



Evidence-based Risk Assessment of Ecological Damage due to Groundwater Abstraction; the Case of Doñana Natural Space, Spain

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Abstract

Many regions of the world are facing mounting water stress as competition increases for this vital resource that may become scarcer under future climates. More water is being allocated to our needs for food, public supply, hydro-electric power and industrial goods to support growing populations and mounting life-style expectations. To achieve this, less water is often being retained for water-dependent ecosystems. Environmental protection agencies and conservation organisations have highlighted the resulting threat to freshwater biodiversity and associated ecosystem services that support human livelihoods and well-being. Careful assessments are therefore required to advise on the optimum allocation of water and to determine the risk of developments that require redistribution of water resources.

Along the northern fringes of the Guadalquivir River delta and estuary in southern Spain about 40% of all jobs derive from agriculture. The production of olives, fruit trees, rice and berries is a major component of the local economy producing large exports, but it requires significant water from local rivers and the underlying aquifers. The economy is also reliant on tourism that brings many thousands of people to the area in the summer for which groundwater abstraction is augmented. The delta is the location of the Doñana wetland complex of lagoons, marshlands, fixed and mobile dunes that was designated as a Biosphere Reserve by UNESCO in 1980, as wetland of international importance (Ramsar Site) under the Convention on Wetlands in 1982 and as a World Heritage Site by UNESCO in 1994. Fears have been expressed that increasing human water use is putting the wetlands at risk of drying out, despite efforts by the river basin authority to limit abstraction to sustainable levels.

This paper reports on a methodology that analyses best available eco-hydrological scientific knowledge together with information on the likely success of abstraction control measures to determine the risk to the wetland ecosystem of current and future planned water allocation. The method was applied to Doñana by the joint UNESCO/IUCN/Ramsar Reactive Monitoring mission to in 2020. The results are also provided in the paper, which raised many important scientific and related political, legal and social issues concerning the impacts of water withdrawals on the ecology of the wetlands. The methodology has wide application to environmental water allocation assessments.

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Abstracto

Muchas regiones del mundo se enfrentan a un creciente estrés hídrico a medida que aumenta la competencia por este recurso vital que puede escasear en climas futuros. Se está destinando más agua a nuestras necesidades de alimentación, suministro público, energía hidroeléctrica y bienes industriales para apoyar a la creciente población y a las crecientes expectativas de estilo de vida. Para conseguirlo, a menudo se retiene menos agua para los ecosistemas que dependen del agua. Las agencias de protección del medio ambiente y las organizaciones conservacionistas han destacado la amenaza resultante para la biodiversidad del agua dulce y los servicios ecosistémicos asociados que sustentan los medios de vida y el bienestar de los seres humanos. Por lo tanto, es necesario realizar evaluaciones cuidadosas para asesorar sobre la asignación óptima del agua y determinar el riesgo de los desarrollos que requieren la redistribución de los recursos hídricos.

En la franja norte del delta y el estuario del río Guadalquivir, en el sur de España, cerca del cuarenta por ciento de los puestos de trabajo proceden de la agricultura. La producción de aceitunas, árboles frutales, arroz y bayas es un componente importante de la economía local que produce grandes exportaciones, pero requiere una cantidad importante de agua de los ríos locales y de los acuíferos subyacentes. La economía también depende del turismo, que atrae a muchos miles de personas a la zona en verano, para lo cual se aumenta la extracción de agua subterránea. En el delta se encuentra el complejo de humedales de Doñana, formado por lagunas, marismas y dunas fijas y móviles, que fue designado Reserva de la Biosfera por la UNESCO en 1980, humedal de importancia internacional (Sitio Ramsar) en virtud de la Convención sobre los Humedales en 1982 y Patrimonio de la Humanidad por la UNESCO en 1994. Se ha expresado el temor de que el creciente uso del agua por parte del ser humano esté poniendo en riesgo de desecación a los humedales, a pesar de los esfuerzos de la autoridad de la cuenca fluvial por limitar la extracción a niveles sostenibles.

Este documento informa sobre una metodología que analiza los mejores conocimientos científicos ecohidrológicos disponibles junto con información sobre el éxito probable de las medidas de control de las extracciones para determinar el riesgo para el ecosistema del humedal de la asignación de agua actual y futura prevista. El método fue aplicado a Doñana por la misión conjunta UNESCO/UICN/Ramsar de Seguimiento Reactivo a en 2020. Los resultados también se presentan en el documento, que plantea muchas cuestiones científicas importantes y cuestiones políticas, jurídicas y sociales relacionadas con los impactos de las extracciones de agua en la ecología de los humedales. La metodología tiene una amplia aplicación en las evaluaciones de la asignación de agua en el medio ambiente.

Keywords World Heritage · Ramsar · Water · Abstraction · Risk · Systematic review

Introduction

We are now living in an era of unprecedented human influence on Earth's environment, termed the *Anthropocene* (Crutzen 2002). Water demand is rapidly increasing for agriculture, public supply, hydropower generation and industry to support growing populations and mounting life-style expectations. Our exploitation of global water resources is such that human influence is a significant element of the global hydrological cycle (Savenije et al. 2014; Abbott et al. 2019). Yet nearly 80% of the world's population is exposed to high levels of threat to water security (Vörösmarty et al. 2010) and this may worsen under future climates (Singh et al. 2014), so the pressure on water resources will only increase. To address this, water is progressively being diverted from water-dependent ecosystems to direct human use.

Irrigation is the most important water use sector accounting for about 70% of the global freshwater withdrawals and 90% of consumptive water uses. Some 43% of the total consumptive irrigation water use ($1277 \text{ km}^3 \text{ yr}^{-1}$) comes from groundwater (Siebert et al. 2010). Environmental protection agencies and conservation organisations have highlighted the resulting threat to freshwater biodiversity and associated

ecosystem services that support human livelihoods and well-being. Major policy initiatives, such as the European Water Framework Directive (European Commission 2000) have been implemented, over 170 countries have signed the Convention on Wetlands (Ramsar Convention 2018) pledging to conserve and sustainably use their wetlands and development projects should employ environmental impact assessments (Glasson and Therival 2019) to prevent ecological damage. Yet, driven primarily by water management actions, freshwater biodiversity is continuing to decline rapidly at the global scale and the index of freshwater wildlife populations has fallen by 83% since 1970; more than double the rate of species decline found in marine and terrestrial ecosystems (WWF 2018). Many wetlands have been degraded by unsustainable groundwater withdrawals, such as the Azraq wetlands, Jordan (Fariz and Hatough-Bouran 1998) and Las Tablas de Damiel, Spain (Llamas 1989). Careful assessments are therefore increasingly required to advise on the allocation of water between competing uses and to determine the environmental risks of developments that require redistribution of water.

Many studies do not allow sufficient time or resources to collect new data or undertake new analysis. An alternative

approach to hydrological impact assessment was developed for the UK Environment Agency that used available information to ascertain whether wetlands were degraded (i.e. failing to meet the European Habitats Directive) due to water abstraction (Acreman and Miller 2007). In this paper, we develop the approach and apply it to the Doñana wetland complex in southern Spain, where the relationship between groundwater abstraction for agriculture and impacts on ecosystems has been debated for many decades (Suso and Llamas 1993).

