC (mm mm^{-1})	soil available water capacity	0.07–0.12	0.06–0.11

This extensive vegetation cover may be the reason for the increase of the maximum canopy storage (CANMX) and the decrease of CN2. In areas with natural vegetation, CN2 is lower because of the better soil cover and the higher interception. Agriculture is scarce in the Ompólveda River Basin, and the lands are often abandoned, obtaining CN2 values lower than those reported in other Mediterranean basins already cited. Most similar values have been found in Panagopoulos et al. (2011) for forest land cover in central Greece. Plant uptake compensation factor (EPCO) and ESCO values were reduced after calibration, thus increasing the evapotranspiration generated by the model. The same circumstance has been found in most of the Mediterranean SWAT applications cited.

Figure 6.1.4a shows the observed and simulated discharges for the calibration period on a monthly basis (monthly basis was chosen as the final objective of modeling is the simulation of future monthly discharges into the Pareja Limno-reservoir). The model satisfactorily reproduced the order of magnitude of the observed discharges and their change tendency in time. The R^2 values were 0.78 ($p < 0.001$) monthly and 0.85 ($p < 0.005$) annually. Nevertheless, discharge was underpredicted, especially during 1989, 1991, and 1992, whereas the largest flow peak occurred in 1996 and was accurately predicted by the model. The scattergram showed in Fig. 6.1.4a also reflects this underprediction because the value of the slope γ is <1 ($\gamma = 0.78$). Following Moriasi et al. (2007), the statistical performance of NSE and RSR was "good" on a monthly basis (0.67 and 0.57, respectively) and "satisfactory" and "good" on an annual basis (0.60 and 0.59, respectively). A good calibration procedure may use multiple statistics, each covering a different aspect of the hydrography, so that the whole hydrograph would be covered. The three statistics used in this research cover the three major categories of quantitative statistics described by Moriasi et al. (2007) (standard regression [R^2], dimensionless [NSE], and error index [RSR]), giving strength to the calibration procedure. Moreover, the existence of an important limestone aquifer and the use of input data with the most detailed scale among all the SWAT applications found in Mediterranean areas introduce complexity into the model and may make the calibration procedure more difficult, so the result obtained can be considered acceptable.

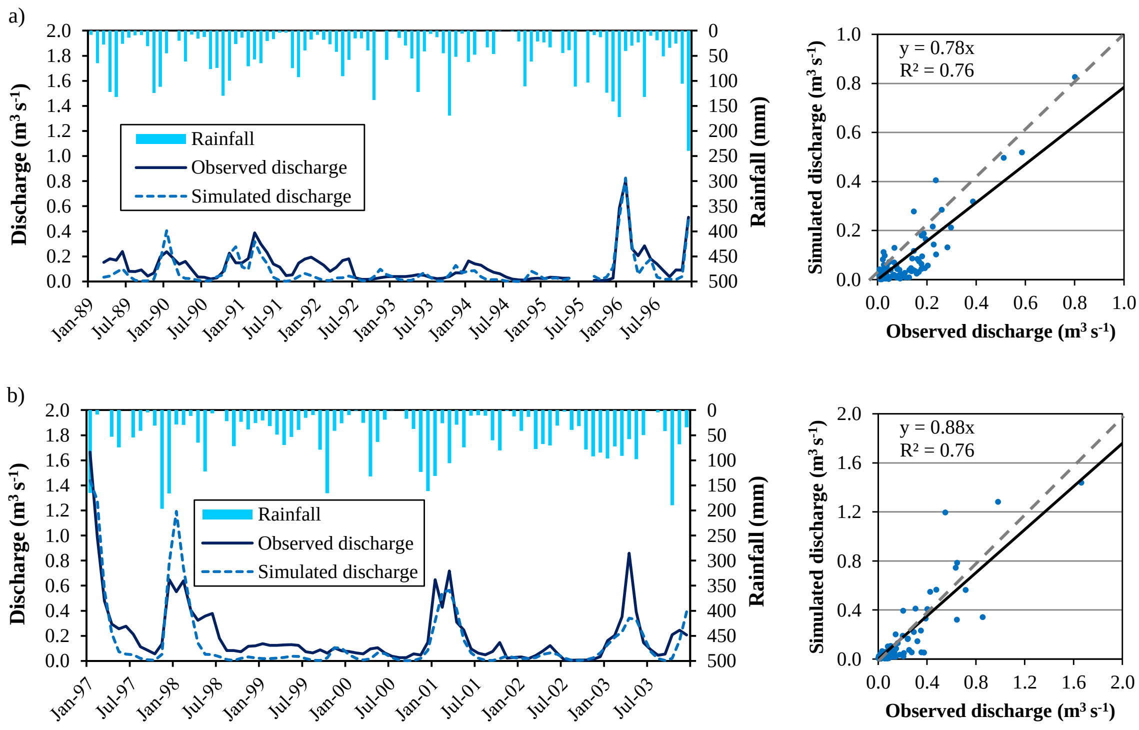

Fig. 6.1.4. Observed and simulated mean monthly discharges and rainfall during the calibration (1989–1996) (a) and validation (1997–2003) (b) periods.

b) Validation and hydrologic response of the basin

Once the model was calibrated, the next step was its validation with the observed data at the Pareja gauging station for years 1997 to 2003. Figure 6.1.4b shows the observed and computed discharges for the validation period. The adjustment observed is better than in the calibration period. The R^2 values were 0.77 ($p < 0.001$) monthly and 0.98 ($p < 0.001$) annually. Discharges were slightly underpredicted most of the time, but a peak flow was overpredicted in 1998. The scattergram (Fig. 6.1.4b) also showed better adjustment, and the value for the slope was closer to 1 (γ = 0.88). Statistical indexes NSE and RSR showed a "good" monthly performance (0.70 and 0.55, respectively) and a "very good" annual performance (0.83 and 0.38, respectively).

Overall, the model had good performance during the calibration period and good or very good performance during the validation period. This is not usual because parameters are optimized during model calibration, and better performance ratings are expected during the calibration period (Gassman et al., 2007; Moriasi et al., 2007). The SWAT model has been described to be weak in simulating short-term thunderstorms and very dry conditions (Feyereisen et al., 2007) and was not developed to model little watersheds with small reaches (Plus et al., 2006). These circumstances, along with the highly detailed input used and the heterogeneity and variability of the Ompólveda River Basin, may have made the SWAT application difficult. Nevertheless, results presented remain satisfactory in a basin considerably different from other Mediterranean basins where SWAT has been applied (e.g., Conan et al., 2003; Galván et al., 2009).

The model predicted that mean annual rainfall in the Ompólveda River Basin for the total simulation period (591 mm) is mainly removed through evapotranspiration (61.7%) but suggested 30.5% of deep aquifer percolation and 7.8% of river discharge in the outlet of the basin. According to the model, total discharge is mainly composed of groundwater flow (59.8%), followed by lateral flow (37.2%) and a small percentage of surface flow (3.0%).

The river discharge percentage given by the model (7.8%) is slightly lower than the percentage registered in the gauging station (10%) as was seen in the calibration and validation results. The groundwater flow given by the model (≈60%) is lower than the percentage Molina-Navarro et al. (2010) obtained using hydrograph separation techniques (≈70%). A high percentage of the remaining flow was predicted as lateral (≈37%), but this value could be a little high, to the detriment of the groundwater flow. In short, SWAT makes a satisfactory prediction of total flow, providing an acceptable estimation of its components.

The model gives an AET percentage of 61.7%. However, a percentage of 89% was obtained using the PET data obtained in the weather station installed next to the Pareja Limno-reservoir. This difference could be due to the estimation by the model of a 30.5% of deep aquifer percolation, which, regarding the knowledge of the basin, is not real: SWAT was not developed to model little basins (Plus et al., 2006) and considers regional groundwater fluxes that do not exist in the Ompólveda River Basin. Summing up this percentage to the AET term, a 92.2% is obtained, very close to that obtained with the weather station data.

6.1.3.2. Limno-reservoir hydrologic feasibility assessment

a) Predicted water balance

Water balance in the Pareja Limno-reservoir was performed for 2008 and 2009 using the discharge data predicted with SWAT. Figure 6.1.5a shows the results obtained. The balance predicts a negative water surplus during summer in 2008 and summer and autumn in 2009. Consequently, the water level would drop under the fishway level, decreasing in the whole limno-reservoir. The main reason of these negative surpluses is the very low water discharges, together with the elevated evaporation rates during summer (>250 mm in July and August). Figure 6.1.5a also shows that water consumption in Pareja village has little effect on the balance, even during summer, when the population quadruples and water use is five times higher.

Regarding rainfall, 2008 and 2009 were normal years (average rainfall ±15%). The last wet year recorded at the Escamilla weather station was 2003, after which two normal (2004 and 2006) and two dry years (2005 and 2007) followed. The continuous absence of abundant precipitation causes the emptying of the limestone aquifer, the main water source during summer and early autumn, yielding the very low discharge that is responsible for the phenomenon observed. The existence of relatively long sequences of normal and dry years, or even two or more consecutive dry years, is usual in the Iberian Peninsula (Font, 1983), and it is expected to become more frequent due to climate change (Iglesias et al., 2005).

Negative surpluses were compared with the water levels recorded in the Pareja Limno-reservoir from May 2008 to December 2009 (Fig. 6.1.5b). Months with negative surpluses practically matched up with those when water level was below the fishway level. This fact suggests that SWAT is a useful tool to predict water discharges in the Ompólveda River Basin and to assess the hydrologic feasibility of the limno-reservoir.

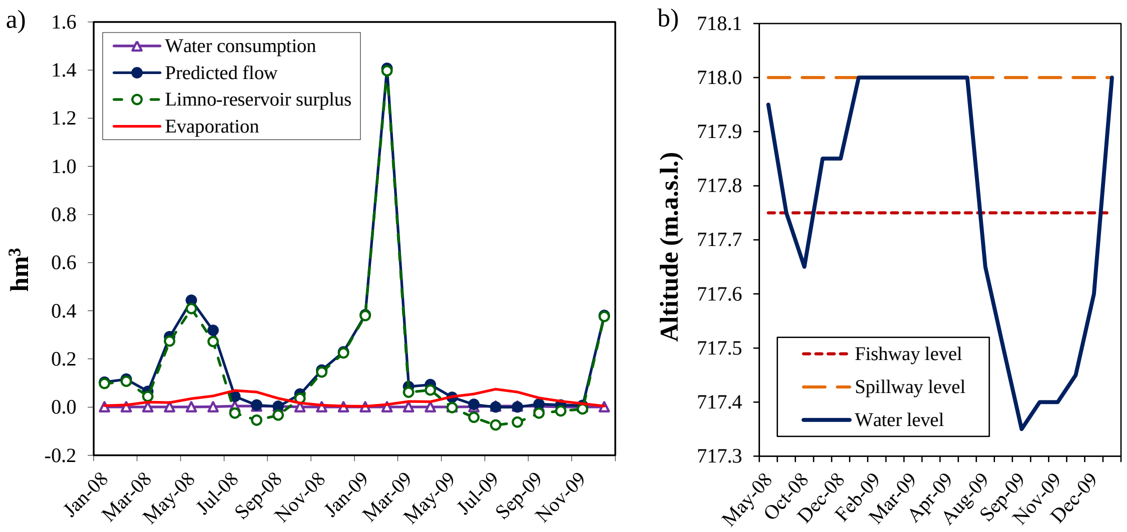

Fig. 6.1.5. Water balance in the Pareja Limno-reservoir for 2008 and 2009 using the discharge data predicted with SWAT (a) and actual water levels in the limno-reservoir (b).

b) Feasibility assessment, environmental and socioeconomical implications

The results obtained in the predicted water balance using SWAT, and corroborated with field observations, suggest that the conservation of a constant maximum water level in the Pareja Limno-reservoir cannot be ensured after a sequence of years without abundant precipitation. The decrease of the water levels may compromise the hydrologic feasibility of this infrastructure during summer months. To make things worse, this season is the most favorable to the development of aquatic and leisure activities aimed to satisfy the socioeconomic demand of the surroundings.

The existence of a drawdown zone (during summer and/ or autumn) does not allow the limno-reservoir to mitigate the environmental impacts generated by the construction of large reservoirs. The loss of a maximum water level, coupled with the scarce flow in the Ompólveda River (low dilution capacity), may worsen the water quality in the Pareja Limno-reservoir (Molina Navarro et al., 2011, 2012).

6.1.4. CONCLUSIONS

The SWAT model was applied to the Ompólveda River Basin. After calibration and validation, the model showed an overall good agreement between observed and simulated discharges despite the small size of the basin, its heterogeneity, and the highly detailed scale of the inputs. The model estimation of the water flow components is acceptable. However, the model is somewhat inaccurate when simulating AET, assuming a percolation to a deep aquifer that does not exist in this basin.

The SWAT model was used to simulate the water yield into the limno-reservoir during 2008 and 2009, establishing a water balance there. Results showed the absence of water surplus in summer 2008 and summer and autumn 2009, matching up with the decrease of the water level observed in the limno-reservoir. This fact suggests the usefulness of the SWAT model to assess the hydrologic feasibility of the Pareja Limno-reservoir.

The permanence of a constant water level at the maximum capacity of the limno-reservoir cannot be guaranteed during the whole year mainly due to the low water discharges in the Ompólveda River during summer and early autumn after a sequence of normal and dry years. This fact questions the hydrologic feasibility of the Pareja Limno-reservoir during summer months, precisely when its use as a recreational infrastructure is greatest.

6.1.5. Acknowledgments

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6.2. Hydrological and water quality impact of climate and land use change scenarios

This section reproduces the text of the following manuscript:

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A. and Jeppesen, E. Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. Submitted to *Journal of Hydrology* on 16/04/2013 (Manuscript ID: HYDROL14693)

Abstract

Water scarcity and water pollution constitute a big challenge for water managers in the Mediterranean region today and will exacerbate in a projected future warmer world, making a holistic approach for water resources management at the catchment scale essential. We expanded the Soil and Water Assessment Tool (SWAT) model developed for a small Mediterranean catchment to quantify the potential effects of various climate and land use change scenarios on catchment hydrology as well as the trophic state of a new kind of water body, a limno-reservoir (Pareja Limno-reservoir), created for environmental and recreational purposes. We also checked for the possible synergistic effects of changes in climate and land use on water flow and nutrient exports from the catchment. Simulations showed a noticeable impact of climate change in the river flow regime and consequently the water level of the limno-reservoir, especially during summer, complicating the fulfilment of its purposes. Most of the scenarios also predicted a deterioration of trophic conditions in the limno-reservoir. Fertilization and soil erosion were the main factors affecting nitrate and total phosphorus concentrations. Combined climate and land use change scenarios showed noticeable synergistic effects on nutrients exports, relative to running the scenarios individually. While the impact of fertilization on nitrate export is projected to be reduced with warming in most cases, an additional 13% increase in the total phosphorus export is expected in the worst-case combined scenario compared to the sum of individual scenarios. Our model framework may help water managers to assess and manage how these multiple environmental stressors interact and ultimately affect aquatic ecosystems.

Keywords: catchment modelling, climate change, land use management, limno-reservoir, Mediterranean, SWAT

Resumen

La escasez de agua y su contaminación son grandes retos actuales para la gestión del agua en la región mediterránea y está previsto que se intensifiquen debido al cambio climático, haciendo esencial una aproximación holística a la gestión del agua a escala de cuenca. Hemos ampliado el modelo SWAT (Soil and Water Assessment Tool) aplicado a una pequeña cuenca mediterránea para cuantificar los efectos potenciales de varios escenarios de cambio climático y de ordenación del territorio en la hidrología y también en el estado trófico de un nuevo tipo de masa de agua, un

limnoembalse (el Limnoembalse de Pareja), creado con fines ambientales y recreativos. También hemos evaluado los posibles efectos sinérgicos entre los cambios en el clima y en los usos del suelo sobre el caudal y la exportación de nutrientes en la cuenca. Las simulaciones han mostrado un notable impacto del cambio climático en el régimen hidrológico del río y, consecuentemente, en el nivel del agua del limnoembalse, especialmente en verano, complicando así el cumplimiento de sus funciones. La mayoría de los escenarios también han augurado un deterioro del estado trófico en el limnoembalse. La fertilización y la erosión del suelo parecen ser los principales factores responsables de las concentraciones de nitrógeno y fósforo total. Los escenarios combinados de cambio climático y de ordenación del territorio mostraron un notable efecto sinérgico en la exportación de nutrientes con respecto al resultado individual de los mismos. El impacto de la fertilización en la exportación de nitrato se verá reducido con el cambio climático en la mayoría de los casos. Sin embargo, un incremento adicional de la exportación de fósforo total del 13% se espera en el peor caso de los escenarios combinados, en comparación con la suma individual de escenarios. El enfoque propuesto puede servir de ayuda a los gestores del agua para evaluar cómo los múltiples factores ambientales considerados pueden interactuar y, en última instancia, afectar a los ecosistemas acuáticos.

