Groundwater abstraction has caused extensive ecological damage to the Doñana World Heritage Site, Spain

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Abstract

Acreman et al. (2022) reviewed evidence for ecological damage to the Doñana wetlands (UNESCO World Heritage Site [WHS] and Ramsar site), Spain, associated with intensification of groundwater use, particularly for agriculture. Acreman et al. presented a multistep methodology for evidence-based risk assessment that involves identification of conservation issues, and a systematic review of scientific evidence for ecological damage and its causes. However, they involved few local scientists, used a questionable methodology in stakeholder selection and involvement, used a flawed conceptual framework, and an incomplete literature review. We propose improvements to their methodology. They overlooked or misinterpreted key evidence, and underestimated the impacts that abstraction for irrigation for red fruits (mainly strawberries), rice and other crops has had on Doñana and its biodiversity. They reported groundwater level depletion of up to 10 m in the deep aquifer, but wrongly concluded that there is no evidence for impacts on the natural marsh ecosystem, the dune ponds or the ecotone. Groundwater drawdowns are actually up to 20 m, and have inverted the formerly ascending vertical hydraulic gradient in discharge areas. Phreatic levels have been lowered from 0.5 to 2 m in some areas. Groundwater abstraction has caused multiple ecological impacts to temporary ponds and marshes in the WHS, as well as to terrestrial vegetation, and should be urgently reduced. Furthermore, Acreman et al. focused on groundwater quantity while overlooking the importance of severe impacts on quality of both surface and groundwater, intimately connected to the use of agrochemicals for irrigated crops.

Keywords Groundwater overexploitation, Impact evaluation, Mediterranean wetland, Ramsar Site, Water pollution, World Heritage

Introduction

The Doñana wetlands in the mouth of the Guadalquivir River in Andalusia, south-west Spain, are an iconic and highly protected ecosystem, but one which is highly threatened by a range of impacts (Scheffer et al. 2015, Fernández-Delgado 2017, Camacho et al. 2022). Like many protected areas in other countries (Huggins et al. 2023), Doñana's watershed and groundwatershed are underprotected. The most important remaining natural wetlands are protected within a National Park, Natura 2000 site, a UNESCO World Heritage Site, Biosphere Reserve and a Ramsar site, and are a small remnant of the much larger area of natural wetlands present in the delta of the Guadalquivir River before transformations began (Green et al. 2018). Their hydrology is complex, and surface hydrology has been strongly modified by human intervention for over the past century (Méndez et al. 2012). The remaining natural wetlands, as well as areas of ricefields, fish ponds and solar salt works that have replaced former natural wetlands, provide important ecosystem services (Zorrilla-Miras et al. 2014). The neighbouring Guadalquivir estuary, currently largely disconnected from Doñana's wetlands, provide further ecosystem services, such as a nursery role for marine species that inhabit the Gulf of Cádiz (Llope 2017).

Acreman et al. (2022) (AEA from hereon) reviewed evidence for ecological damage to the Doñana wetlands, while promoting a methodology that involves five key steps. These include scoping of conservation issues with stakeholders (Step 1), development of a sound conceptual framework (in their case, a Drivers-Pressures-State-Impact-Response [DPSIR] framework; Step 2), systematic review of scientific evidence for ecological damage and its causes (Step 3), assessment of implications (Step 4) and verification of findings (Step 5). Their methodology is not specific to hydrology and water quantity issues, but that was the focus of their review. In particular, they focused on the impact of groundwater withdrawal (the key issue raised by stakeholders), which has increased massively since the 1970s due to agricultural and urban expansion, notably for the production of red fruits (strawberries, raspberries, blueberries, blackberries) and for beach tourism (with around 100,000 people using groundwater in summer). Whilst previous research has highlighted the impacts of this withdrawal (e.g. Díaz-Paniagua and Aragonés 2015; Green et al. 2017; Rodríguez-Rodríguez et al. 2021; Camacho et al. 2022), AEA concluded there is little or no evidence of such impacts. We strongly disagree with their conclusions.