Method

Step 1. Scope issues

The first step in any analysis is to understand the problem. This involves reading readily-available literature to assess general issues and points of view including scientific, legal, administrative and political matters. Not all knowledge and points of view are written down, so an important activity is to discuss the issues and any actions being taken with a wide range of stakeholders including regulatory authorities, NGOs, local government, national government, government agencies, local communities, businesses, relevant Conventions and international bodies and knowledgeable scientists. The output from this step is an outline of situation, issues and perspectives on how the system functions.

Step 2. Develop framework

The second step is to organise the scoping of information using a framework that helps formulate understanding of the system into a logical structure. There are many frameworks available, some are conceptual such as the Source, Pathway and Receptor framework (DETR et al. 2000) often used for pollution incidents to identify the source of the pollution, how it moves through the environment and how it impacts on specific ecosystems. Frameworks can also take the form of landscape diagrams showing locations of key features and links between them. It can be tested using knowledge collected about the site (step 4). The precise framework should be selected to best describe the system under study and the issues to be analysed.

Step 3. Undertake systematic evidence review

The third step is to assemble a database of evidence relating to the site and issues raised in the scoping. This requires definition of an evidence collection strategy and a search protocol, which includes possible sources of evidence, such as peer-reviewed science journal papers, reports

and information on web sites, and how the evidence will be found, such as web searches (e.g. Web of Science and Google scholar) and requests to stakeholders. Unpublished data can be requested but assessments frequently do not have sufficient time for their analysis. The protocol also needs to include a set of search terms or key words and inclusion/exclusion criteria (e.g. including only evidence based on data, excluding personal uncorroborated views). Evidence is then collated using the methods defined in the protocol and included in or excluded from database using the criteria. The final phase of the review is to produce a report of the evidence found, including level of certainty and gaps in knowledge. Some iteration may be required, such as making new requests for supporting evidence where no scientific information can be found relating to views held by stakeholders.

Step 4. Assess implications

The fourth step is to interpret the evidence and to assess if it is consistent with system understanding, the issues raised and actions being taken. One aspect of this is to use the evidence to test and quantify the conceptual framework, taking account of the level of certainty of available evidence and gaps in knowledge. It may also be necessary to consider future scenarios to project how the conceptual framework may alter under new circumstances. The results of the assessment should then be formulated into recommendations for adapting actions already being taken and further actions required, along with their associated risk, and a strategy to fill essential key gaps.

Step 5. Verify and report findings

The fifth step is to invite independent peer review of findings and recommendations. This may unearth evidence not found in the previous searches. The recommendations are then revised as necessary and the final report distributed widely to all stakeholders.

Application

Step 1. Scope issues

A Reactive Monitoring Mission to Doñana, organized jointly between the UNESCO World Heritage Centre, IUCN and the Secretariat of the Ramsar Convention on Wetlands, took place in February 2020, on the invitation of the Spanish government and as requested by the World Heritage Committee (UNESCO/IUCN/Ramsar 2021). To be included on the UNESCO World Heritage List, sites must

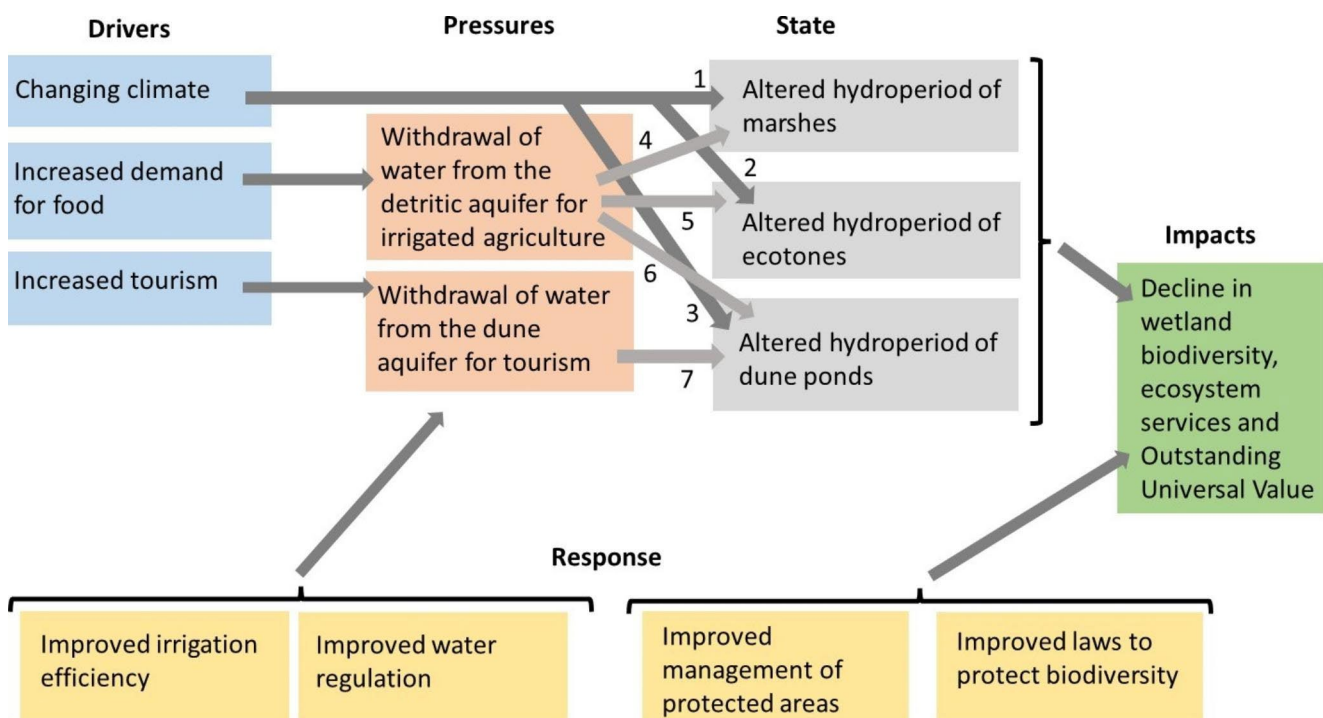


Fig. 1 Drivers-Pressures-State-Impact-Response framework to illustrate the issues in Doñana described by stakeholders. Numbered arrows denote links to be tested with evidence

be of Outstanding Universal Value (OUV) and meet at least one out of ten selection criteria (UNESCO 2019). The OUV is the benchmark against which States Parties and the World Heritage Committee monitor sites’ state of conservation. The 2020 mission was tasked to assess the potential impacts of current and future developments and water management on the OUV of the property.

The mission included field visits, synthesis of publicly-available information on the World Heritage Centre’s website (UNESCO. 2021) material provided by national, regional and local government authorities, non-governmental organisations, businesses, scientists and other stakeholders. No primary research was undertaken, no new metrics were calculated, no new analysis, modelling or statistical testing was carried-out. The information gathered indicated perspectives on how the Doñana ecosystem functions, issues and potential solutions.