Palabras clave: cambio climático, limnoembalse, mediterráneo, modelización a escala de cuenca, ordenación del territorio, SWAT

6.2.1. INTRODUCTION

Water pollution and water scarcity are affecting Europe's water resources and overexploitation of water, in particular, has led to complete dry-out or shrinking of natural water bodies in western and southern Europe. To maintain and improve the essential functions of freshwater ecosystems, a holistic management approach is required, based on insight into both river basin water and nutrient cycles and freshwater ecosystem functioning. The main aim of the EU water policy is to ensure that a sufficient quantity of good-quality water is available for people's needs and for the environment (EEA, 2012). The European Water Framework Directive adopted in 2000 (hereafter, WFD (OJEU num. 327, 2000)) established a new framework for water management: EU Member States should achieve a good status in all bodies of surface water by 2015. Achieving a good status involves meeting certain standards for quality and quantity of waters.

The continuing presence of a range of pollutants (e.g., excessive nutrient levels) in Europe´s waters threatens aquatic ecosystems. Excessive nutrient levels may render water bodies aesthetically unpleasant and unsafe for recreational activities, for example by stimulating the growth of bloom forming and potentially toxin producing blue-green algae. Hence, nutrient enrichment caused by agriculture can create eutrophication problems and agriculture is the largest contributor of nitrogen pollution in Europe (EEA, 2012). The effects of changes in land use and landscape management, in particular the expansion of agriculture, on water quality have been reported worldwide (e.g. Arbuckle and Downing, 2001; Carpenter et al., 1998).

Water flow regime and water level fluctuations are also major determinants of ecosystem functioning and services in river and lake ecosystems. Even though there can be high natural variation in flow regimes, many European rivers have their seasonal or daily flow regimes changed for various uses, with a significant impact on ecosystems (EEA, 2012). Accounting for climate change effects is one of the main challenges for water administrations in Europe (EEA, 2012), as it affects the availability of freshwater for ecosystems (IPCC, 2007). In spite of the extensive research on climate change, publications that use downscaling methods to examine seasonal hydrological impacts are still not abundant (Fowler et al., 2007; Raposo et al., 2013) not least for the Mediterranean region, and existing studies often use simple average annual climate data to infer changes in water availability (e.g. Kalogeropoulos and Chalkias, in press). The Mediterranean region, already subjected to water scarcity and drought today (MMA, 2007a), will be particularly vulnerable in the future. Regional climate model simulations have given a collective picture of substantial drying and warming in this region (Giorgi and Lionello, 2008; Somot et al., 2008). For central Spain, several reports have predicted a reduction in water resources of 20- 40% by the end of the 21st century (e.g. IPCC, 2007; van Vliet et al., 2013). Water quantity and water quality are closely linked (EEA, 2012) and some investigations have predicted that climate change may have profound effects on nutrient loading and eutrophication (Jeppesen et al., 2009; Jeppesen et al., 2011; Moss et al., 2011; Trolle et al., 2011). Thus, holistic management tools, accounting for multiple environmental stressors such as land use management and climatic forcing, are needed to assess how stressors interact and ultimately affect the aquatic ecosystems.

Water level fluctuations due to water exploitation and climatic influences also cause some undesirable effects in large Mediterranean reservoirs. Besides having socioeconomic impacts, these negative effects include the development of an arid drawdown zone, which is a landscape impact and also leads to the loss of bank vegetation and nesting places for aquatic birds (MMA and CNEGP, 1996; Molina-Navarro et al., 2010). Water managers have taken some actions to mitigate these impacts in Spain. One such attempt is to construct small dams in the riverine zone of large reservoirs, generating small water bodies with rather constant water level independent of the management of the larger main reservoir. They have been termed “limno-reservoirs”, since they rather resemble a lake than an ordinary reservoir (Molina-Navarro et al., 2010).

The Pareja Limno-reservoir (Guadalajara Province, central Spain) was built in 2006 and was the first Spanish limno-reservoir to serve environmental and recreational purposes (Molina-Navarro et al., 2012). However, some uncertainties about its environmental quality arose after its construction and for impact assessment a Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) using its ArcGIS interface (Winchell et al., 2009) was developed for the Ompólveda River basin flowing into the Pareja Limno-reservoir. The main objective was to evaluate its usefulness as a tool to assess the hydrological viability of the Pareja Limno-reservoir, based on present land use and climate conditions (Molina-Navarro et al., in press).

SWAT applications in the Mediterranean region are limited, but has been successfully applied in a few catchments, for instance for the purpose of modelling nutrient exports (e.g. Boskidis et al., 2010; Panagopoulos et al., 2011a) and evaluating the effects of land use management on water and nutrient exports (e.g. De Girolamo and Lo Porto, 2012; Panagopoulos et al., 2011b; Pisinaras et al., 2010) or climate change (Kalogeropoulos and Chalkias, in press; Varanou et al., 2002). In Spain, SWAT has recently been applied to evaluate the effects of best management practices on NO_3 export (Cerro et al., in press), the vulnerability of agriculture in a climate change context (Savé et al., 2012) and the potential impacts of climate change on groundwater recharge (Raposo et al., 2013).

The objective of our study was to analyze the potential effects of both changes in climate and land use management on water discharge and availability, nutrient loads and water quality of the Pareja Limno-reservoir. We have expanded the SWAT model for the Ompólveda River basin in two ways. Firstly, we have set up and calibrated the model to account for the nutrient export and consequent load to the Pareja Limno-reservoir (nitrate and total phosphorus - hereafter NO_3 and TP). Secondly, we have developed and applied several climate change and land use management scenarios to quantify the potential effects on the river basin hydrology and nutrient export, as well as on the Pareja Limno-reservoir water quality. We have followed the approach by Nielsen et al. (2013) to couple the SWAT model with the simple and empirical model by Vollenweider and Kerekes (OECD, 1982) to estimate reservoir TP concentrations, which we used as a proxy for the trophic status of the limno-reservoir. We have also performed water balances for the Pareja Limno-reservoir using the climate change scenario output, thereby estimating the water level fluctuations in the limno-reservoir. We anticipate strong impact on the Ompólveda River basin hydrology due to climate change, which could also affect the nutrients loading and consequently lead to deterioration in the trophic state of the limno-reservoir. Changes in land use management may also alter the nutrient export in the basin and might show synergistic effects with climate change (Jeppesen et al, 2009; Moss et al., 2011). Particularly, we envisage that an increasing of agricultural surface and/or fertilizers use would enhance nutrient export.

6.2.2. MATERIAL AND METHODS

6.2.2.1. Study site

The Ompólveda River catchment is located in the upper Tagus River basin (South of Guadalajara Province, central Spain) (Fig. 6.2.1). It has an approximate area of 88 km^2 and altitude in the basin ranges between 718 and 1137 m.a.s.l. Climate in the basin has Mediterranean characteristics: annual average temperature is around 13.0 °C, with cold winters and warm summers. Average annual rainfall recorded at the Escamilla station (in the upper catchment) is around 600 mm.

The catchment has rural features and natural vegetation is the main land coverage. Thus, 37% of the catchment is covered by forests (pine and holm oak) and 36% by scrubland, occasionally combined with pasture. Twenty five percent of the catchment is agricultivated, mainly including non-irrigated cereal crops (17%) and olives orchards (7%, many of them abandoned). There are about 300 inhabitants in the catchment, mostly living in the village of Pareja.

The Pareja Limno-reservoir was built in 2006 in the riverine zone of a sidearm of the much larger Entrepeñas Reservoir (Fig. 6.2.1), where the Ompólveda River discharges. The limno-reservoir has a capacity of 0.94 hm^3, a potential inundation area of 26 ha and an average depth around 4 m. More detailed features of the study site can be found in Molina-Navarro et al. (in press).

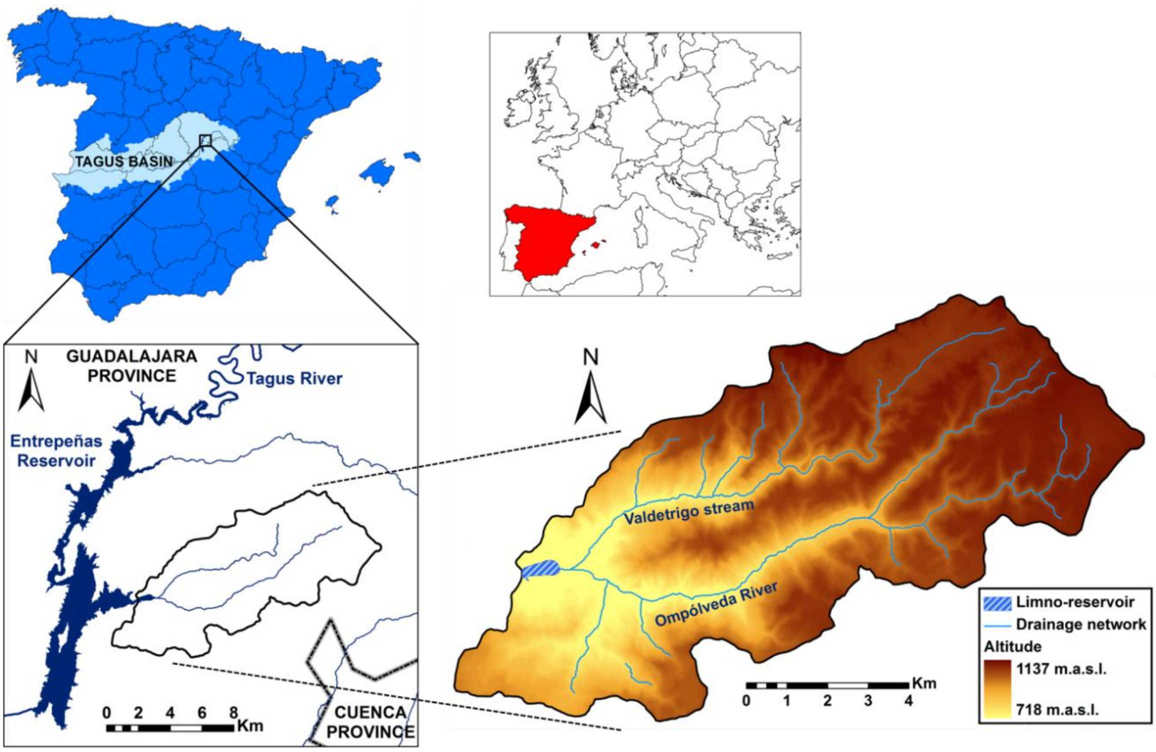

Fig. 6.2.1. Location of the Ompólveda River basin and the Pareja Limno-reservoir

6.2.2.2. Model development and calibration

To calibrate N-NO_3 and TP loads, some improvements were necessary in the SWAT model. Nutrients data for calibration were collected in the period Spring 2008 – Summer 2011 (Molina-Navarro et al., 2012). However, the model was created with rainfall data input from the Escamilla rainfall station, which was closed by the end of 2009 when a Davis Vantage Pro2 weather station was established next to the Pareja Limno-reservoir in October 2009. Rainfall data during the period when both stations were operational was compared and differences between the two stations were not statistically significant (T-test, T=0.75, P=0.46). Subsequently, the rainfall time series from the Escamilla station was expanded with data from the new station to enable calibration of nutrients exports during the period 2008-2011.

Regarding the agricultural operations, “Agricultural land-generic” land use selected in the original model was replaced by “Winter barley”, the dominant crop in the area (>80%) according to INE (2009) and field observations. Management operations for winter barley were introduced in SWAT after consulting local farmers. First, tillage operations are carried out with cultivator in late autumn or early winter, depending on the rainfall. They are followed by a first fertilizing application with 15-15-15 fertilizer (350 Kg ha^{-1}) and planting. Then, in March, top dressing ammonium nitrate is applied (140 Kg ha^{-1}, 30% N content). Finally, harvest and kill operations are carried out in July.

Soil erosion processes are often reported to have a strong relationship with nutrient losses in Mediterranean catchments (Panagopoulos et al., 2011a). In the SWAT version used, erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995), which is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978). Arévalo (2008) determined with detailed fieldwork the USLE vegetation cover factor (USLE_C) for the main land uses in the study area. Therefore, default values of USLE_C were replaced by Arévalo (2008) values (Cereal crops=0.27, pine forest=0.18, holm oak forest=0.17, scrubland and olive orchards=0.188 and pasture=0.012). Twenty one percent of the scrubland area and 29% of the pine (or pine combined with holm oak) forest in the catchment were planted in terraces. The USLE support practice factor (USLE_P) was modified following Wischmeier and Smith (1978) and values of 0.817 and 0.75 were assigned for scrubland and forest, respectively.

Total runoff in the SWAT model was re-validated (no discharge related parameters were changed) against flow measurements obtained during field work between 2009 and 2011 with an OTT C2 Small Current Meter. Daily loads of $N\text{-}NO_3$ and TP were calculated with the nutrients concentration and runoff values determined during field work for the period Spring 2008 – Summer 2011 (SWAT output for runoff was used in the first four samplings as measured discharge values were not available). Nutrient loadings were manually calibrated by monitoring changes of selected performance statistics, including Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), coefficient of determination (R^2) and percent bias (PBIAS, positive values indicate model underestimation bias and negative values indicate model overestimation bias) (Moriasi et al., 2007). Visual inspection of simulated model output against observed data was also done.

Nutrient calibration was performed by adjusting the parameters showing highest sensitivity (Table 6.2.1). Most of these parameters have been used for calibration in other SWAT applications in Mediterranean areas (e.g. Boskidis et al., 2010; Panagopoulos et al., 2011a; Pisinaras et al., 2010). No independent validation could be conducted for an additional and separate time series due to data limitations.

Table 6.2.1. SWAT parameters calibrated and their final values

Parameter	Description	Units	Initial value	Final value
NPERCO	Nitrogen percolation coefficient	-	0.2	1.0
CMN	Rate factor for humus mineralization of active organic nitrogen	-	0.0003	0.0030
ANION_EXCL	Fraction of porosity from which anions are excluded	fraction	0.5	1.0
CDN	Denitrification exponential rate coefficient	-	1.4	0.1
SDNCO	Denitrification threshold water content	fraction	1.1	0.9
RCN	Concentration of nitrogen in rainfall	mg N l^{-1}	1.0	1.2
PSP	Phosphorus sorption coefficient	-	0.4	0.6
PHOSKD	Phosphorus soil partitioning coefficient	m^3 Mg^{-1}	175	135
GWSOLP	Soluble P concentration in groundwater loading	mg P l^{-1}	0.000	0.018
PPERCO	Phosphorus percolation coefficient	10 m^3 Mg^{-1}	10	10

6.2.2.3. Design of scenarios

a) Climate change scenarios

Climate change scenarios were created using data provided by the Spanish meteorological service (AEMET). AEMET has the latest regional climate projections available for central Spain. They are based on a set of scenarios for greenhouse gas emissions using different models and downscaling techniques (AEMET, 2012). Projections have been applied to 374 temperature stations (daily maximum and minimum temperature) and 2324 rainfall stations all around the country, offering daily values for the periods 2046-65 and 2081-00 (or the whole 21st century, depending on the model) and the IPCC greenhouse gas emission scenarios B1, A1B and A2 (IPCC, 2007). They were completed between 2011 and 2012 (AEMET, 2012). The Escamilla rainfall station, located at the border of the study catchment, was used to develop the SWAT model and is one of the stations with available projections. The Torrejón station was selected as temperature station being the station with available projections situated closest to the catchment (≈70 km east). Only projections with data available for both 2046-65 and 2081-00 and all three emission scenarios were used, yielding 11 projections in total. More information about these regional projections can be found in Brunet et al. (2009) and AEMET (2012).

Data from the 11 projections were combined and averaged to obtain monthly averages of rainfall and daily maximum and minimum air temperatures for the different scenarios and periods. The same average values were calculated for measured values at the Torrejón and Escamilla stations during the modelling period (1989-2011). Differences between projected and measured values were used to develop (by adding the difference to the daily measurements in the base scenario) and run six climate change scenarios corresponding to the three emission scenarios and the periods 2046-65 and 2081-00. Temperature increases ranged from 1.3 °C to 3.9 °C (annual average). Annual average precipitation decreased in all the scenarios, ranging from -2.9% to -11.5%. Rainfall seasonality also varied, increasing in winter but generally decreasing in the remaining seasons (Table 6.2.2).

Table 6.2.2. Monthly averages for projected and measured values of precipitation (mm) (a), daily maximum temperature (°C) (b) and daily minimum temperature (°C) (c).

a)

	BASELINE	**SCENARIO B1**		**SCENARIO A1B**		**SCENARIO A2**	
	1989-11	**2046-65**	**2081-00**	**2046-65**	**2081-00**	**2046-65**	**2081-00**
J	48.9	79.9	76.6	70.9	83.5	84.0	78.9
F	41.0	65.0	65.6	64.8	64.0	64.9	64.0
M	41.0	66.0	61.6	61.1	68.6	64.1	64.9
A	64.3	49.5	43.6	43.8	40.7	49.0	43.5
M	70.5	35.9	33.3	35.1	34.5	34.3	30.7
J	34.4	31.0	29.0	31.7	29.0	30.3	25.7
J	10.8	21.5	18.4	20.7	19.2	21.6	19.0
A	18.4	18.1	18.0	18.1	18.7	18.1	17.3
S	35.8	24.3	22.6	23.7	22.6	24.3	21.5
O	80.9	40.5	36.5	40.3	39.4	39.7	30.5
N	69.3	63.0	56.5	66.5	57.3	62.5	53.9
D	72.3	75.9	73.3	79.2	75.4	74.0	70.1
Annual	**587.6**	**570.6**	**535.0**	**555.8**	**552.7**	**566.8**	**520.1**

b)

	BASELINE	**SCENARIO B1**		**SCENARIO A1B**		**SCENARIO A2**	
	1989-11	**2046-65**	**2081-00**	**2046-65**	**2081-00**	**2046-65**	**2081-00**
J	10.8	12.4	13.0	13.0	13.8	13.1	13.9
F	13.5	14.1	14.7	14.9	15.6	14.9	15.8
M	17.3	17.2	18.1	18.0	18.5	17.8	18.9
A	19.2	20.5	21.6	21.9	22.8	21.4	23.1
M	23.8	25.2	27.0	26.4	28.2	26.2	28.4
J	29.9	30.1	31.5	31.6	33.5	31.5	34.1
J	33.5	34.3	35.7	35.4	37.5	35.3	38.2
A	33.0	34.5	35.4	35.3	37.3	35.3	38.1
S	27.5	29.5	30.7	30.5	32.2	30.6	32.8
O	20.9	22.8	23.6	23.8	25.0	23.8	25.6
N	14.7	16.5	17.3	16.9	18.2	17.2	18.4
D	10.9	13.2	13.7	13.6	14.5	13.6	14.7
Annual	**21.3**	**22.5**	**23.5**	**23.4**	**24.8**	**23.4**	**25.2**

c)

	BASELINE	**SCENARIO B1**		**SCENARIO A1B**		**SCENARIO A2**	
	1989-11	**2046-65**	**2081-00**	**2046-65**	**2081-00**	**2046-65**	**2081-00**
J	0.6	3.1	4.0	3.4	4.5	3.9	5.1
F	1.4	3.7	4.3	4.1	4.9	4.3	5.5
M	4.0	5.6	5.9	5.9	6.6	5.8	7.3
A	6.0	7.3	8.0	8.2	8.8	7.9	9.7
M	10.0	10.7	11.6	11.6	13.0	11.2	13.4
J	14.4	14.5	15.7	16.0	17.5	15.5	18.1
J	17.2	17.9	19.0	19.1	20.7	18.6	21.3
A	17.2	18.4	19.0	19.2	21.0	18.8	21.4
S	13.2	14.9	15.6	15.6	17.1	15.4	17.9
O	9.1	10.1	10.9	10.7	11.9	10.8	12.8
N	4.3	6.3	6.7	6.7	7.3	6.7	8.3
D	1.7	4.1	4.7	4.5	5.3	4.4	5.7
Annual	**8.3**	**9.7**	**10.4**	**10.4**	**11.5**	**10.3**	**12.2**

b) Land use management scenarios

Six land use management scenarios were designed based on the recent history of the catchment, the information collected from local farmers and other possible management interventions of modelling interest.

- Land abandonment: Recent history in the catchment shows how people have moved from the villages to the cities (rural exodus). Four villages in the catchment have become almost abandoned (Torronteras, Hontanillas, Villaescusa de Palositos and Tabladillo) and are today inhabited just by one or two families. As a consequence, agricultural land use has been reduced, a development that is likely to continue. This scenario considers that 25% of the agricultural land turns into scrubland and that 25% of scrubland is replaced by forest.

- Aridity scenario: According to several reports published by Spanish Administrations, climate change may cause effects in the natural vegetation. They predict that forests may migrate to higher areas, being replaced by scrubland, which would resist better the new conditions (Fernández-González et al., 2005; Herranz Sanz et al., 2009). This scenario foresees that 25% of the forest turns into scrubland (range brush in the mixed forest and garrigue in the holm oak forest).

- Fertilization reduction: Other authors have already applied SWAT to other Mediterranean catchments, modelling the reduction of fertilizer application. They assume that farmers currently over-apply nitrogen (De Girolamo and Lo Porto, 2012) or that fertilization reduction is a convenient management practice (Panagopoulos et al., 2011b). We apply a 25% reduction of fertilizer application.

- Agriculture expansion: Although according to current local expectations it does not seem probable that an agricultural expansion will occur in the catchment, it is interesting to check the effects of an expansion though, seen in the light of the continuously growing demand for food production concomitantly with the increasing world population. A 25% increment of the agricultural surface, occupying current scrubland areas, has been tested in this scenario.

- Rotation of winter barley and peas: In other areas of the Guadalajara province, some local farmers are growing winter barley or wheat in rotation with peas. They point out two advantages: Firstly, peas enrich soil with nitrogen and the cereal harvest in the two following years increase. Secondly, they receive a higher subsidy. The scenario was implemented in SWAT by simulating plantation of winter barley for three years and then one year growing peas. Tillage operations for peas require the use of both plough and cultivator, usually in January, followed by plantation in February. Harvest and kill operations take place in June, and fertilization is not required. Management operations for winter barley remain as described in 6.2.2.2.

- Sunflower: According to local farmers, cereal crops are also being replaced by sunflower in other areas of the Guadalajara province. Replacement of winter barley by sunflower was modelled in this scenario. Tillage and planting operations are like those described for peas, but take place in February and April, respectively. Top dressing fertilizer is applied in May (ammonium nitrate, 100 kg ha^{-1}). Harvest and kill operations occur in October.

c) Combined scenarios

The most pessimistic (A2) and most optimistic (B1) climate change scenarios applied were combined with the presumably most pessimistic seen from an environmental quality perspective ("Agriculture expansion") and most optimistic ("Land abandonment") land use management scenarios in both projection time frames considered. "Land abandonment" may be the most probable scenario as well. A2 seems also the most probable climate change scenario according to the current CO_2 emissions (Manning et al., 2010). Eight new scenarios were consequently generated, checking the possible synergistic effects of climate and land use changes on runoff and nutrient exports. Twenty scenarios were tested with SWAT (apart from the baseline), presented with codes in Table 6.2.3.

Table 6.2.3. Codes for the different scenarios simulated.

Code	Scenario	Code	Scenario	Code	Scenario
BS	Baseline scenario	**FR**	Fertilization reduction	**B1i+AE**	Combined B1i+AE
B1i	B1 (46-65)	**LA**	Land abandonment	**B1ii+LA**	Combined B1ii+LA
B1ii	B1 (81-00)	**AS**	Aridity scenario	**B1ii+AE**	Combined B1ii+AE
A1Bi	A1B (46-65)	**AE**	Agriculture expansion	**A2i+LA**	Combined A2i+LA
A1Bii	A1B (81-00)	**WBP**	Winter barley + peas	**A2i+AE**	Combined A2i+AE
A2i	A2 (46-65)	**SF**	Sunflower	**A2ii+LA**	Combined A2ii+LA
A2ii	A2 (81-00)	**B1i+LA**	Combined B1i+LA	**A2ii+AE**	Combined A2ii+AE

6.2.2.4. Hydrological and water quality assessment

a) Water availability

Annual average runoff discharges in the Ompólveda River basin obtained in the different scenarios were compared. The contributions of different flow components and potential evapotranspiration (PET) were compared between all scenarios.

In order to predict the effects of climate change on the water level of the Limno-reservoir, monthly average water balances were calculated for each scenario according to Molina-Navarro et al. (in press), including direct rainfall on the limno-reservoir surface as an additional input. Direct evaporation measured in the adjacent Entrepeñas Reservoir was re-calculated monthly for each scenario by multiplying by the same factor as PET changes in SWAT simulations.

A 0.5 m resolution bathymetric survey was carried out in autumn 2010, and the hypsographic curve of the Pareja Limno-reservoir was calculated. Using this curve and the results of the water balances, monthly average water levels in the Pareja Limno-reservoir were derived, predicting the time that the water level would be below the ordinary outflow level (717.75 m.a.s.l.).

b) Nutrients

$N\text{-}NO_3$ and TP exports were compared between scenarios, in terms of both nutrient load and concentrations, looking for the factors making a difference.

The effects of the different scenarios on the water quality of the Pareja Limno-reservoir were estimated using the empirical model by Vollenweider and Kerekes (OECD, 1982):

(1) $P_{lake} = 1.55 \cdot (P_{in}/(1+(R_t^{0.5})))^{0.82}$

Where P_{lake} is the internal annual average reservoir phosphorus concentration (µg l^{-1}), P_{in} is the annual average phosphorus concentration of inflowing water and R_t is the reservoir water retention time (years). This model assumes that the longer the retention time, the higher the loss percentage of the added phosphorus during its passage through the lake. It is consequently based on an equilibrium and may not describe properly all the processes of TP concentrations in a reservoir (e.g. internal loading), but provides an annual average TP concentration (Jensen et al., 2005; Søndergaard, 2007). It is a simple and widely used model and has already been successfully applied to estimate internal TP reservoir concentrations from SWAT-predicted TP inflows in areas with sparse data (Nielsen et al., 2013). Results obtained in BS were compared with measured data from the years 2009 and 2010.

Phillips et al. (2008) have recently compiled a series of regression equations predicting growing season mean chlorophyll *a* (Chl *a*) from TP. These equations were tested with the data available from the Pareja Limno-reservoir. All of them over-predicted Chl *a* from TP, but the OECD (1982) equation (2) yielded a better result.

(2) $\text{Log}_{10}\ \text{Chl}\ a = -0.432 + 0.79 \cdot \text{Log}_{10}\ \text{TP}$

Although the Vollenweider and Kerekes (OECD, 1982) model originally gives annual and not growing season TP concentrations, we used this equation to check how Chl *a* may vary in the different modelled scenarios. Both TP and Chl *a* concentrations obtained for the Pareja Limno-reservoir were used as a proxy for trophic status following MMA (2000). Values were compared with the reference and ecological status conditions (e.g. Cardoso et al., 2007; EC, 2009; Poikane et al., 2010) that have been described following the requirements of the WFD (OJEU num. 327, 2000).

6.2.3. RESULTS

6.2.3.1. Model performance

Runoff generated by the model fitted approximately the flow measurements obtained during field work. Although it represented adequately its dynamics, it was generally underestimated (Fig.

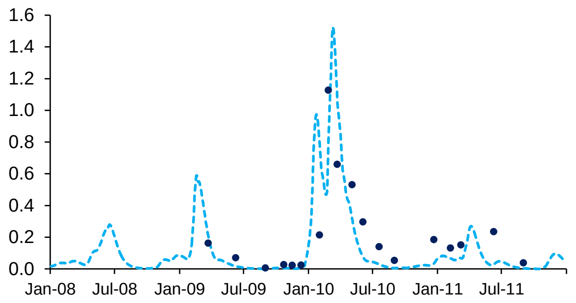

Fig. 6.2.2. Observed (points) and simulated (dashed line) daily discharges during the field work period ($m^3\ s^{-1}$).

6.2.2). Re-validation of the model against these field measurements showed the following statistical performance: NSE: 0.44, R^2: 0.60 and PBIAS: 13.4.

Several model parameters were changed during calibration of daily loadings (kg) of N-NO_3 and TP (Table 6.2.1). Dynamics of both N-NO_3 and TP were adequately represented by the model, although generally underestimated (Fig. 6.2.3). Statistically, the model showed a slightly better performance for TP (NSE: 0.57, R^2: 0.80 and PBIAS: 38.0) than for NO_3 (NSE: 0.51, R^2: 0.66 and PBIAS: 45.2).

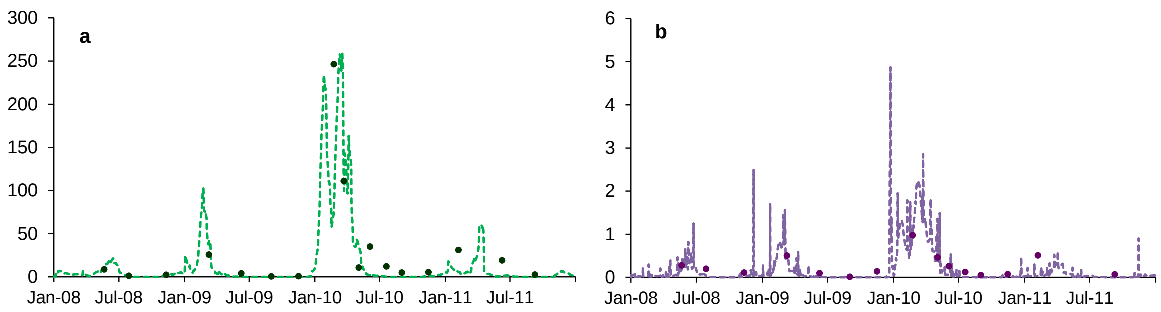

Fig. 6.2.3. Observed (points) and simulated (dashed lines) N-NO3 (a) and TP (b) loads ($Kg\ d^{-1}$).

6.2.3.2. Effects of scenarios in water availability

a) Runoff alterations

Annual average river discharge modelled for BS was 0.14 $m^3\ s^{-1}$. Most of the climate change scenarios evaluated showed a negative effect on the discharge. A1Bi and A2ii showed the highest runoff reductions (-22.2% and -48.7%) in the medium and long term, respectively. Land use management scenarios exhibited lower effect on runoff relative to climate change scenarios, with LA and SF showing the highest decreasing and increasing effects, respectively (-7.6% and +7.3%) (Fig. 6.2.4). The combined scenarios did not demonstrate any significant synergistic effect on hydrology. Only in A2ii+LA was the reduction of runoff compared to BS lower than the sum of the reductions emerging when running the A2ii and LA scenarios individually (-0.070 $m^3\ s^{-1}$ vs. -0.079 $m^3\ s^{-1}$).