The lagoons, marshlands, fixed and mobile dunes of the Doñana wetland complex in southern Spain are noted internationally for their exceptional beauty, unspoilt nature, particularly its vast flat expanses of wilderness, diverse habitats and species, particularly colonies of nesting birds (García Novo and Marín Cabrera 2006). The wetland area originally covered around 250,000 ha. The protected area (including National Park, Nature Park and their buffer zones) totalling 108,429 ha, referred to in this paper as ‘Doñana’, was designated as a Biosphere Reserve by UNESCO in 1980, as a wetland of international importance under the Ramsar

Convention in 1982 and as a World Heritage Site by UNESCO in 1994. Doñana is also a Natura 2000 site under the European Habitats Directive. As with other wetlands, it is the presence of water for some significant period of time which creates the soils, its micro-organisms and the plant and animal communities, such that the land functions in a different way from either aquatic or dry habitats (Mitsch and Gosselink 2015).

About 170,000 people live in the vicinity of Doñana, which has been occupied since pre-Roman times (Rodríguez-Ramírez et al. 2016). It provides income to local communities via (eco)tourism and as the setting for the El Rocío pilgrimage. About 40% of all jobs in the region derive from agriculture activities (production of olives, fruit trees, rice, and berries) and a high percentage of the red fruits consumed in Europe (strawberries, blueberries, raspberries, blackberries) are produced on the irrigated, sandy soils near Doñana (UNESCO/IUCN/Ramsar 2021). These agricultural activities and other human uses require a large volume of groundwater; about 100 hm³ per year or about 40% of recharge to aquifers underlying Doñana; this abstraction currently exceeds sustainable limits, putting strain on the aquifers, and in 2020 the Spanish Authorities declared some aquifers officially overexploited (Custodio et al. 2009; CHG 2019). This has given rise to fears that the Outstanding Universal Value (OUV) of Doñana, recognized by the World Heritage Convention, is in danger from lack of water due to this agricultural water use (WWF 2019, 2020).The quality

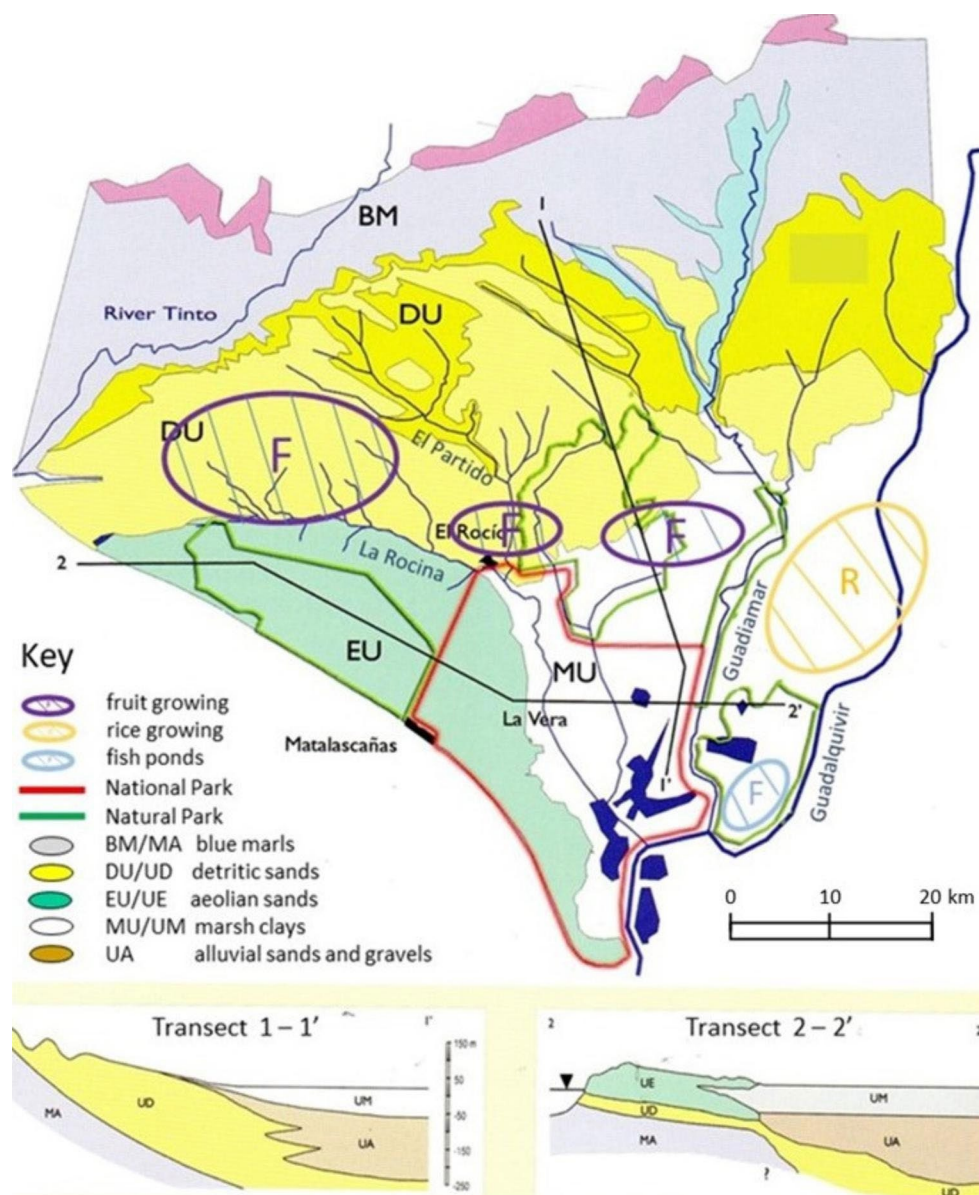


Fig. 2 Major rivers, surface geology, fruit and rice growing areas and fish ponds. Transects showing geological strata (after Manzano and Custodio 2006). The World Heritage property is depicted by the red line (Doñana National Park). The Ramsar Site includes in addition the areas delineated with green lines (Natural Park)

of aquifer water is generally good (Manzano et al. 2008, 2009), although in agricultural and urban zones, nitrates and sulphates are present in the upper layers of the detritic aquifer (Manzano et al. 2008, 2016; Olías et al. 2008; Higuera et al. 2011; Paredes et al. 2020) as are naturally occurring radio nuclides (Bolívar et al. 2008). There is also some concern that untreated domestic wastewater could be entering the system containing pharmaceuticals such as ibuprofen (Camacho-Muñoz et al. 2010).

The key question being asked by stakeholders was how to limit the water abstraction from the aquifers beneath

Doñana to prevent degradation of the wetland ecosystems, whilst maintaining livelihoods for local people.