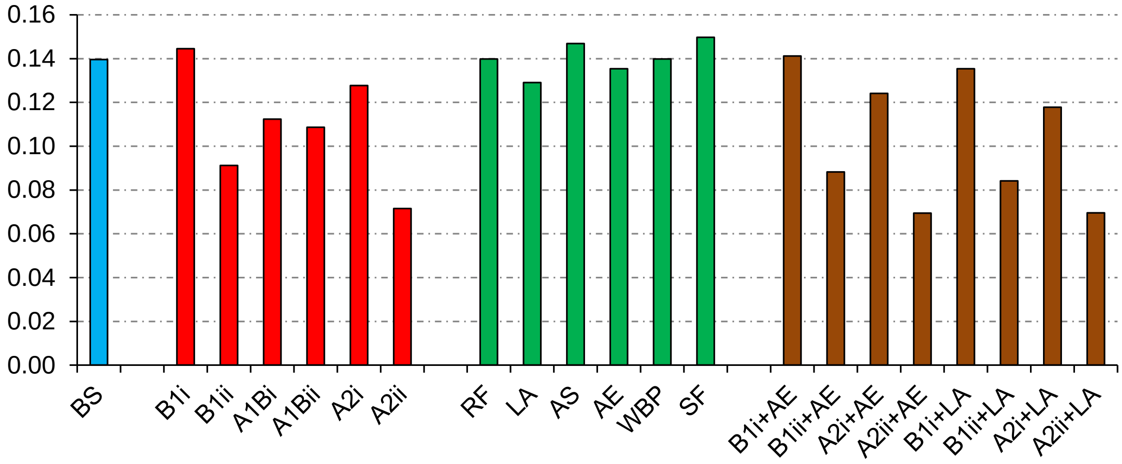

Fig. 6.2.4. Annual average runoff (m^3 s^{-1}) for the baseline conditions (blue) and the climate change (red), land use management (green) and combined (brown) scenarios. For abbreviations see Table 6.2.3.

The contribution of the different components of the river flow remained similar in the land use management scenarios, but showed variations in the climate change scenarios. Groundwater flow contribution decreased with climate change (from 62.5% in BS to 31.3% in A2ii), consequently increasing the direct flow contribution (surface and lateral flow) (Table 6.2.4). PET increased in the climate change scenarios according to the temperature variations, with a maximum increase of 13.4% in A2ii (Table 6.2.4).

Table 6.2.4. Changes in the Ompólveda River flow components and PET in the climate change scenarios.

Scenario	BS	B1i	B1ii	A1Bi	A1Bii	A2i	A2ii
Total flow (mm)	50.3	52.0	32.9	40.5	39.1	46.0	25.8
% Groundwater flow	62.5	62.1	45.7	53.6	50.0	57.5	31.3
% Direct flow	37.5	37.9	54.3	46.4	50.0	42.5	68.7
% PET increase	-	3.4	7.5	7.0	12.0	6.9	13.4

b) Limno-reservoir water balance and levels

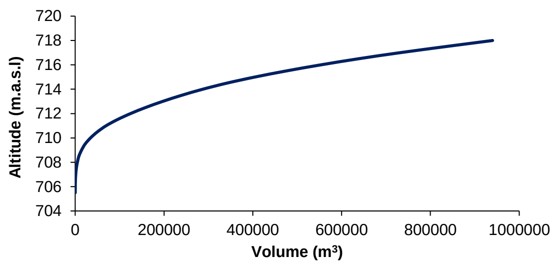

Fig. 6.2.5. Hypsograph for Pareja Limno-reservoir based on the bathymetric survey carried out in 2010. The calculation of water balances for the climate change scenarios, along with the hypsographic curve, yielded the predicted monthly average water levels in the Pareja Limno-reservoir (Fig. 6.2.6).

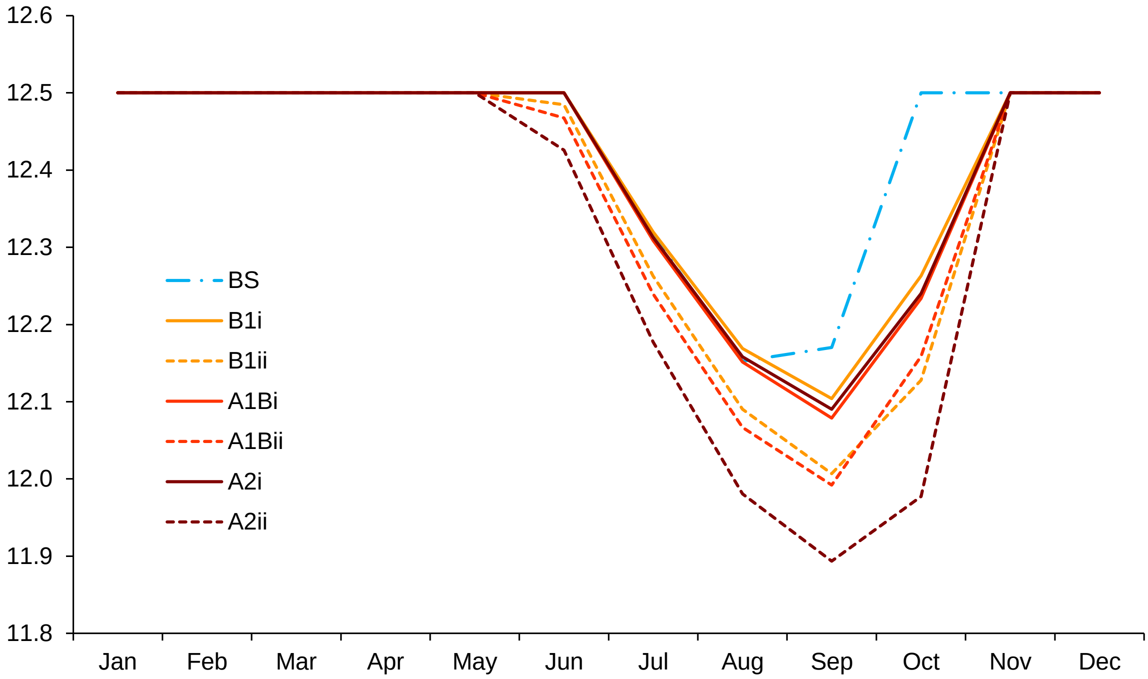

Fig. 6.2.6. Predicted monthly average water level decrease (m) in the Pareja Limno-reservoir under different climate change scenarios.

The maximum level decrease varied from 0.35 m in BS to 0.61 m in A2ii. The number of months with water levels below the ordinary outflow level (717.75 m) also increased, being 3 months in BS but raising to 4 months in the climate change scenarios for the period 2046-65 and 5 months in those for the period 2081-00 (Fig. 6.2.6). In all scenarios, the water level recovered to base levels during winter.

6.2.3.3. Effects of scenarios on nutrients

a) Nutrient loads and concentrations

In BS, the average annual nutrient exports within the watershed were 5680 kg N-NO_3 and 116 kg P, but with large inter-annual variability. The corresponding average concentrations in the river discharge were 1.0 mg N-NO_3 l^{-1} and 17.0 µg P l^{-1}, respectively.

The N-NO_3 export in the watershed varied in the climate change scenarios similarly to the runoff variation (Fig. 6.2.7a). N-NO_3 concentrations showed similar values, lower for B1ii and A2ii (Fig. 6.2.7b). A different pattern appeared in the land use management scenarios: both N-NO_3 export and concentrations showed a maximum value in AE (16.3% and 22.8%, respectively, higher than in scenario BS), and a minimum value in the SF scenario (22.1% and 22.4%, respectively, lower than in scenario BS). N-NO_3 decreases were observed in FR and LA as well, while increased in WBP and only slight N-NO_3 changes were found in AS (Fig. 6.2.7).

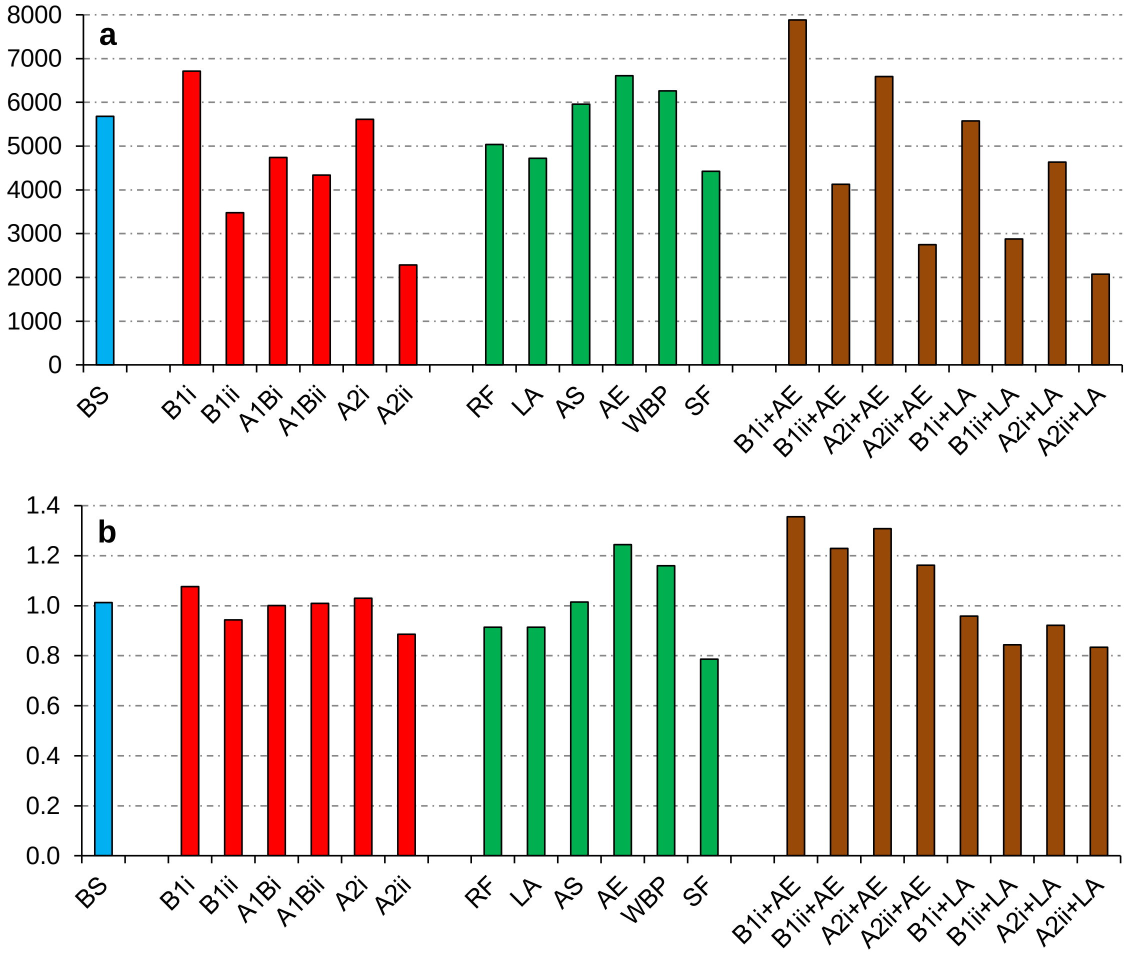

Fig. 6.2.7. Annual average N-NO_3 export (Kg) (a) and concentration (mg l^{-1}) (b) for the baseline conditions (blue), climate change (red), land use management (green) and combined (brown) scenarios. For abbreviations see Table 6.2.3.

The TP export increased in most of the climate change scenarios, except for B1ii and A2ii. The highest TP export was seen in A1Bi (42.3% higher than in BS) (Fig. 6.2.8a). TP concentration in the inflow to the reservoir was higher in all the climate change scenarios than in BS, reaching a maximum value of 25.4 µg P l^{-1} in A1Bii (49.6% higher than in BS) (Fig. 6.2.8b). The variability of both TP export and concentration was lower in the land use management scenarios. In both cases, the highest values were obtained in AE (14.1% and 11.5% higher TP export and concentration than in BS) and lowest values were obtained in LA (13.6% and 3.9% lower than in BS) (Fig. 6.2.8).

In the climate change scenarios, the TP export showed a strong statistical relationship with the amount of direct runoff (surface flow + lateral flow) (R^2: 0.98). The TP concentration showed a strong correlation with the sediment load from the HRUs modelled by SWAT in all the scenarios (R^2: 0.96).

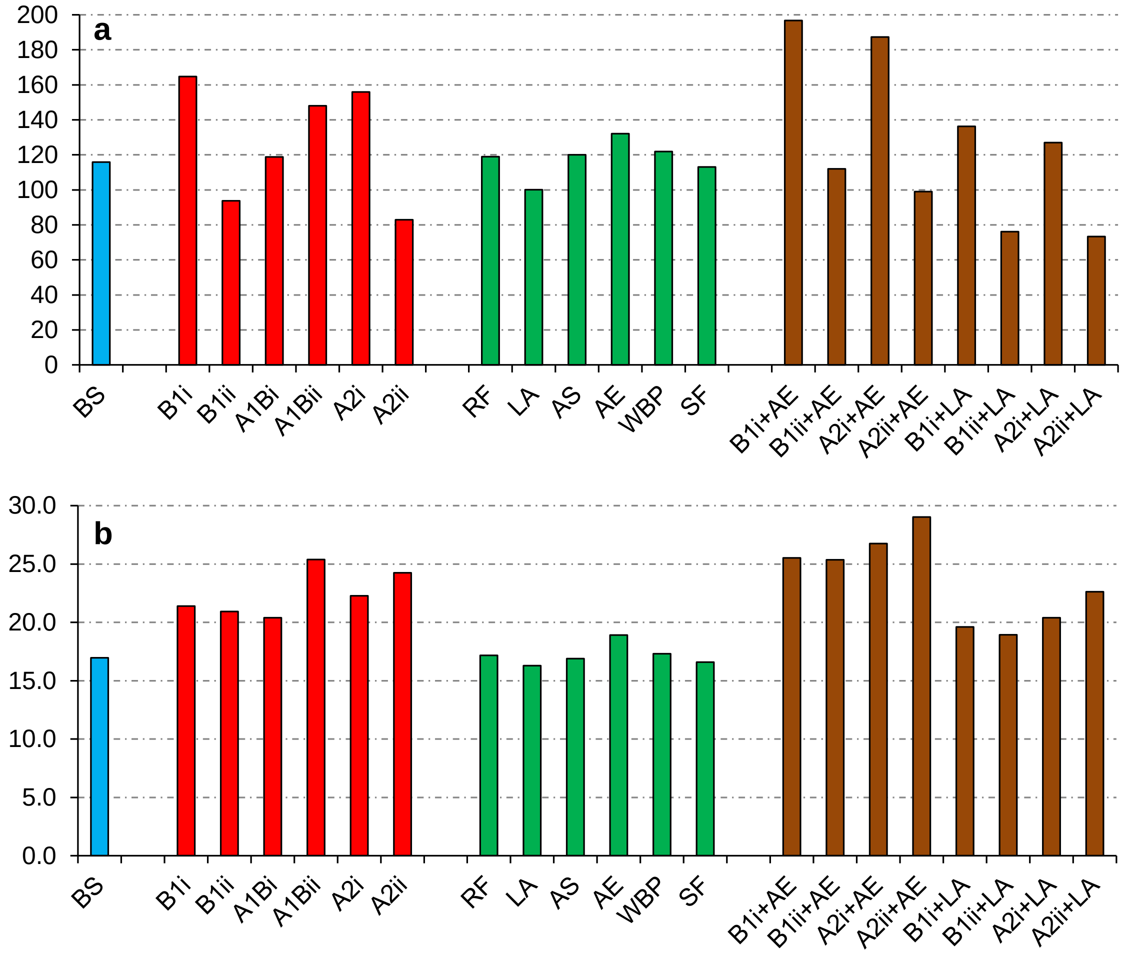

Fig. 6.2.8. Annual average TP export (Kg) (a) and concentration (µg l^{-1}) (b) for the baseline conditions (blue), climate change (red), land use management (green) and combined (brown) scenarios. For abbreviations see Table 6.2.3.

In the combined scenarios, cumulative effects of land use and climate change on the N-NO_3 export were noticeable during the second climate change period (2081-2100). Relative to BS, B1ii+AE and A2ii+AE showed a -27.3% and a -51.6% reduction of the annual N-NO_3 export, -4.9% and -8.1% more than when adding the scenarios individually. The effect was the opposite when modelling LA and climate change combined. B1ii+LA and A2ii+LA showed a -49.3% and a -63.5% reduction of the annual N-NO_3 export, which is -6.3% and -13.1% less than the sum of the individual scenarios (Fig. 6.2.7a). The increase in N-NO_3 concentrations (1.01 mg l^{-1} in BS) was 0.05 mg l^{-1} higher in all the combined scenarios of climate change and in AE than in the sum of individual scenarios (Fig. 6.2.7b).