Step 2. Develop framework

The Drivers-Pressures-State-Impact-Response (DPSIR) framework, developed for describing the interactions between society and the environment (European Environment Agency 1998) was applied to Doñana to illustrate the functioning of the system described by stakeholders (Fig. 1) and to provide our conceptual understanding. We believe this is the first use of the DPSIR framework for this

type of assessment. The key issue is the claim that habitats within Doñana are being degraded by increased water use, driven by increasing food demand and tourism (arrows 4, 5, 6 and 7 in Fig. 1), which is leading to loss of biodiversity and ecosystem services. In response, farmers are increasing irrigation efficiency and the authorities are improving water regulation and wetland protection.

The second framework employed was a map and cross-sections shown in Fig. 2 that describe the spatial relationship, in plan form and vertically, between various features of Doñana and the surrounding area. Three major wetland habitats dominate Doñana. The marshes on either side of the Guadamar river support over 300 bird species when inundated during the winter, including a large number of aquatic birds that usually reach 500,000 individuals including ducks and waders e.g. black-tailed godwits *Limosa limosa* (Kloskowski et al. 2009). Flooded rice-growing areas and aquaculture ponds provide additional food sources for birds outside of the protected areas (Toral et al. 2012; Walton et al. 2015). In summer, virtually the whole of this ecosystem dries out (Suso and Llamas 1993). Hydrological dynamics, including flood duration and connection between water bodies, largely determine the high biodiversity of the marshes, particularly invertebrate community structure (Alcorlo et al. 2014) with 224 phytoplanktonic taxa (Reyes et al. 2008) and biological processes, such as large seasonal and interannual production of the greenhouse gases CO₂, CH₄ and N₂O (Tortosa et al. 2011). The Guadamar River supports a variety of fish species, though the community was altered by the pollution incident in 1998 (de Miguel et al. 2014) from a spill of heavy metal-laden mining waste (Pain et al. 2003; Hernández et al. 1999; Giró et al. 2002). The second key wetland habitat is the ponds within the aeolian sand dunes. The dune pools are rich in wildlife (Blanco et al. 2013). More than 124 taxa of macroinvertebrates (Díaz-Paniagua et al. 2010) and at least 55 hydrophytes species have been recorded, plus several endemic zooplankton species. Eight of the 11 amphibian species of this area require temporary ponds for breeding. *Acidobacteria* play an important role in ecological functioning (Zimmermann et al. 2012). Some bird species such as Marbled Teal, *Marmaronetta angustirostris*, are known to breed in the pools, although they predominantly prefer the marshes (CMAOT 2018). The third much smaller, but ecologically-important habitat is the ecotone along the margin of the marshes, called La Vera that supports cork oak (*Quercus suber*) woodlands, which provide important bird nesting sites.

Three key geological units are noteworthy. First, the detritic aquifer exposed at the surface north of Doñana (DU, yellow on Fig. 2) but dips below other strata, including the marsh clays and aeolian sands. Second, the marsh clays (MU, white in Fig. 2) that support the Doñana marshes.

Third the aeolian sands (EU, green in Fig. 2) that house the dune ponds. A widely held belief amongst most stakeholders is that water within the detritic aquifer feeds the marshes, dunes and ecotones, thus high groundwater abstraction is degrading the Doñana's ecosystem.

Step 3. Undertake systematic evidence review

A detailed scientific approach was taken to collate best available knowledge of Doñana to test the conceptual understanding and make recommendations. Searches were undertaken of international databases including Web of Science and Google Scholar using a range of key words including Doñana, wetland, marshes, ponds, ecosystem, fish, invertebrates, amphibians, mammals, water, groundwater, river flow and hydrology. The searches returned 374 publications related to the interactions between water and the ecosystems of Doñana. From these, 64 publications were found to include knowledge relevant to the study and a further 9 publications, data and additional experience were provided by experts and interested organisations. Salient information was extracted from the 73 publications and draft text produced, which was independently peer-reviewed by three Spanish experts. Following submission of the report 14 further publications were provided by experts making 87 in total. There are undoubtedly additional publications and unpublished data existing which we have not yet found. However, the information within the 87 publications in the reference list revealed the following understanding of the relationships between water and ecosystems in Doñana.

The detritic aquifer

The detritic aquifer is composed of alluvial and aeolian deltaic deposits from the Pliocene-Quaternary age (Salvany and Custodio 1995), which are highly heterogeneous in character with strata of sand, gravel and marl (UPC 1999; Naranjo-Fernández et al. 2019). To the SE, this aquifer is confined under the impermeable sediments of the marshes (Custodio 1995; de Castro Ochoa and Muñoz-Reinoso 1997; Manzano et al. 2001). The aquifer is composed of four main groundwater bodies whose hydrodynamic behaviours are depended on soil uses and hydrogeological characteristics (Custodio et al. 2009; Naranjo-Fernández et al. 2020a, b). Water is abstracted from the aquifer primarily for agriculture, particularly growing fruits, such as strawberries (now covering 6000 ha), cotton and rice (Fig. 2). Rice is a particularly high consumer of water in summer, at the time of least availability. The Confederación Hidrográfica del Guadalquivir (CHG) has recorded water levels in 292 piezometers across the aquifer with some data starting in 1974. The area has been suffering a dry period since 2011,

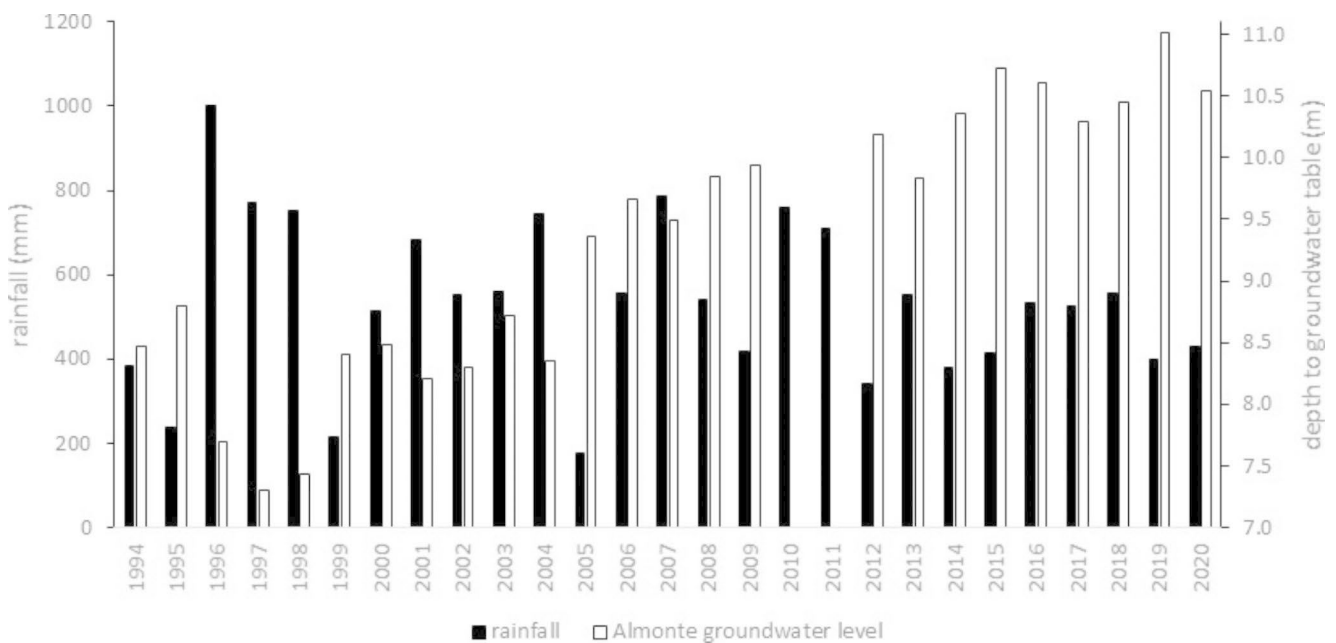


Fig. 3 Rainfall (mm) and depth to annual minimum groundwater table (m) averaged for 20 boreholes in the Almonte groundwater unit 1994 to 2020 with missing data for 2010 and 2011. (Data from Confederación Hidrográfica del Guadalquivir)

but even taking low rainfall into account some aquifer water levels are lower than during the great drought of the mid-1990s, though others are higher (UPC 1999; Lozano 2004; Custodio et al. 2009). In many piezometers, groundwater levels are consistent with rainfall, but in others levels were found to be low and declining, which is consistent with the configuration of the regional groundwater flow pattern (Trick and Custodio 2004; de Stefano et al. 2015).

In 2009, the European Commission started to investigate the declining water level situation and in 2014 it began procedures to sanction the Spanish Government due to the infringements in groundwater management. In 2020 the CHG declared that three of the four groundwater bodies – La Rocina, Almonte and Marismas - are at risk of failing to achieve Good Status under the European Water Framework Directive, which requires that groundwater levels only vary slightly from undisturbed conditions. Figure 3 shows declining groundwater levels in the Almonte aquifer unit along with rainfall data. The Spanish governments' plan to restore the aquifers to Good Status (Berbel et al. 2012) includes reducing abstraction and the substitution of groundwater for surface water from dams (e.g. Agrío in the Guadiamar) and other catchments (such as the Guadiana River) to provide irrigation water.

In 2015 the estate “Finca Los Mimbrales” was purchased for 50 million euros by the Spanish government (CHG), with 6.8 hm³ of water rights. The positive effect on the detritic aquifer has been immediate (CHG 2016). Some 5 hm³ per year have already been provided to offset groundwater abstraction and an additional 20 hm³ per year (originating

from outside of the Guadiana basin) was approved in 2018. A Special Management Plan of the Irrigation Zones specifies annual water extraction limits for certain water bodies based on the condition of the aquifer. In July 2020, about 500 wells representing 6.4 hm³ of abstracted water were regularized, making these henceforth subject to the Extraction Plan and remotely controlled water meters. Wells and farmland not included under the Plan are considered illegal, and no additional lands can be converted to farmland. Some sources have estimated that there are more than 1,000 unauthorized wells, 1,700 suspicious irrigation ponds, and 3,000 hectares of illegal farms. CHG had been monitoring illegal farming twice a year (spring and autumn) since 2016 using remote sensing (LANDSAT 8 and Sentinel 2 satellites). The average surface (2016–2020) of farming outside any management plan was 1013.6 ha, which amounts to 4.56 hm³ of water per year using the CHG allocations (CHG 2021), although illegal uses can be higher. This satellite-based tracking of wells and farms supports the enforced closure of illegal wells, which may involve a 7-year practical, administrative and legal process if the farmer chooses to litigate using all possible legal options and resources. Since 2015, almost 500 wells have been closed and the process is ongoing.

The marshes

The marshes cover just over 35,000 ha (Huertas et al. 2017). They are an estuarine and deltaic floodplain composed of Quaternary clay of very low permeability (Salvany

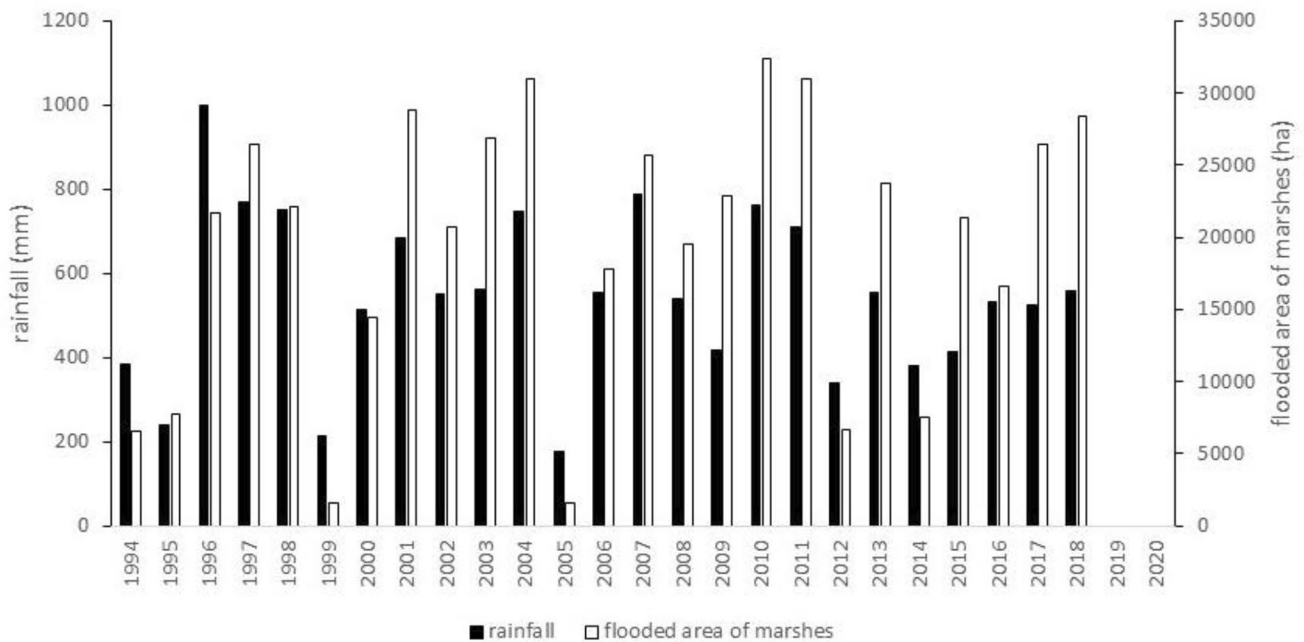


Fig. 4 Rainfall (mm) and annual maximum flooded surface area (ha) in the Doñana marshes from 1994 to 2018. Source: EBD-CSIC

et al. 2011) up to 100 m thick (Suso and Llamas 1993), which separates them hydrologically from underlying aquifers (Konikow and Rodriguez 1993). The marshes depend predominantly on rainfall and surface flows for their water supply (Custodio et al. 2009; Green et al. 2017) and can be classified as a flood-pulse system (Junk et al. 1989). Water levels and extent of inundation are determined by direct rainfall and, more importantly by high surface flows arriving rapidly after winter rainfall in the river basin upstream (Arambarri et al. 1996; Dolz et al. 2006; Olías et al. 2008). The principal water source is the Guadamar River, an affluent of the Guadalquivir River (Kohfahl et al. 2019a). In the 1960s, prior to the designation of the National Park, the connection between the upper and mid reaches of Guadamar basin and the marshes was severed by embankments and the floodplain marshes became non-functional. Water was diverted to an old oxbow lake (El “Brazo de La Torre”) and then directly to the Guadalquivir River, bypassing the marshes, which were left with an effective basin of only 490 km². Water levels were kept high by the embankments (“La Montaña del Río”). This lasted 50 years and was partially reversed in 2015, when the CHG, as part of Doñana 2005 programme, opened several connections between the channel and the marshes in OUV of Doñana.