Synergistic effects were most significant for TP, for the TP export especially noticeable for the period 1946-65. Relative to BS, in the combined scenarios B1i+AE and A2i+AE, a +69.9% and a +61.7% increase in the annual TP export were observed, being +13.5% and +13.0% higher than when summing up the effects of the scenarios individually. The opposite effect was observed for LA. Increasing values of annual TP export were +17.7% and +9.65% in B1i+LA and A2i+LA, while the sum of individual scenarios yielded additional mean increases of +11.0% and +4.6%, respectively. The TP export decreased in the before-mentioned scenarios during 2081-00 and the synergistic effects were less significant (Fig. 6.2.8a). For the TP concentrations the increase compared to BS (17.0 µg l^{-1}), in the four climate change scenarios modelled with AE, was noticeably higher (between +8.4 µg l^{-1} and +12.1 µg l^{-1}) than the sum of the effects from the individual scenarios (between +5.9 µg l^{-1} and +9.2 µg l^{-1}). Again, the opposite effect was observed for LA. The increase in TP concentrations in the combined scenarios was lower (ranged from +2.0 µg l^{-1} to +5.7 µg l^{-1}) than the sum of individual effects (ranged from +3.3 µg l^{-1} to +6.3 µg l^{-1}) (Fig. 6.2.8b).

b) Limno-reservoir water quality

Predicted annual mean in-lake TP concentrations for 2009 and 2010 were 11.2 µg P l^{-1} and 8.4 µg P l^{-1}, respectively. Average concentrations from measured values were <11.3 µg P l^{-1} in 2009 and <10.0 µg P l^{-1} in 2010 ("<" indicates that some or all the samples were below the limit of detection -10 µg P l^{-1}).

As expected in-lake TP concentrations were lower than inflow concentrations, but followed a similar pattern. In all the climate change scenarios the TP concentration was higher than in BS. Maximum in-lake TP concentration was modelled for the A2i+AE scenario (16.5 µg P l^{-1}, 43.0% higher than in BS). The effect of AE on increasing TP is again higher under climate change than under baseline conditions.

Both the TP in-lake concentration and the summer Chl *a* estimated from the TP values were close to the boundary between the oligotrophic and mesotrophic states in BS. Climate change simulations generally predicted a deterioration of the trophic state, falling into the mesotrophic category. In the land use management scenarios, AE also exhibited a decrease, albeit it was lower than that provoked by climate change. The worst trophic status was predicted in the combined scenarios (Fig. 6.2.9).

All the TP values obtained were still lower than the reference conditions designed for Mediterranean lakes following the WFD requirements (Fig. 6.2.9a). All the Chl *a* values are also below the Good/Moderate ecological status class boundary for Mediterranean calcareous reservoirs (Fig. 6.2.9b).

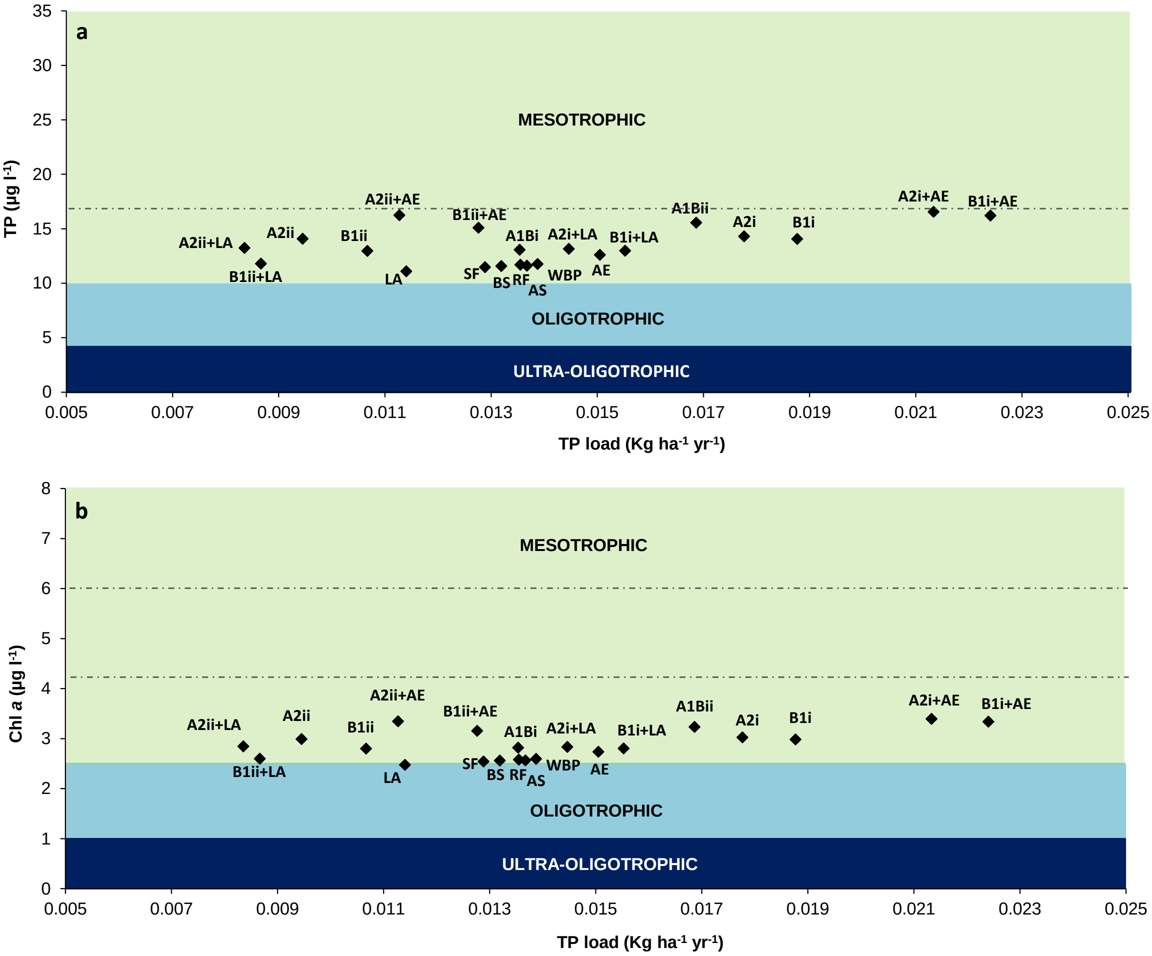

Fig. 6.2.9. (a) Annual mean in-lake TP concentration predicted for all the scenarios according Vollenweider and Kerekes (OECD, 1982) from the inflow concentration of TP and the water retention time in the limno-reservoir. (b) Chl *a* concentration predicted according to OECD (1982) from the in-lake TP concentration. Trophic classifications according to MMA (2000) are presented in the background. Dashed lines indicate TP reference conditions (a) and the Good/Moderate ecological status class boundary interval for Chl *a* (b) obtained following the WFD requirements. For abbreviations see Table 6.2.3.

6.2.4. DISCUSSION

6.2.4.1. Model performance

There are some uncertainties in the runoff model re-validation against the measured data from the more recent years (2009-11). First, it was originally calibrated and validated with monthly data (Molina-Navarro et al., in press), while daily values were used in this work; second, rainfall data from the last two years was taken from the Pareja station instead of the Escamilla station (although they did not show statistically significant differences -see 6.2.2.2-); and third, observed daily runoff data was calculated from discrete measurements of flow velocity with a small current meter, with its consequent margin of error. Despite this, the model reproduced adequately the patterns of the observed discharges and their magnitude (Fig. 6.2.2). Compared to the performance statistics for daily data in the SWAT model review summarized by Gassman *et al.* (2007) and the summary statistics from the literature review in Moriasi *et al.* (2007), the model re-validation (NSE: 0.44, R^2: 0.60 and PBIAS: 13.4) may be considered satisfactory. Nevertheless, the runoff was generally underpredicted.

A separate time series for validation of nutrient load dynamics was not available. Thus, the model was just calibrated, which implies a modest simulation of the overall nutrient loading. Other authors have also experienced the same difficulties obtaining modest results when only discrete monitoring data was available (e.g. De Girolamo and Lo Porto, 2012; Nielsen et al., 2013).

Calibration was done by changing manually the values of the parameters showing highest sensitivities (Table 6.2.1). For $N\text{-}NO_3$, NPERCO was increased to 1 to lower percolation, and the rate factor for humus mineralization (CMN) was increased to 0.003. Cerro et al. (in press) also needed to increase NPERCO when calibrating SWAT to a similar size catchment in northern Spain. A value of 1.2 was assigned to RCN considering the last observations made by EMEP for the Campisábalos station (also located in the Guadalajara province) (EMEP, 2012) and rainfall composition data published for Madrid (Hontoria *et al.*, 2003), the location closest to the catchment where rainfall chemistry data was found through a literature survey. Parameters related to denitrification were also updated as, by model default, denitrification did not occur in the catchment. The soil moisture condition threshold (SDNCO) for initialization of denitrification was changed, allowing denitrification to begin at lower moisture conditions (90% saturation). Once denitrification was activated, CDN decreased to 0.1, obtaining an annual average denitrification rate of 0.91 kg ha^{-1}. This value is in agreement with those reported by Barton et al. (1999), considering that forest is the main land use in the catchment. One of the most influential parameters on the $N\text{-}NO_3$ calibration was the fraction of porosity from which anions are excluded (ANION_EXCL), which was set up as 1 for all the soils in the catchment.

The statistical performance of the model for $N\text{-}NO_3$ (NSE: 0.51, R^2: 0.66 and PBIAS: 45.2) was acceptable compared to the multiple model applications reviewed by Gassman et al. (2007). Regarding general performance ratings given by Moriasi *et al.* (2007), $N\text{-}NO_3$ predictions were "satisfactory" (it must be considered that these ratings are given for a monthly time step and that our model was calibrated with daily values that usually show even lower ratings). The model reproduced satisfactorily the dynamics in the $N\text{-}NO_3$ loading, including peak loadings (Fig. 6.2.3a). The statistics for model calibration were strongly dependent on the peak loading captured in February 2010 when the Ompólveda River showed one of the highest discharges in recent years. The $N\text{-}NO_3$ load was generally underpredicted, which may be attributed to several factors: Firstly, also flow discharge was underpredicted. Secondly, $N\text{-}NO_3$ underprediction was particularly pronounced at the end of the calibration period. During dry periods (first half of the calibration), nitrate is stored in the soil pore water. When dry periods are followed by intense rainfall events (second half of the calibration), percolation of soil pore water occurs, increasing the nitrate loading (Menció et al., 2011). SWAT may not accurately model this process. Thirdly, the reason for $N\text{-}NO_3$ underprediction may be the omission of possible N inputs in the catchment, for instance from dry deposition or from N fixation performed by some legume species included in the scrubland floristic composition.

The concentration of soluble phosphorus in the groundwater flow (GWSOLP) was one of the most sensitive parameters for TP. It has also been modified for calibration in other SWAT applications for the Mediterranean area (e.g. Boskidis et al., 2010; Pisinaras et al., 2010). A value of 0.018 mg l^{-1} was assigned to this parameter. PPERCO was also an influential parameter, and finally the default value (10) was selected, as in other cases for Mediterranean catchments (e.g. Panagopoulos et al., 2011a). Also PSP and PHOSKD are relevant parameters for TP calibration (e.g. Panagopoulos et al., 2011a; Pisinaras et al., 2010) and were therefore calibrated too. Phosphorus availability index (PSP) was increased to 0.6, corresponding to the fraction of fertilizer P in solution after an incubation period (Winchell et al., 2009). The phosphorous soil partition coefficient (PHOSKD) was decreased to 135 m^3 Mg^{-1}, thus increasing the concentration of soluble phosphorus in surface runoff (Winchell et al., 2009).

The statistical performance of the model for TP was slightly better than for $N\text{-}NO_3$ (NSE: 0.57, R^2: 0.80 and PBIAS: 38.0), being between the “satisfactory” and “good” ratings given by Moriasi et al. (2007). Again, the model reproduced satisfactorily the dynamics of the TP load, although the values were generally underpredicted (Fig. 6.2.3b). Besides the model’s underprediction of runoff, it should be noted that some of the observed values used for calibration were actually around the limit of detection by the analytical method.

6.2.4.2. Effects of scenarios on water availability

a) Runoff alterations

Climate change scenarios showed a noticeable impact on the river flow regime due to the generally decreasing rainfall and the increasing evapotranspiration. River discharge increased slightly in B1i, but decreased in the remaining scenarios, up to a 48.7% decrease in A2ii (long term scenario, Fig. 6.2.4). The results obtained are in agreement with predictions of the effects of climate change on water resources conducted for the Iberian Peninsula by other authors. Iglesias et al. (2005) predicted a 17% average reduction of the water resources for 2060. The last Synthesis Report published by the IPCC (2007) and more recently the results of van Vliet et al. (2013) have suggested a runoff decrease between 20 and 50% in central Spain by the end of the 21st century.

Land use management scenarios did not show effects as severe as the climate change in the river flow regime. LA predicted a 7.6% reduction in river discharge (Fig. 6.2.4). A denser vegetation cover in this scenario may increase evapotranspiration and thereby decreased runoff, especially of groundwater. The opposite effect was found when simulating conversion of forest into scrubland (AS), which is in agreement with the findings by Pisinaras et al. (2010) for deforestation.

The contribution of the components of the river flow may also vary with climate change, increasing surface flow but decreasing groundwater flow (Table 6.2.4). The annual average of precipitation decreased in all climate change predictions, but increased in winter (Table 6.2.2). Thus, most of the precipitation may concentrate in winter. Higher rainfall rates may more frequently exceed the soil infiltration capacity, creating higher surface flow (Horton, 1933). A pronounced decrease of the groundwater flow in climate change scenarios for a Mediterranean catchment has already been observed by Varanou et al. (2002). For northern Spain, Raposo et al. (2013) and Savé et al. (2012) and have also predicted a significant influence of climate change on the temporal variability in water availability due to changes in rainfall seasonality, which may concentrate during the winter season.

b) Limno-reservoir water balance and levels

The Pareja Limno-reservoir was built with the objective of being at its maximum level throughout the year. The aim was to avoid the wide fluctuations of the shoreline that usually occur in reservoirs (Wetzel, 2001), providing the population with a place to develop recreational activities, as well as a resource for rural and nature tourism (Molina-Navarro et al., 2010). However, after periods of scarce precipitation, it has been seen that the level goes below its maximum during summer and autumn, when the groundwater flow is predominant (Molina-Navarro et al., 2012b). Both the general decrease in river discharge and the reduction of the groundwater runoff caused by climate change may worsen this situation and threaten the hydrologic feasibility of the limno-reservoir.

Our predictions of water level in the limno-reservoir for the different climate change scenarios confirmed this threat. In BS, the water level is below the average ordinary outflow level during July-September (3 months). This is in agreement with observations. The initial filling of the Pareja Limno-reservoir finished by the end of 2007 and the level has been under the ordinary outflow during the periods August’08-October’08, July’09-December’09 and June’12-January’13. The water level will be below the outflow during 4 and 5 months in the short term and long term climate change scenarios respectively (in average), reaching lower levels (Fig. 6.2.6). It is also expected that the Pareja village will be supplied with water from Tagus River within a few years (MMA, 2007b). However, the water consumption component in the balance represents such a small amount that levels hardly change when removing it.

Lowest levels are expected during summer when the limno-reservoir is mainly supposed to fulfil its function as an infrastructure for recreational purposes (swimming, non-engine aquatic sports or nature tourism, among others). Shallower parts of the limno-reservoir would be periodically exposed, reducing the recreational value to potential users. An arid band would appear in the drawdown zone of the limno-reservoir, impacting the landscape, possibly affecting its beauty and its attraction as a tourist resource (MMA & CNEGP, 1996). Moreover, the absence of a surface water outflow during these periods and the consequent increase in water retention time may have negative implications for the water quality beyond those that we have described here (Wetzel, 2001).

6.2.4.3. Effects of scenarios on nutrients

a) Nutrients loads and concentrations

The N-NO_3 concentration in the inflow to the reservoir varied just slightly from BS in the climate change scenarios (Fig. 6.2.7b). N-NO_3 export reductions seem to be mainly governed by the magnitude of the runoff, as has been described by other authors (e.g. Panagopoulos et al., 2011b; Varanou et al., 2002). In the land use management scenarios the scene is different. SF, in which just top dressing fertilizer is applied, showed the lowest N-NO_3 load and concentration, followed by LA. In WBP, despite reducing fertilization in the year of rotating peas, N-NO_3 increases, probably due to N fixation (Fig. 6.2.7).