Figure 4 shows that rainfall and the annual maximum flooded area have fluctuated since 1984, but there is no visually evident long-term decline in flooded area. Some years of low rainfall coincided with limited flooding, such as 2005, although in both 2014 and 2020 most of marshes were inundated even though rainfall was only around 400 mm.

The Agrio dam (capacity 21 hm³) constructed on the Guadamar in 1977 has had a minor effect on inundation. In its middle reaches, the Guadamar runs over the detritic aquifer and there is a groundwater inflow to the river of 30 l s⁻¹ (IGME undated). This flow is insignificant (< 1%) in winter and spring when Guadamar flows are on average 3500–6700 l s⁻¹, which causes flooding of the marshes. The maximum contribution the detritic groundwater can make to Guadamar flows is about 25% in late summer, assuming the groundwater flow is at 30 l s⁻¹ and river flow is at its lowest (on average 126 l s⁻¹) in September, at which time the marshes are normally already dry.

Some small rivers that flow into the marshes, such as the La Rocina and El Partido, are mainly fed by rainfall but are also partially fed by the detritic aquifer (Trick and Custodio 2004; García-Novo et al. 2007). Recorded flows in the La Rocina River declined during 1970–1974 probably due to local groundwater abstraction (Yagüe and Llamas 1984) and forest encroachment. The latter impact may have been more important as there was some recovery of the aquifer in 1996–7 following removal of eucalyptus trees in the main recharge area (Manzano 2002). Generally, La Rocina flows were lower post 2004 than pre 2004 in times of similar low rainfall conditions, possibly due to lower groundwater levels in the detritic aquifer. However, adjacent areas of floodplain marshes have not been reduced (Díaz-Delgado et al. 2016) and no reports of negative ecological impacts were found.

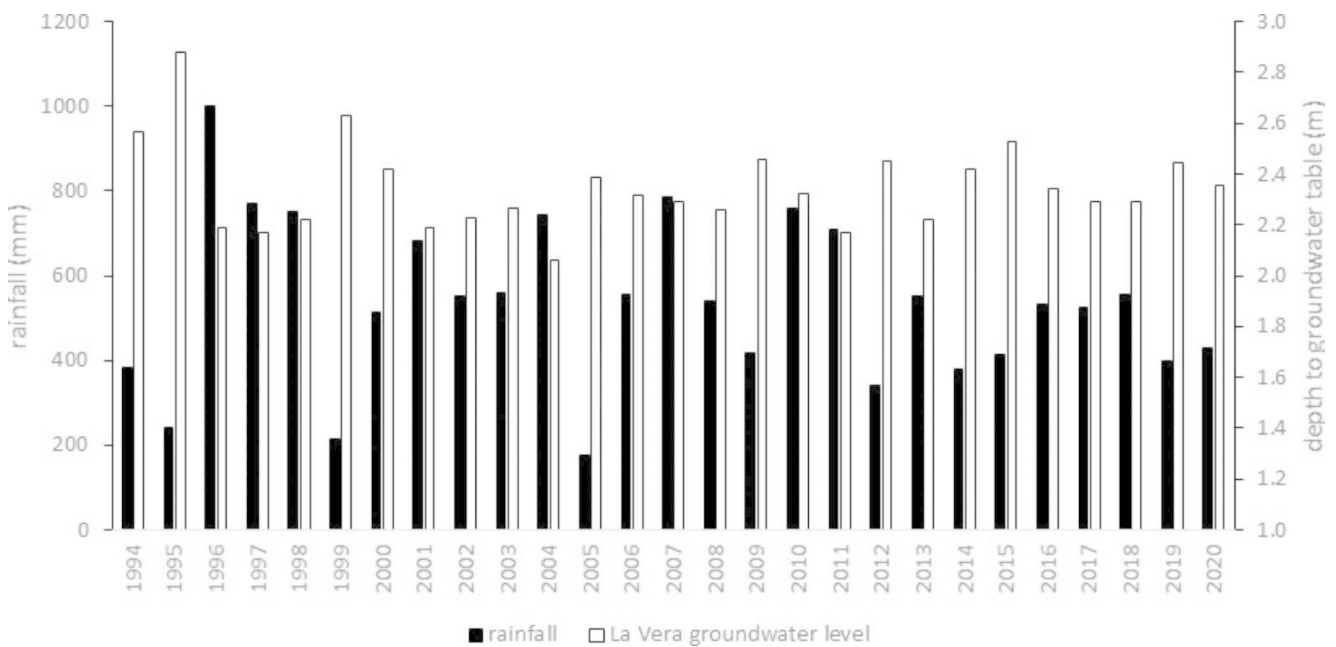


Fig. 5 Rainfall (mm) and depth to annual minimum groundwater table (m) averaged for 48 boreholes at La Vera 1994 to 2020. (Data from Confederación Hidrográfica del Guadalquivir)

The dune ponds

The dunes support numerous temporary ponds whose natural inundation and drying cycles are crucial to support their biodiversity (Williams et al. 2001; Florencio et al. 2014, 2020), such as zooplankton (Serrano and Fahd 2005) and diatoms (Blanco et al. 2013). The dunes also support permanent ponds, such as Santa Olalla. The ponds appeared around the year 1550 when conditions became wetter (Manzano et al. 2019). Around 20% of the total water inflows to the dune ponds comes from rainfall and 80% (Fernández-Ayuso et al. 2018) from the Quaternary aeolian sand aquifer in the dunes (Sacks et al. 1992). Some ponds are discharge sites for groundwater from the aeolian aquifer, e.g. Santa Olalla and Sopotón, whilst other ponds recharge the aquifer, e.g. Zahillo (Ayuso 2019). The aeolian aquifer sits on top of the detritic aquifer (Salvany et al. 2010); hydro-geological modelling has demonstrated interaction between the two aquifers at Los Sotos (Juárez et al. 2012) and there is some minor interaction near Charco del Toro, but the full extent of aquifer connectivity is uncertain. The aeolian aquifer is recharged predominantly by local winter rainfall (Molano-Leno et al. 2018) with 64% finding its way into the aquifer (Kohfahl et al. 2019b). Annual rainfall has decreased generally in recent years.