Fertilization seems to be the main factor governing the difference in the N-NO_3 exports in the land use change scenarios, decreasing its load and concentrations when less fertilizer is applied or the agricultural surface is reduced. The same has been observed in other Mediterranean catchments (e.g. Boskidis et al., 2010; Cerro et al., in press; Panagopoulos et al., 2011b). This fact should be considered in the future development of the study area concerning N-NO_3 loads into the Pareja Limno-reservoir. Besides, synergistic effects have been observed between climate and land use change scenarios. They were especially noticeable for the N-NO_3 export during the second climate change period (2081-00). In climate change scenarios combined with AE, annual N-NO_3 export decreased proportionally more than in the individual sum of scenarios. However, the reduction of N-NO_3 exports caused by LA was found to be less effective in the combined scenarios than when adding the individual scenario results (Fig. 6.2.7a). It seems that both agriculture expansion and land abandonment would play a less relevant role in the annual N-NO_3 export under climate change conditions than in the current climate, possibly due to the reduced runoff discussed above. On the other hand, the N-NO_3 concentration increased slightly more in the combined scenarios of climate change and AE than in the sum of individual scenarios, which seems appropriate since a reduced runoff diminishes the dilution capacity for all kinds of pollution.

TP export did not follow the total runoff variation, although it showed a strong relationship with direct flow (surface + lateral). TP concentration increased in all the climate change scenarios. Land use management scenarios seemed to have less effect on TP than that observed for N-NO_3, though maximum TP export was also found in AE (Fig. 6.2.8a).

The strong relationship found between the TP concentration and the sediment load suggests that soil erosion is one of the main sources of TP in the catchment, which has also been observed in the SWAT model results of other Mediterranean catchments (e.g. Panagopoulos et al., 2011a). Despite decreasing annual runoff, the sediment load is higher in all the climate change scenarios than in BS, and the TP load is higher in most of them. The climate change alteration of rainfall seasonality, which may cause more intense precipitation and higher surface flow, is likely the main factor for the increasing sediment load (Porta i Casanellas et al., 1994) and TP.

These observations agree with the studies conducted on P transport. Sharpley et al. (1994) stated that surface runoff serves as the primary flow pathway for P transport. In a small research watershed in Pennsylvania, Buda et al. (2009) reported that dissolved reactive P was predominant in the surface runoff, but particulate P arising from erosion accounted for relevant percentages in some areas with a high slope gradient (33% of TP for 10% slope gradient and 43% of TP for 18% slope gradient). However, not only surface runoff may play a role in the P transport. When rainfall exceeds the soil infiltration capacity, a surface runoff event occurs (Horton, 1933). Dunne and Black (1970) stated that the return flow of subsurface water (i.e. lateral flow) may also contribute to these runoff events, along with direct precipitation, and other authors have demonstrated the importance of this return lateral- flow on P concentration and losses in runoff (e.g. Zheng et al., 2004). Buda et al. (2009) also discovered that this kind of runoff event was related to high P loads and pointed out that identifying runoff generation mechanisms is important from the perspective of P release and transport in surface runoff. The strong relationship found between direct runoff (surface + lateral) and TP load in the climate change scenarios matches the findings of these authors. The highest direct runoff and TP loads may occur after extensive rainfall events, as reflected by SWAT model (Fig. 6.2.3b, maximum TP load on 23-dec-09, the time of the largest rainfall event since dec-08).

In land use management scenarios, land use changes seem to drive the variations in sediment load and, consequently, in TP load and concentrations. The highest TP was found in AE (Fig. 6.2.8), in which cereal agriculture, an erosion-prone land use (Wischmeier and Smith, 1978) substitute scrubland. The lowest TP was found in LA (Fig. 6.2.8) where the scrubland and forest surface increase, protecting soil from erosion and diminishing the connectivity of surface runoff and TP export (Sharpley et al., 2008). The relevance of fertilization for TP seems to be lower than for $N\text{-}NO_3$. Noticeable synergistic effects were observed in the combined scenarios. Combined scenarios B1i+AE and A2i+AE (2046-65 period) showed a higher TP export increase than when adding the effects of individual scenarios. It means that the agriculture expansion may have a more harmful effect on the TP load within a climate change context than in the present situation. In contrast, in combined scenarios for the same period and LA, TP export increased less than the sum of effects of individual scenarios. In this case, it means that the land abandonment may play a more consistent role in reducing the TP load within a climate change context than in the current climate. These synergistic effects seem consistent with the discussion above: agricultural expansion and land abandonment are land uses that are, respectively, prone and protective to soil erosion; during climate change, erosive rainfall events seem to increase and our results suggest that soil erosion is the main source of TP. The same effects were observed for TP, but in this case for all the eight combined scenarios. In the most pessimistic scenario (A2ii+AE), TP load and concentration in the outflow were 62% and 58% higher than in BS, potentially constituting a threat to the maintenance of a favourable water quality in the Pareja Limno-reservoir (see 6.2.4.3).

b) Limno-reservoir water quality

The annual mean in-lake TP concentration estimated with the Vollenweider and Kerekes equation (OECD, 1982) was consistent with the field observations, although only few data were available for comparison.

The higher TP input led to deteriorating trophic conditions in most of the model scenarios, generally creating a switch from an oligo-mesotrophic to a mesotrophic state. No scenario showed a noticeable improvement in water quality (Fig. 6.2.9). However, despite TP input inducing an increase in in-lake TP concentrations, all the values were lower than the reference conditions assigned to Mediterranean lakes (16.6 μg l^{-1}) within the framework of the EU FP6 Research Project REBECCA (Cardoso et al., 2007). As to Chl *a* in REBECCA, the EC (2009) determined that the Good/Moderate ecological status class boundary for Mediterranean calcareous reservoirs was in the range 4.2-6.0 μg l^{-1} and the reference conditions for Chl *a* in the range 1.8-2.6 μg l^{-1} (EC, 2009; Poikane et al 2011). Values simulated for all the scenarios, even the combined ones, are below the Good/Moderate class boundary. Simulated Chl *a* concentrations are also below the critical levels over (6.0-9.0 μg l^{-1}) which the proportions of Cyanobacteria may increase in a threshold-like manner (Ptacnik et al., 2008; Solheim et al., 2008).

Interpretation of the TP and Chl *a* results must be done with caution, however. Firstly, TP-Chl *a* relationships, despite widely used, have a large uncertainty (Søndergaard et al., 2011). Secondly, EU Mediterranean ecological status metrics have been developed with data from a group of deep and large reservoirs (EC, 2009). They may have different ecological behaviour than the Pareja Limno-reservoir, and, generally speaking, a different ecological behaviour than shallower Mediterranean lakes and reservoirs. For phytoplankton composition metrics, we found that the indices developed for the Mediterranean did not work properly for the Pareja Limno-Reservoir (unpublished results). It is important to acknowledge that our simple limno-model based on the OECD equations (OECD, 1982) may not reflect all processes related to TP and Chl *a* concentrations within the limno-reservoir. In-lake processes such as thermal dynamics, evaporation, oxygen depletion, trophic relationships, algal blooms or internal loading of phosphorus may be affected by climate change and could enhance the effects of eutrophication more than we predicted (Jeppesen et al., 2009; Trolle et al., 2011).

We did not simulated the in-lake NO_3, but the increases in N-NO_3 load and concentration observed for several scenarios may also to some extent affect the limno-reservoir water quality. Although in most studies phosphorus is considered the most important limiting nutrient, in many instances nitrogen can also play an important role for primary production, as it was seen for a small Spanish lake close to our study area (Camacho et al., 2003). Nitrogen pollution may cause a variety of negative effects in lakes and reservoirs such as acidification, eutrophication, occurrence of toxin producing algae, aquatic animals mortality or loss of submerged macrophytes that leads to a turbid state (Camargo and Alonso, 2006; Jeppesen et al., 2011) and its reduction is one of the priorities in the European water legislation (EEA, 2012). Camargo and Alonso (2006) concluded that levels of total nitrogen lower than 0.5-1.0 mg N l^{-1} could prevent aquatic ecosystems from severe eutrophication. Our results suggest that agriculture expansion may lead inflow N-NO_3 concentration to exceed this threshold. Jeppesen et al. (2011) and Ozen et al. (2011) also suggested that nitrogen in-lake concentration in Mediterranean areas may increase in a future warmer climate due to enhanced water evaporation, which would enhance its negative ecological and toxicological effects (Camargo and Alonso, 2006).

A deteriorating water quality may prevent the Pareja Limno-reservoir from fulfilling its function as an infrastructure for recreational purposes. The model provides the deciding policy makers with an approximation of how land uses and climate changes may affect the water quality in the Pareja Limno-reservoir in the near future. The implementation of fertilizer and land use management plans could be appropriate in the catchment, as already suggested for other Mediterranean locations (e.g. De Girolamo and Lo Porto, 2012; Panagopoulos et al., 2011a, 2011b). Reducing fertilization, replacing the present crops or carrying out actions to combat soil erosion (e.g. reforestation reducing the hydrologic connectivity) may decrease the inputs of both N-NO_3 and TP into the Pareja Limno-reservoir. These initiatives should be taken in order to guarantee the feasibility of the limno-reservoir from a water quality perspective. A high frequency monitoring program for flow and nutrients in the Ompólveda River and in the reservoir itself, re-location of the Pareja gauging station and reactivation of the Escamilla rainfall station would be desirable too. It would provide information about the evolution of the different water quality variables and could allow the generation of an even more robust model for further scenario testing.

6.2.5. CONCLUSIONS

The SWAT model previously developed for hydrological study purposes in the Ompólveda River basin was expanded to simulate discharge and nutrient loads to the Pareja Limno-reservoir and to model impacts of potential climate change and land use management scenarios on the reservoir. The model generally performed satisfactorily.

Climate change scenarios showed a noticeable impact on the river flow regime, with a decreasing river discharge up to 48.7% in the worst case by the period 2081-00. The model also predicted an increase of surface flow due to a change in rainfall seasonality and decreasing groundwater flow. These circumstances may threaten the hydrological feasibility of the limno-reservoir. Its water level is already below the ordinary outflow 3 months per year (in average). With climate change, this period may expand to 4 or 5 months, reaching lower levels and complicating the function of the Pareja Limno-reservoir as a recreational and environmental infrastructure.

The main factors governing changes in N-NO_3 and TP concentrations in the inlet seemed to be fertilization and soil erosion. Most of the scenarios predicted a deterioration of trophic conditions in the Pareja Limno-reservoir and a switch from an oligo-mesotrophic to a mesotrophic state, which may threaten the maintenance of a favourable water quality. Although a good ecological status would still be expected in all scenarios following the EU metrics, this must be regarded with caution as metrics have been developed for deep and large Mediterranean reservoirs. The model provide some guidelines to decision makers as to how to avoid deteriorated water quality in the Pareja Limno-reservoir induced by interacting and synergistic effects of climate change and land use management.

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6.2.7. References

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7. Environmental feasibility of the Pareja Limno-reservoir: Final remarks

7. ENVIRONMENTAL FEASIBILITY OF THE PAREJA LIMNO-RESERVOIR: FINAL REMARKS.

Throughout this thesis dissertation the environmental quality and feasibility of the Pareja Limno-reservoir have been discussed from different perspectives. This chapter attempts to string these discussions together, trying to respond to those uncertainties on the environmental feasibility of the limno-reservoir that emerged after its construction.

7.1. Water availability

The Pareja Limno-reservoir was aimed at preserving a constant water level. However, in the first years of operation this goal has not been met. Ompólveda River discharge was very low during summer and early autumn after a sequence of normal and dry years and evaporation lowered the water level below the ordinary outflow, specifically in the periods August'08-October'08, July'09-December'09 and June'12-January'13. During 2010 and 2011 there was a permanent water surplus throughout the year. Thus, the annual average period of water lever below the ordinary outflow was 3 months.

The decrease of the water levels may compromise the hydrologic feasibility of the Pareja Limno-reservoir during summer when the limno-reservoir is mainly supposed to fulfil its function as an infrastructure for recreational purposes. The limno-reservoir may develop a drawdown zone and a small arid band could appear, impacting the landscape, possibly affecting its beauty and its attraction as a tourist resource (MMA and CNEGP, 1996; Molina-Navarro et al., 2010).

Average contribution of groundwater flow was calculated with different methods (e.g. Remeneiras, 1974; Custodio and Llamas, 1983) and estimated around 60%-70% of total discharge. This result reveals the quantitative importance of groundwater in the Ompólveda River basin, playing an essential role in the preservation of the Pareja Limno-reservoir water level, especially in summer, when baseflow is almost the unique water input. An upper carbonate plateau and an underlying aquitard configure the hydrogeological sketch of the basin responsible for maintaining the abovementioned baseflow despite the absence of rainfall.

Additionally to the water resources decrease already observed in the last decades (CHT, 2008), several reports have predicted a reduction of 20-50% in central Spain by the end of the 21st century (e.g. IPCC, 2007; van Vliet et al., 2013). This fact could have important consequences in the hydrological feasibility of the Pareja Limno-reservoir because it could mean that the riverine dam has been oversized with respect to the real water input provided by the Ompólveda River.

The SWAT model was found useful as a tool to assess the hydrologic feasibility of the limno-reservoir and climate change was simulated. Climate change scenarios showed a noticeable impact on the river flow regime. In the most unfavourable scenario (A2), which seems also the most probable according to the current CO_2 emissions (Manning et al., 2010), river discharge may be reduced up to 50% by the end of the 21st century. The contribution of groundwater runoff also decreases with climate change. According to predictions, the water level in the Pareja Limno-reservoir will be below the outflow, in average, during 4 (2046-65) and 5 months (2081-00) per year, respectively, reaching lower levels than in the present climate. Lowest levels are expected during summer and shallower parts of the limno-reservoir would rise to the surface, reducing the recreational value to potential users and multiplying the effect of the negative impacts described above.

7.2. Water quality

Generally speaking, results obtained suggest that the present water quality of the Pareja Limno-reservoir is suitable for its recreational and environmental purposes. Physico-chemical water quality was characterized by a slight alkalinity and high conductivity because of high SO_4^{2-} and Ca^{2+} levels. The concentrations of faecal indicator bacteria (total coliforms and enterococci) fulfilled the requirements of the EU Bathing Water Directive (OJEU num. 64, 2006). The limnological analyses (nitrogen compounds, total phosphorus, chlorophyll *a* and zooplankton), following several authors criteria (including Carlson, 1977; OECD, 1982 and Camargo and Alonso, 2006), denoted an oligo-mesotrophic state in the Pareja Limno-reservoir. Besides, the native microbiological community was dominated by oligotrophs. The application of phytoplankton metrics (Catalán et al., 2003; Padisák et al., 2006; EC, 2009 and Marchetto et al., 2009) according to the EU Water Framework Directive (OJEU num. 327, 2000) revealed a *High* ecological status in the Pareja Limno-reservoir for most of the sampling surveys. These results are consistent with the original expectation of a good water quality favoured by the characteristics of the Ompólveda River basin (small size, natural vegetation and low human activity).

Nevertheless, the results also revealed that water quality may deteriorate in several circumstances, especially during winter and summer. In winter, intense precipitation and consequently high runoff volumes in the Ompólveda River led to an increasing of faecal indicator bacteria and nutrients concentrations in the Pareja Limno-reservoir. This fact has been already reported by other authors (e.g. Haggarty et al., 2010; Hong et al., 2010 -bacteria-; Álvarez-Cobelas et al., 2008; Buda et al., 2009 -nutrients-).