The response of aeolian aquifer groundwater levels around La Mogeja, Charco del Toro, Santa Olalla and Dulce to abstraction from shallow boreholes (14–17 m deep) at Matalascañas, Mimbres state, Palacio de Doñana and El Acebuche was assessed by groundwater flow modelling

(Lozano 2004). Maximum water level lowering was 0.75 m for every hm^3 of increased abstraction.

Abstraction of water to supply the recently developed tourist town of Matalascañas (especially in the summer when 90,000 tourists arrive) comes from a set of seven wells up to 150 m deep, taking water from both the aeolian dune aquifer and the much deeper underlying detritic aquifer (Aguilera et al. 2019). Some near-by dune ponds, such as Charco del Toro, appear to have been affected by the pumping (Lozano 2004; Manzano et al. 2005), with changes in their hydroperiods (Bustamante et al. 2016) i.e. they dry-out faster and for longer and more often than in the past and have an increased dependency on direct rainfall, putting wetland habitats at risk (Díaz-Paniagua and Aragonés 2015). Lowering of the aquifer has changed the acidity of some ponds (because the rain is more acidic than the groundwater), which can affect amphibian breeding (Serrano et al. 2016) changing the relative abundance of major solutes in shallow groundwater around some wetlands (e.g. Charco del Toro; Lozano et al. 2002), which could impact vegetation and microorganism), and has negatively impacted woody vegetation (Antunes et al. 2018) although pine tree mortality has also been linked to the droughts of 1979–83 (Muñoz-Reinoso 2001; Muñoz-Reinoso and Castro 2005). This drying trend does not coincide with a decreasing trend in rainfall (Dimitriou et al. 2017) and the greatest changes in hydroperiod have been reported in the ponds located near, < 1 km, to the pumping area and least in the ponds at a further distance, around 5.6 km (Serrano and Serrano 1996; Lozano 2004; Dimitriou et al. 2017). Some dune ponds appear now to be recharging

the aquifer by downward percolation of water rather than being supported by it through upward aquifer discharge (Manzano et al. 2013; Cifuentes Sánchez, *pers. comm*). In other ponds, such as Santa Olalla, the primary surface water body that alone covers 65% of the total flooded area, no resulting damage has been identified (Fernández-Ayuso et al. 2019) and their past hydroperiods have persisted.

To address environmental concerns regarding water abstraction, plans have been put forward to close wells nearer the impacted ponds and to transfer water from Huelva for public supply. This should remedy the impact of pumping on dune ponds currently affected, but levels may take several decades to recover. Temperature increases and the expansion in the dunes of non-native pine trees (that use more water than short vegetation) over recent decades may have contributed to changes in some ponds. Current action of replacing them with native vegetation should help raise water-table levels (Trick and Custodio 2004).

Ecotones

Some groundwater from the detritic and the aeolian dune aquifer discharges as springs along the contact between the clays of the marshes and the sand dunes producing important ecotones, particularly groundwater-fed creeks and phreatophyte forests. These temporarily saturated ecotones support hygrophilic meadows, cork oaks and ferns and provide nesting habitat for many birds. Near to the north ecotone, fed by the detritic aquifer, water table levels have declined by 10 m since the 1970s, but no published scientific reports of associated negative ecological impacts were found. In contrast, water table levels at the west, called La Vera and which is fed by water from the aeolian aquifer, have fluctuated slightly with rainfall but remained fairly constant, on average, over the past 27 years (Fig. 5). Although individual boreholes have shown some declined since the late 1980s (UPC 1999; Lozano 2004; Juárez et al. 2012) and formerly permanent creeks Arroyo Mimbrales, Soto Grande and Soto Chico have become seasonal ravines. These ecotones may be at risk from abstraction of the detritic aquifer but impacts seem to vary locally.

Step 4. Assess implications

The evidence assembled for Doñana indicates that water table levels in the detritic aquifer has been severely lowered by abstraction for irrigated agriculture. The actions proposed by CHG to recover Good Status are appropriate by stopping all illegal abstractions will take several years and aquifer recovery may take longer. Inundation of the marshes results from winter rainfall and resultant river flow derived from surface runoff, so this is not affected by aquifer abstraction.

Summer wetness in the marshes may be reduced in areas fed by groundwater-fed streams, such as La Rocina River, whose flow has decline since 2000. The response of water levels in the ecotones to detritic aquifer levels varies considerably; in some cases, water levels have remain unchanged for 27 years whilst in other water levels have decline by 10 m. However, even in the latter case, no evidence of negative ecological impacts has been reported. The hydroperiod of some ponds within the aeolian dunes has altered these ecosystems. This has resulted from abstraction from wells in the dune aquifer near to Matalascañas, not from abstraction from the detritic aquifer. Plans to move the offending wells in short term are appropriate to resolve this problem. In a longer term, the total replacement of pumping by surface water is proposed. This would mean the total closure of the wells. Overall, there is a lack of evidence that the Doñana wetlands have been negatively impacted by abstraction from the detritic aquifer. Actions in place are likely to result remove any current risk. However, improved understanding including conceptual and computer models need to be formulated to assess future risks.

The European Environment Agency (2016) stated that countries of the Mediterranean have experienced decreased precipitation and increased temperature over past decades and this trend is projected to worsen. Furthermore, climate change projections suggest significant reductions in recharge to the aquifer – 25–55% less for La Rocina and 43–68% less for Marismas aquifer bodies (Guardiola-Albert and Jackson 2011) - which could lead to reduced groundwater levels in the future and cause additional negative impacts, such as changes to endangered Mediterranean waterbird populations (Ramírez et al. 2018) and winter migrating birds (Ramo et al. 2015) and small mammals (Santoro et al. 2017). In contrast, winter precipitation is likely to increase, which may expand the area of marshes inundated. Further studies of rainfall, recharge and links between the detritic aquifer, stream flow, ecotones and marshes are essential to developing management strategies that mitigate climate change effects on the property and guarantee optimal conditions for groundwater resources in the future (Naranjo-Fernández et al. 2020b).

Overall, the evidence suggests that the conceptual framework (Fig. 1) can be revised to show that abstraction for agriculture from the detritic aquifer is unlikely to cause habitat loss or degradation and species loss within the Doñana floodplain marshes or dune ponds, but it may affect some of the ecotones and small streams, such as La Rocina. Thus arrows 4 and 6 in Fig. 1 can be deleted, whereas red arrow 5 could be dotted to denote spatial variation in potential impacts. Arrow 7 remains to show that abstraction from the dune aquifer can alter the hydroperiod of the dune ponds. The evidence further confirms the framework in terms of

potential impacts in the future under climate change (arrows 1, 2 and 3). The framework could be extended to incorporate water quality such as potential impact of agrochemicals and pharmaceuticals.

Step 5. Verify and report findings

The assessment reported in Step 4 was independently peer reviewed by experts from Spain and, following minor amendments, included within a report to the World Heritage Committee (UNESCO/ IUCN/Ramsar 2021), which was distributed to stakeholders and is freely available to download.