Summer drought decreases the Ompólveda River discharge and diminishes the dilution capacity for all kinds of pollution during this season, as it was seen for faecal indicator bacteria. In addition, reduced discharge in summer was essentially groundwater runoff. It presented the highest SO_4^{2-} and Ca^{2+} concentrations (from gypsum dissolution) and consequently showed high electrical conductivity and worse physico-chemical water quality (Sánchez-Montoya et al., 2012). However, the Pareja Limno-reservoir was seen to exert a buffer effect, softening these seasonal variations observed in the Ompólveda River. Besides the river input, phytoplankton biovolume and chlorophyll *a* concentration showed the highest values in the Pareja Limno-reservoir during summer, probably as a result of higher water temperatures, thermal stability, enhanced light climate and higher water residence time (Margalef, 1978; Souza et al., 2008; Molina-Navarro et al., in press). The water quality deterioration in both seasons, winter and summer, was also reflected when analysing the phytoplankton community following Reynolds et al. (2002), changing the dominance of the functional phytoplankton groups.

The application of the SWAT model (Winchell et al., 2009) coupled with the Vollenweider and Kerekes model (OECD, 1982) predicted an increase of total phosphorus concentration as a consequence of climate change, which would lead to deterioration of trophic conditions. Higher total phosphorus seems to be associated with an increasing of sediment load, probably due to the occurrence of more intense precipitations during winter. The fate and transport of faecal bacteria is also related to the sediment transport (Droppo et al., 2011; Gao et al., 2011), thus microbiological water quality may also be affected by climate change. The model also predicted that an agriculture expansion would lead to an increase of inflow nitrate concentration and would have a noticeable synergistic effect with climate change, increasing total phosphorus concentration as well. Lake internal processes were not modelled in this thesis, but they may be affected by climate change and could enhance the effects of eutrophication more than predicted (Jeppesen et al., 2009; Jeppesen et al., 2011; Trolle et al., 2011). Water quantity and water quality are closely linked and runoff reduction predicted for climate change will increase the water retention time, which may have negative implications for the water quality beyond those described (Wetzel, 2001; EEA, 2012).

A deteriorated water quality may prevent the Pareja Limno-reservoir from fulfilling its function as an infrastructure for recreational and environmental purposes. Thus, water managers may pay attention to the abovementioned factors that could suppose a threat to water quality and take initiatives in order to guarantee the feasibility of the limno-reservoir from the water quality perspective. Factors affecting water quality in summer may have special relevance, since the Pareja Limno-reservoir mainly serves its recreational functions during this season.

7.3. Sedimentation risk

The sedimentation rate estimated in the Pareja Limno-reservoir was 0.29% per year, a low value compared with those reported for many reservoirs (around 4-5%; Zarris et al. 2011). The low sedimentation rate is connected to the low sediment delivery ratio observed in the Ompólveda River basin. This is a consequence of the low connectivity between the stream network and the limno-reservoir, favoured by the basin characteristics (natural vegetation, basin shape and a National Road surrounding the limno-reservoir perimeter, among others) (de Vente et al., 2005). These conditions assure the environmental feasibility of the limno-reservoir from the sedimentation risk perspective.

Nevertheless, basin sediment yield does not necessarily represent the severity of on-site erosion problems (de Vente et al., 2005) and areas with severe erosion were detected after in-situ soil loss monitoring. As other authors predicted (Savé et al., 2012 and Raposo et al., 2023), SWAT simulation suggested that climate change will modify the rainfall seasonality. It may concentrate during the winter season, causing more intense precipitation and consequently increasing sediment load (Porta i Casanellas et al., 1994). Results obtained are useful deciding where to take proper measures against high erosion risk in order to combat the limno-reservoir sedimentation, nowadays and in a climate change context.

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8. Conclusions

8. CONCLUSIONS

8.1. Ompólveda River basin and Pareja Limno-reservoir features.

Ompólveda River basin hydrology

- Approximately 10% of the average annual rainfall in the basin (around 600 mm) becomes average annual runoff input in the Pareja Limno-reservoir (around 5.2 hm^3), indicating an important water loss via actual evapotranspiration. Runoff volume was found to be very sensitive decreasing rainfall.

- Groundwater runoff accounts for 60%-70% of total runoff, in average, with higher percentages during dry years. This reveals a great quantitative importance of baseflow in the Ompólveda River basin. An upper carbonate plateau and an underlying aquitard configure the hydrogeological sketch of the basin, which is able to maintain a permanent water flow in the river despite the absence of rainfall.

- The dissolution of calcite and gypsum minerals controls the hydrogeochemistry of the Ompólveda River basin. The geochemical analyses suggested a calcite oversaturation throughout the basin. Water evolves from Ca-HCO_3 type in the upper basin, dominated by limestone, to Ca-SO_4 type in the lower basin, where gypsum-enriched deposits surface and give the water a high electrical conductivity.

Pareja Limno-reservoir characteristics

- The Pareja Limno-reservoir showed a warm monomictic stratification pattern.

- The limno-reservoir water was slightly alkaline and the predominant major ions were SO_4^{2-} and Ca^{2+} due to the gypsum dissolution in the lower Ompólveda river basin. They led to conductivity values ranging from 744 to 1464 µS cm^{-1}, showing lower values in winter (high surface runoff input) and higher during summer and autumn (essentially baseflow input). This temporal pattern was more noticeable in the Ompólveda River outlet, while the Pareja Limno-reservoir showed a buffer effect.

- The functional group approach was found useful to study the phytoplankton in the Pareja Limno-reservoir. Assemblage B (centric diatoms) dominated the phytoplankton community since its habitat template matches up with the limno-reservoir characteristics. Nevertheless, 77 species were identified and 20 of them were descriptor (>5% of total biovolume).

- The zooplankton species richness was high (32 species). Rotifers seemed to be the best adapted in the Pareja Limno-reservoir among the three primary zooplankton groups, probably because the Pareja Limno-reservoir fulfils their feeding requirements.

- The oligotrophic microorganisms, well adapted to the environmental conditions, predominate in the microbiological community, which seemed affected by nutrient depletion (besides other factors) and may be limited by phosphorous during dry periods.

Catchment erosion and sediment yield

- An average gross hillslope erosion around 6 T ha^{-1} $year^{-1}$ was estimated in the Ompólveda River basin, using a simple *in-situ* methodology designed specifically for this study. This result falls in line with the findings of other authors in Mediterranean areas. Some areas with high risk of soil erosion were found in the hillsides of the main valleys (erosion rates were over 45 T ha^{-1} $year^{-1}$).

- Annual sedimentation estimated in the Pareja Limno-reservoir was 2032 T (2690 m^3). This implies that the specific sediment yield of the Ompólveda River basin was around 0.23 T ha^{-1} $year^{-1}$ and consequently the approximate basin sediment delivery ratio was 3.9%. The low connectivity in the basin may be the main reason for this low ratio.

8.2. Environmental feasibility of the Pareja Limno-reservoir

Hydrological feasibility

- The average retention time of the limno-reservoir has been estimated around 70 days. However, very low discharges during summer and early autumn and high evaporation caused a decreasing of the Pareja Limno-reservoir water level below the ordinary outflow level during 3 months per year (on average). Thus, the permanence of a constant water level at the maximum capacity of the limno-reservoir cannot be guaranteed. This fact questions its hydrological feasibility.

- The SWAT model was successfully applied in the Ompólveda River basin. The establishment of water balances in the Pareja Limno-reservoir proved its usefulness as a tool to assess the hydrological feasibility of the limno-reservoir.

- Climate change scenarios were simulated with SWAT. They showed a noticeable impact on the river flow regime, reducing discharge up to 50% by the end of the 21st century in the A2 scenario and decreasing baseflow contribution, which is the dominant flow component during the dry season. The climate change would mean the expansion of the period with the water level below the ordinary outflow to 4 or 5 months. The limno-reservoir may develop an arid drawdown zone, which is precisely the impact that the limno-reservoir is intended to mitigate.

Water quality

- The water quality appeared to be good enough to satisfy the environmental and recreational use of the Pareja Limno-reservoir. The analyses of nutrients (nitrogen compounds and total phosphorus), chlorophyll *a* and biological communities suggested an oligo-mesotrophic state in the limno-reservoir.

- The application of phytoplankton metrics in accordance with the Water Framework Directive denoted generally a *High* ecological status. However, none of the composition metrics showed an accurate response to trophic state and the ecological status assessment must be taken with caution.

- Total coliforms and enterococci concentrations in the limno-reservoir fulfilled the requirements of the European Union Bathing Water Directive, buffering the higher levels observed for these microorganisms in the Ompólveda River.

- Water quality may become deteriorated in winter, since high precipitation and runoff favour nutrients and microorganisms transport. In summer, the proliferation of phytoplankton and the increasing of electrical conductivity also lead to a lower water quality.

- The SWAT simulation of nutrient loads and the subsequent estimation of total phosphorus and chlorophyll *a* concentrations predicted a deterioration of trophic conditions in the limno-reservoir during climate change. It could switch from an oligo-mesotrophic to a mesotrophic state.

- Land use change simulations revealed that an expansion of agriculture (increase of fertilizer application) may deteriorate the limno-reservoir water quality, as well as showing a synergistic effect with climate change.

Sedimentation risk assessment

- The annual sedimentation rate estimated for the Pareja Limno-reservoir was around 0.29%, which is a low value compared to those reported in other reservoirs worldwide. This low value seems to guarantee the environmental feasibility of the Pareja Limno-reservoir from the sedimentation risk perspective.

- The methodology applied to study the soil erosion and the sediment yield was simple and affordable. It was proved useful to identify where the erosion problems are most severe, which allows to decide where to take proper measures against high erosion risk. In addition, it may be a valuable tool to perform analogous studies in similar infrastructures.

8.3. Future research lines

The findings of this doctoral dissertation give way to new questions. They open the possibility of starting other lines of research regarding the environmental feasibility of the Pareja Limno-reservoir or other similar infrastructures (operating or in design). The new research lines may include:

1. Get a deeper knowledge about the **hydrogeology** of the Ompólveda river basin by means of:
    a. The refinement of the estimation of groundwater recharge via isotopic methods.
    b. The systematic hydrogeological monitoring to allow the application of groundwater flow models (e.g. MODFLOW).

2. Improve the assessment of the **ecological status** of the limno-reservoir through:
    a. The analysis of the other four biological quality elements proposed in the European Water Framework Directive besides phytoplankton (i.e. phytobentos, macrophytes, macroinvertebrates and fish fauna).
    b. The application of metrics calibrated for small Mediterranean lakes and reservoirs.

3. Application of complex **aquatic ecosystem models** in the Pareja Limno-reservoir to:
    a. Understand the key processes in the limno-reservoir ecosystem dynamics.
    b. Assess the climate change, land use change, ecosystem restoration actions or internal processes effects in the limno-reservoir, among other stressors.

4. Model the **sediment load** of the Ompólveda river basin by:
    a. Performing a systematic measurement of sediment load to enable the model calibration and validation.
    b. Applying sediment transport modelling tools at catchment scale like SWAT. Relocation of the Pareja gauging station and reactivation of the Escamilla rainfall station would be desirable for this purpose.

At present, we are carrying out a new project (PEII11-0276-4395) to refine the environmental feasibility assessment of the Pareja Limno-reservoirs and perform a similar study in the remaining limno-reservoirs of the Castilla-La Mancha region. Some of the research lines suggested are being applied in this project.

8. CONCLUSIONES

8.1. Caracterización de la cuenca del río Ompólveda y del Limnoembalse de Pareja

Hidrología de la cuenca del río Ompólveda

- La aportación anual media del río Ompólveda al Limnoembalse de Pareja (alrededor de 5.2 hm^3) representa aproximadamente un 10% de la precipitación media anual (alrededor de 600 mm), lo que revela una importante pérdida por evapotranspiración. Se ha observado que el caudal circulante es muy sensible a los descensos de precipitación.

- La aportación de base representa, en media, un 60%-70% del caudal total, alcanzando mayores porcentajes en los años más secos; ello realza la importancia cuantitativa de esta aportación en la cuenca del río Ompólveda. El medio hidrogeológico sobre el que se desarrolla la cuenca del río Ompólveda lo configura una paramera carbonatada y un acuitardo subyacente, lo que facilita el mantenimiento de un flujo permanente en el río aun en momentos de ausencia de precipitación.

- La disolución de calcita y de yeso controla la hidrogeoquímica de la cuenca del río Ompólveda. La sobresaturación de calcita es la tónica dominante en todas las muestras analizadas. El agua evoluciona de bicarbonatada cálcica en la cuenca alta -dominada por calizas- a sulfatada cálcica en la cuenca baja -dominada por un sustrato yesífero-, lo que le confiere una alta conductividad eléctrica.

Características del Limnoembalse de Pareja

- El Limnoembalse del Pareja es monomíctico templado, de acuerdo con el patrón de estratificación observado.

- El agua del limnoembalse es ligeramente alcalina, siendo los iones mayoritarios dominantes el sulfato y el calcio, debido a la disolución de yeso en la cuenca baja. La conductividad eléctrica varía entre 744 y 1464 $\mu S\ cm^{-1}$, con valores menores en invierno (alto aporte de escorrentía directa) y mayores en verano y en otoño (prioridad del flujo subterráneo). Este patrón temporal, resultó más evidente en el tramo bajo del río Ompólveda, queda amortiguado en el limnoembalse.

- Se ha procedido al análisis de grupos funcionales, revelándose como una metodología útil para estudiar el fitoplancton en el Limnoembalse de Pareja. La comunidad fitoplanctónica está dominada por el grupo B (diatomeas centrales), puesto que su hábitat de referencia coincide con las características del limnoembalse. No obstante, se han identificado 77 especies de las cuales 20 han sido descriptoras (>5% de biovolumen total).

- Se ha observado una alta riqueza de especies de zooplancton (32 especies). De los tres grupos principales de zooplancton, los rotíferos parecen ser el mejor adaptado debido a que el limnoembalse satisface sus requerimientos nutricionales.

- Los microorganismos oligotróficos, bien adaptados a las condiciones ambientales, son los predominantes en la comunidad microbiana, sugiriendo el estudio que podría estar afectada por la depleción de nutrientes (entre otros factores) y limitada por el fósforo durante periodos secos.

Erosión y producción de sedimentos en la cuenca

- La erosión bruta media en la cuenca del río Ompólveda se ha estimado en unas 6 T ha^{-1} $año^{-1}$, empleando para ello una metodología diseñada "*ad hoc*" para este estudio. Este valor es concordante con los resultados obtenidos por otros autores en áreas mediterráneas, aunque en algunas zonas puntuales de la cuenca, como las laderas de los valles principales, existe alto riesgo de erosión (con tasas que superan las 45 T ha^{-1} $año^{-1}$).

- Se ha estimado que la aportación anual de sedimentos al limnoembalse es de 2032 T (2690 m^3). Ello supone que la producción específica de sedimentos en la cuenca del río Ompólveda es de 0.23 T ha^{-1} $año^{-1}$ y, por lo tanto, solo un 3,9% de los sedimentos movilizados en la cuenca alcanzan el limnoembalse. La poca conectividad en la cuenca parece ser el principal motivo del bajo porcentaje obtenido.

8.2. Viabilidad ambiental del Limnoembalse de Pareja

Viabilidad hidrológica

- Se ha estimado que la tasa de renovación media del agua del limnoembalse es de unos 70 días. Sin embargo, el escaso caudal del río en verano y en los primeros compases del otoño y las altas tasas de evaporación provocan el descenso del nivel de agua del limnoembalse por debajo del nivel del aliviadero durante un periodo medio continuo de tres meses al año. Por lo tanto, la permanencia de una lámina de agua de nivel constante no está garantizada, lo que pone en cuestión la viabilidad del limnoembalse.

- Se ha establecido satisfactoriamente el modelo de funcionamiento hidrológico en la cuenca del río Ompólveda utilizando el código SWAT. La utilidad de este modelo como herramienta para evaluar la viabilidad hidrológica ha quedado probada mediante la simulación de los balances hidrológicos en el limnoembalse.

- Se han simulado diversos escenarios de cambio climático con el modelo SWAT, observándose un impacto notable en el régimen de caudales, que llegaría a reducirse hasta un 50% a finales del siglo XXI en el escenario A2, disminuyendo además la aportación de base, que es la componente principal durante el estiaje. El cambio climático podría suponer un incremento a 4 ó 5 meses del periodo medio anual con niveles de agua por debajo de la cota de evacuación por el aliviadero; con el inevitable desarrollo de una banda árida cuya evitación fue uno de los motivos de construcción de esta infraestructura.