Discussion and conclusions

Although many studies of potential threats to wetlands of water withdrawal have used some of the steps in this methodology, we believe this is the first time a robust synthesis has been defined using the DPSIR framework and systematic review methodology. It provides the basis for a widely applicable tool.

The conceptual framework defines a hypothesis for ecosystem functioning that can be tested with available evidence. Our searches found no evidence of a significant impact of detritic aquifer abstraction for agriculture on marsh inundation nor on the hydroperiod of the dune ponds. Evidence was found of groundwater declines in some ecotones, in response to detritic aquifer abstraction, though not in others, but no evidence was found of ecological degradation. Similarly, abstraction has reduced flow in small streams, such as La Rocina, whilst some ecological degradation might be anticipated in response, no evidence of this was found. The lack of causal connection becomes the best hypothesis as it is founded on current knowledge and understanding. It cannot be proven but could be disproven if ecological impacts of detritic aquifer abstraction are recorded. Recovery of water levels in the detritic aquifer should remove any risks to the ecological condition of the OUV of Doñana. In contrast evidence is strong that the aeolian dune aquifer abstraction significantly influences the hydroperiod of the dune ponds near to abstracted wells. Stopping water withdrawals from the dune aquifer should help the dune ponds recover. Climate change is likely to become the greatest risk to alteration of the ecological condition of all parts of the wetlands.

Adopting a precautionary management approach entails reducing abstraction from the detritic aquifer to sustainable levels to ensure that no Doñana wetlands are at risk of degradation. This would have significant implications for irrigated agriculture. Aquifer recovery is being implemented in

the detritic and aeolian aquifers and is particularly urgent in the latter to restore the dune ponds. The driver for this is the EU Water Framework Directive, which requires that water table levels under abstraction vary only slightly from undisturbed conditions. This approach should maintain the functioning of wetland ecosystems dependent on groundwater from those aquifers.

The methodology highlighted gaps in knowledge and the need for management tools, including an eco-hydrological computer-based model of Doñana that incorporates the different groundwater aquifers, surface water, evaporation, land cover type, irrigation water use and species water requirements. As an example, Schweiger et al. (2016) used structural equation modelling to assess wetland ecological response to altered hydrological conditions in the Rocky Mountain National Park, USA. Models can underpin decision-support systems, such as those used in the Colorado River Basin, USA, to assess water availability for consumptive use and environmental needs under different scenarios (CWCB 2009). Such a model is highly desirable for World Heritage sites that are inscribed on the UNESCO World Heritage List for their OUV and for which the identification of key monitoring indicators is thus relatively straightforward. An eco-hydrological model for Doñana is urgently required to calculate the water requirements of the World Heritage site to maintain its OUV, and the potential deterioration of the ecosystem that would result from not meeting these needs. This necessitates quantification of relationships between the ecological features that define the OUV and hydrological components (e.g. rainfall, evaporation, river flows and groundwater levels). Construction of an eco-hydrological model of the World Heritage property based on the results of the research, and consideration of the possible need of a buffer zone, including the surrounding catchment basin (covering the Ramsar Site and EU Natura 2000 area), would allow the impacts of various scenarios to be defined, including abstraction of groundwater, removal of trees, building of dams and climate change. Such an eco-hydrological model would help local managers project potential ecological degradation of Doñana's ecosystem from a changing climate. Disagreements between experts might be overcome by holding a workshop to present data and results, particularly related to evidence over connection between the detritic aquifer and the marshes, dunes and ecotones.

The complexity of the natural environment around Doñana shows that eco-hydrological assessments require very detailed study, using difficult to obtain data. Assessing the impact of groundwater abstraction on wetlands has, in particular, proved notoriously difficult because of complex relationships between aquifers and overlying ecosystems. For example, three wetlands in Eastern England

(Langmere, Ringmere and Fenmere) are visually very similar and geographically close to each other, but they work hydrologically in very different ways (Acreman and José 2000). Langmere is in direct hydrological contact with the underlying Chalk aquifer and its water regime is controlled by groundwater fluctuations. Ringmere is partially separated from the same aquifer by a lining of organic matter (an aquitard), but is still largely controlled by groundwater. In contrast, Fenmere is isolated from the Chalk aquifer by a low-permeability clay layer (an aquiclude) and its water levels are controlled exclusively by rainfall and evaporation. To address this issue, Howard and Merrifield (2010) developed an index of groundwater dependency by analysing geospatial data for three ecosystem types in California that depend on groundwater.

It took comprehensive datasets and detailed computer modelling of Las Tablas de Daimiel wetlands, in central Spain, to show that they are fed both by the upper Guadiana River and groundwater discharging from the La Mancha aquifer when groundwater levels are high and that the direction of groundwater flow is reversed (with water moving downwards from the wetlands to recharge the aquifer) when groundwater levels are low (Bromley et al. 2001).

When such complexity is not accounted for, assessments have often simply categorised wetlands as ‘at risk’ if they overly an aquifer that has a water abstraction regardless of whether evidence exists of hydrological links between the aquifer and wetland. Precautionary approaches are widely applied in groundwater management (e.g. Sousa et al. 2013). The precautionary approach was taken by a group of non-governmental organisations in England to highlight potential threats to wetlands of groundwater withdrawals (Biodiversity Challenge Group 1996; Acreman et al. 2000). It is important for individuals, communities and organisations to raise legitimate concerns over potential negative impacts on the natural environment. However, this must be balanced against raising unnecessary anxiety that can divert attention to unsubstantiated claims of potential risk until they are proven, as opposed to focusing resources, studies and actions where they are most needed. It can also, unnecessarily label water supply companies and farmers, who follow the law, as environmental villains. In the USA there is a requirement to define a minimal threshold of plausibility of risk that acts as a “triggering” condition before action is taken (Pinto-Bazurco 2020), but no similar limit is specified in Europe. It is noteworthy that the precautionary approach *per se* is not a formally adopted principle by the UNESCO World Heritage Committee, the Ramsar Convention on Wetlands or IUCN. Ramsar does recommend that “development of human settlements and other developments in such areas [i.e. wetlands] need to be approached in a precautionary manner” (CoP Resolution X.23, Wetlands and human health

and well-being). The European Habitats Directive Article 6 makes reference to ‘precaution’ in the guidance on Natura 2000 sites (European Commission 2001). Furthermore, the Convention on Biological Diversity (in its preamble) recommends “Where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize such a threat”.

We maintain that application of the systematic approach presented in this paper provides a robust and fair means to assess the scientific evidence of potential impacts of water withdrawals on wetlands and moreover to support decisions on sustainable water allocation between direct use and nature conservation. Uncertainty will always remain, as Voltaire asserted “Uncertainty is an uncomfortable position, but certainty is an absurd one”.

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Author contributions Michael Acreman developed the method, led the study and reviewed the scientific publication. Material preparation, data collection and analysis were performed by Michael Acreman, Robbert Casier and Tobias Salathe. The first draft of the manuscript was written by Michael Acreman. Robbert Casier and Tobias Salathe commented on each version of the manuscript. Michael Acreman, Robbert Casier and Tobias Salathe read and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Statements and Declarations

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