Calidad del agua

- La calidad del agua es adecuada para satisfacer los usos ambientales y recreativos del Limnoembalse de Pareja. Los análisis de nutrientes (compuestos nitrogenados y fósforo total), clorofila *a* y comunidades biológicas sugieren un estado oligo-mesotrófico en el limnoembalse.

- La aplicación de índices de fitoplancton según la Directiva Marco del Agua denota un estado ecológico *Muy Bueno*. No obstante, ninguno de los índices utilizados ha mostrado una respuesta precisa a las variaciones en el estado trófico, por lo que la evaluación del estado ecológico debe tomarse con cautela.

- Las concentraciones de coliformes totales y enterococos en el limnoembalse, cumplen los requisitos de la Directiva de Aguas de Baño de la Unión Europea, amortiguándose los mayores niveles de estos microorganismos observados en el río Ompólveda.

- La calidad del agua puede deteriorarse en invierno debido a que en condiciones de elevadas precipitaciones y altos caudales se favorece el transporte de nutrientes y microorganismos. En verano, la proliferación de fitoplancton y el aumento de la conductividad eléctrica también provocan una minoración de la calidad.

- Las simulaciones de exportación de nutrientes realizadas con SWAT y la posterior estimación de concentraciones de fósforo total y clorofila *a* auguran un deterioro del estado trófico en el limnoembalse en los diversos escenarios de cambio climático, pudiendo pasar de un estado oligo-mesotrófico a un estado mesotrófico.

- La simulación de cambios en los usos del suelo revela que la expansión de la agricultura podría deteriorar la calidad del agua del limnoembalse, produciéndose, además, un efecto sinérgico con el cambio climático.

Evaluación del riesgo de aterramiento

- Se ha estimado una tasa anual de aterramiento del Limnoembalse de Pareja de alrededor del 0.29%, resultando baja en comparación con los valores encontrados en otros embalses a nivel mundial. Dicho valor parece garantizar la viabilidad ambiental del Limnoembalse de Pareja desde el punto de vista del riesgo de colmatación del mismo por aportes terrígenos.

- La metodología utilizada para estudiar la erosión y la producción de sedimentos, sencilla y económica, ha resultado útil para identificar aquellas zonas donde la erosión es más severa, lo que permite decidir dónde deben tomarse las consecuentes medidas para minorar el riesgo alto de erosión. Tal metodología puede convertirse en una herramienta valiosa para desarrollar estudios similares en infraestructuras de este tipo.

8.3. Líneas de investigación futuras

Los resultados de esta tesis doctoral dan lugar a nuevas incógnitas y abren la posibilidad de comenzar otras líneas de investigación en relación a la viabilidad del propio Limnoembalse de Pareja o de otras infraestructuras similares ya operativas, ya en proyecto. Entre estas nuevas líneas de investigación se pueden citar:

1. Profundizar en el **conocimiento hidrogeológico** de la cuenca del río Ompólveda mediante:
    a. La aplicación de métodos isotópicos estimar con mayor precisión la recarga.
    b. La monitorización hidrogeológica sistemática para posibilitar la aplicación de modelos de flujo subterráneo, como el código MODFLOW.

2. Mejorar la evaluación del **estado ecológico** del limnoembalse mediante las siguientes metodologías:
    a. Análisis, además del fitoplancton, de los cuatro indicadores de calidad biológica restantes propuestos por la Directiva Marco del Agua (fitobentos, macrófitos, macroinvertebrados y peces).
    b. Aplicación de índices calibrados para pequeños lagos y embalses mediterráneos.

3. Realizar una **modelización compleja del ecosistema acuático** en el Limnoembalse de Pareja para:
    a. Discernir cuales son los procesos clave en la dinámica ecosistémica del limnoembalse.
    b. Profundizar en el análisis de los efectos del cambio climático, del cambio usos del suelo, de acciones de restauración del ecosistema o de los procesos internos en el limnoembalse, entre otros factores.

4. Modelizar la **descarga de sedimentos** de la cuenca del río Ompólveda aplicando las siguientes metodologías:
    c. Medida y seguimiento sistemático de la carga de sedimentos en el río para posibilitar la calibración y validación de modelos *ad hoc*.
    d. Aplicación de modelos de transporte de sedimentos a escala de cuenca tales como el código SWAT. La reubicación de la estación de aforo de Pareja y la reactivación de la estación de precipitación de Escamilla serían muy deseables para este menester.

En este sentido, este grupo de investigación está desarrollando un nuevo proyecto (PEII11-0276-4395) para progresar en la evaluación de la viabilidad ambiental del Limnoembalse de Pareja y para llevar a cabo estudios similares en el resto de limnoembalses de Castilla-La Mancha, en el que algunas de estas líneas de investigación ya se han iniciado.

Appendix: Curriculum Vitae

1. EDUCATION

- **Master in Secondary School Teaching** (speciality in Biology and Geology). *University of Alcalá* (Alcalá de Henares, Madrid, Spain). 2011-2012.
- **Degree in Environmental Sciences** (5 years). *University of Alcalá* (Alcalá de Henares, Madrid, Spain). 2002-2007 (End of Degree Extraordinary Award)

2. PUBLICATIONS

- **Molina-Navarro, E.**, Martínez-Pérez, S. and Sastre-Merlín, A. ¿Es el tiempo de retención un factor incidente en la calidad del agua del Limnoembalse de Pareja (Guadalajara)? In: *Cuartas Jornadas de Jóvenes Investigadores de la Universidad de Alcalá*, in press.
- **Molina-Navarro, E.**, Martínez-Pérez, S., Sastre-Merlín, A. and Bienes-Allas, R. Hydrologic Modeling in a Small Mediterranean Basin as a Tool to Assess the Feasibility of a Limno-Reservoir. Journal of Environmental Quality, in press. DOI: 10.2134/jeq2011.0360.
- **Molina-Navarro, E.**, S. Martínez-Pérez, A. Sastre-Merlín and D. Martín-Del Pozo. 2012. Limnological characteristics and zooplankton community in a newly created site: The Pareja Limno-reservoir. *Limnetica* 31(1), 95-106.
- **Molina-Navarro, E.**, S. Martínez-Pérez, A. Sastre-Merlín and R. Bienes-Allas. 2011. Studying the viability of a limno-reservoir using SWAT: The Ompólveda River Basin (Guadalajara, Spain) as a case of study. In: *2011 International SWAT Conference – Conference Proceedings*, 458-470. Texas A&M University, College Station, Texas, Estados Unidos.
- **Molina-Navarro, E.**, Martínez-Pérez, S., Sastre-Merlín, A., Soliveri, J., Fernández-Monistrol, I. and Copa-Patiño, J.L. 2011. Microbiological Water Quality and its Relation to Nitrogen and Phosphorous at the Pareja Limno-reservoir (Guadalajara, Spain). *Journal of Environmental Management* 92 (3), 773-779.
- **Molina Navarro, E.**, Bienes Allas, R.; Martínez Pérez, S. and Sastre Merlín, A. 2010. Los limnoembalses de cola y su riesgo de aterramiento: el caso del Limnoembalse de Pareja (Guadalajara). In: *IX Jornadas Españolas de Presas. Comunicaciones.* T&B Editores. Valladolid. ISBN: 978-84-92626-68-7.

- **Molina Navarro, E.,** Martínez Pérez, S. and Sastre Merlín, A (2010). El Limnoembalse de Cola de Pareja (Guadalajara): Aspectos medioambientales e hidrológicos. *Boletín Geológico y Minero* 121 (1), 69-80.

- **Molina Navarro, E.**, Martínez Pérez, S. and Sastre Merlín, A. (2009). Diseño de un observatorio ambiental en torno al limnoembalse de cola de Pareja (Guadalajara). In: *Segundas Jornadas de Jóvenes Investigadores de la Universidad de Alcalá*, 55-66. Alcalá de Henares, Madrid. I.S.B.N.: 978-84-8138-849-7.

3. CONFERENCES

- **E. Molina Navarro**, S. Martínez Pérez, S. and Sastre Merlín, A. 2012. Variación del tiempo de retención en el Limnoembalse de Pareja y su relación con la calidad de agua. IV Jornadas de Jóvenes Investigadores de la Universidad de Alcalá. Alcalá de Henares (Spain). Oral presentation.

- **E. Molina-Navarro**, S. Martínez Pérez, D. Méndez Rubio, I. Mejías Rubio, A. Rojas Vázquez, L.F. Rebollo Ferreiro and M. Martín-Loeches Garrido. 2012. Estudio de la calidad del agua en el tramo medio de la cuenca del río Salado (Guadalajara) realizado como trabajo específico de campo en el Grado en Ciencias Ambientales por la Universidad de Alcalá. 11º Congreso Nacional de Medio Ambiente. Madrid (Spain). Poster.

- **E. Molina-Navarro**, S. Martínez-Pérez and A. Sastre-Merlín. 2012. Influencia de los descensos de nivel en la calidad biológica del agua en el Limnoembalse de Pareja. XVI Congreso de la Asociación Ibérica de Limnología. Guimarães (Portugal). Poster.

- **E. Molina-Navarro**, R. Bienes-Allas, S. Martínez-Pérez and A. Sastre-Merlín. 2012. In-situ soil loss monitoring in a small Mediterranean catchment to assess the siltation risk of a limno-reservoir. European Geosciences Union General Assembly. Viena (Austria). Poster.

- **E. Molina-Navarro**, S. Martínez-Pérez and A. Sastre-Merlín. 2012. Limnological characteristics and trophic state of a newly created site: the Pareja Limno-reservoir. European Geosciences Union General Assembly. Viena (Austria). Poster.

- A. Sastre-Merlín, S. Martínez-Pérez and **E. Molina-Navarro**. 2012. Groundwater in steppe environments: the wetlands of the “El Hito” Lagoon as a case of study (Cuenca; Spain). European Geosciences Union General Assembly. Viena (Austria). Poster.

- A. Sastre-Merlín, S. Martínez-Pérez, R. Bienes-Allas, **E. Molina-Navarro** and L. Martínez de Baroja. 2012. Influence of the substitution of a grass cover by a mulch on infiltration rate (irrigation with reclaimed water in city parks of Madrid). European Geosciences Union General Assembly. Viena (Austria). Poster.

- I.A. Díaz-Carrión, S. Martínez-Pérez, A. Sastre-Merlín, **E. Molina-Navarro** and R. Bienes-Allas. 2012. Limno-reservoirs as a new landscape, environmental and touristic resource: Pareja Limno-reservoir as a case of study (Guadalajara, Spain). European Geosciences Union General Assembly. Viena (Austria). Poster.

- **E. Molina-Navarro**, S. Martínez-Pérez, A. Sastre-Merlín, M. Verdugo-Althöfer and J. Padisák. 2011. Phytoplankton dynamics based on functional groups and ecological status assessment according to Water Framework Directive in a Mediterranean Limno-reservoir. 7th Symposium of the European Freshwater Sciences. Gerona (Spain). Poster (first award to the best student poster presentation)

- **E. Molina-Navarro**, S. Martínez-Pérez, A. Sastre-Merlín and R. Bienes-Allas. 2011. Studying the viability of a limno-reservoir using SWAT: The Ompólveda River Basin (Guadalajara, Spain) as a case of study. International SWAT Conference. Toledo (Spain). Oral presentation.

- **E. Molina Navarro**, S. Martínez Pérez and A. Sastre Merlín. 2010. Estudio del estado trófico en el Limnoembalse de Pareja (Guadalajara, España): comparación de los índices TSI y EQR. XV Congreso de la Asociación Ibérica de Limnología. Ponta Delgada (Azores Islands, Portugal). Oral presentation.

- S. Martínez Pérez, **E. Molina Navarro**, A. Sastre Merlín and M. Verdugo Althöfer. 2010. Estudio del fitoplancton, zooplancton y los macroinvertebrados en el Limnoembalse de Pareja (Guadalajara, España). XV Congreso de la Asociación Ibérica de Limnología. Ponta Delgada (Azores Islands, Portugal). Poster.

- **E. Molina-Navarro**, S. Martínez-Pérez, A. Sastre-Merlín, J. Soliveri-de Carranza, M.I. Fernández-Monistrol and J.L. Copa-Patiño. 2010. Microbiological Water Quality and its Relation with Nutrients at Pareja Limno-reservoir (Guadalajara, Spain). 1st IWA Spain National Young Water Professionals Conference. Barcelona (Spain). Poster.

- **E. Molina Navarro**, R. Bienes Allas, S. Martínez Pérez and A. Sastre Merlín. 2010. Los limnoembalses y su riesgo de aterramiento: el caso del Limnoembalse de Pareja (Guadalajara). X Jornadas Españolas de Presas. Valladolid (Spain). Poster.

- G. Ramos, S. Martínez, R. Vicente, **E. Molina** and C. Carrera. 2010. La Actualidad Informativa como Aprendizaje Activo en Asignaturas de Ciencias Ambientales. IV Encuentro de Innovación en Docencia Universitaria. Guadalajara (Spain). Oral presentation.

- **E. Molina Navarro,** S. Martínez Pérez and A. Sastre Merlín. 2008. Diseño de un observatorio ambiental en torno al Dique de Cola de Pareja (Guadalajara). II Jornadas de Jóvenes Investigadores de la Universidad de Alcalá. Alcalá de Henares (Spain). Oral presentation.

- **E. Molina Navarro,** S. Martínez Pérez and A. Sastre Merlín. 2008. Diseño y puesta a punto de un observatorio ambiental en torno al Dique de Cola de Pareja (comarca de Sacedón, Guadalajara). I Jornadas de Investigadores en Formación en Ciencias de la Tierra. Madrid (Spain). Poster.

- A.J. Hernández, S. Alexis, **E. Molina** and J. Pastor. 2005. Evaluación de la toxicidad debida a la acción conjunta de metales pesados del suelo en la Cuenca de Pedernales (República Dominicana-Haití) en *Phaseolus vulgaris*. 6º Congreso Ibérico y 3º Iberoamericano de Contaminación y Toxicología Ambiental (CICTA 2005). Cádiz (Spain). Poster.

4. STAYS IN FOREIGN CENTRES

- **Aarhus University**, Department of Biosciences. Silkeborg, Denmark, July-October 2012. Supervised by Prof. Dr. Erik Jeppesen.

- **University of Pannonia**, Department of Limnology. Veszprém, Hungary, October-December 2010. Supervised by Prof. Dr. Judit Padisák.

- **Vrije Universiteit Amsterdam**, Department of Molecular Cell Physiology. Amsterdam, The Netherlands, January-June 2008. Supervised by Prof. Dr. W.F.M. Rölling.

5. PARTICIPATION IN RESEARCH PROJECTS

- Seguimiento ambiental de los limnoembalses de cola de Castilla-La Mancha: “Pareja”, la “Presa Verde” y “El Vicario” (embalses de Entrepeñas, Torre de Abraham y El Vicario, respectivamente). PEII11-0276-4395. *Consejería de Educación, Ciencia y Cultura, Junta de Comunidades de Castilla – La Mancha.* September 2011 - December 2013.

- Diseño y puesta a punto de un observatorio ambiental en torno al dique de cola de Pareja (comarca de Sacedón, Guadalajara). PAI08-0226-1758. *Consejería de Educación y Ciencia, Junta de Comunidades de Castilla – La Mancha*. January 2008 - December 2010.

6. TEACHING

Faculty of Environmental Sciences, University of Alcalá (Alcalá de Henares, Madrid, Spain)

- *"Hydrology and Hydrogeology", 46 hours.*
- *"Natural Resources Management and Conservation", 39 hours.*
- *"Techniques Applied to Field Work*", 35 hours.

7. LANGUAGES

- **English.** Cambridge ESOL Level 2 / Council of Europe Level C1. *University of Cambridge.* December 2011.

8. GRANTS

- 2009-2013. FPI predoctoral fellowship. *University of Alcalá.*
- 2012. Master in Secondary School Teaching. Excellence Grant. *University of Alcalá*.
- 2007-2008. Erasmus Mobility Programme Grant. *Government of Spain.*
- 2002-2006. Academic Excellence Grant. *Government of Madrid.*

9. MISCELLANEOUS

- Reviewer for the journal *Water Research*, December 2011.
- "Number One" Award to the best student of the 2002-2007 Promotion of the Environmental Sciences Degree, handed by the *University of Alcalá Friends Association*.