Doñana is a large, complex ecosystem of great interest to many scientists and other stakeholders based in Spain and beyond. An accurate and comprehensive study of ecological damage is only possible with extensive involvement of scientists from multiple disciplines with local knowledge, especially those involved in long-term research programmes, as well as a sound and transparent methodology for the involvement of all key stakeholders. We find AEA's review to be deficient and inaccurate in many respects, and many of their conclusions to be unsubstantiated. AEA claim there is a lack of evidence that the Doñana wetlands have been negatively impacted by abstraction from what they mistakenly call "the detritic aquifer" (i.e. the deep aquifer, see below). They conclude that abstraction is not a major threat to Doñana, and that previous claims to the contrary cause "unnecessary anxiety" and diversion of limited resources. We dispute this and consider that much existing evidence was overlooked or misinterpreted by the authors, and summarize this evidence below. Furthermore, we consider that current flaws in the management of Doñana's water resources leads to wasteful resource use with elevated costs of opportunity (as argued by Santamaría and Amézaga 1999). We are deeply concerned that the publication by AEA and its flawed conclusions may misguide decision makers and could provide support to those lobbying for maintaining or even increasing current levels of groundwater withdrawals, thus posing an indirect threat to Doñana.

The description of the Doñana area made by AEA has important inaccuracies (see Green et al. 2018 for an alternative) and is seriously outdated in several aspects (see details in Supplementary Information). This is likely connected with the limited involvement of scientists with local knowledge. AEA recognise that assessing the impact of groundwater abstraction is difficult, typically fraught with uncertainties, and requires complex, detailed research. However, they seem reluctant to embrace the precautionary principle, which would advocate that ecological impact should be assumed in the case of major human interventions that may result in irreversible changes such as those often reported in other Mediterranean wetlands (Green et al. 2017). Instead, AEA question the basis for ongoing conservation concern about the existing levels of abstraction, based on their incomplete survey of the scientific literature, repeating the position of Acreman and Salathé (2022) in reply to Camacho et al. (2022).

AEA overlooked evidence of important impacts of abstraction on surface water hydrology, aquatic and terrestrial biodiversity, and water quality (see below). AEA are also wrong about climate change effects and their implications for exacerbating the impacts of groundwater abstraction, stating that "winter precipitation is likely to increase, which may expand the area of marshes inundated". No reference is given for such a claim, and climate models for southern Spain predict a reduction in annual precipitation of 5-30% over the next 100 years (https://www.aemet.es/es/serviciosclimaticos/cambio_climat/result_graficos?w=0&opc1=gua

r&opc2=P&opc3=Anual&opc4=0&opc6=0), together with a strong increase in temperature (Cramer et al. 2018; Rennie et al. 2021). AEA also paid too little attention to the critical importance of the climate crisis for Mediterranean wetlands such as Doñana (Albert et al. 2021; Taylor et al. 2021), and overlooked the way that groundwater withdrawals need further reductions in the face of climate change to conserve the biodiversity in Doñana (Green et al. 2017).

Rebuttal to "Step 1. Scope Issues & Step 2. Develop framework"

A major shortcoming of AEA is the lack of rigour and transparency in reporting the approach, criteria and procedures used for stakeholder participation during the scoping, framework development, and systematic review phases – for which they explicitly declare that such participation was "an important activity". In particular, no details are provided about the methodological approach followed during the scoping procedure; the specific criteria used for stakeholder selection; whether these stakeholders informed step 2 (model selection and architecture), and whether they were identical to those consulted during step 3 (systematic review) or a subset thereof. More importantly, no details on the number, functions and identity of stakeholders are provided. These aspects are of key importance to judge the reliability and transparency of the stakeholder participation process, particularly since the authors indicate that specific stakeholders (most notably, the Spanish government and the National Park authorities) were involved in the assessment and selection of other stakeholders. Even if the authors and the aforementioned stakeholders tried to be perfectly objective in their participation process, the lack of specific criteria and procedures may result in the introduction of undesirable biases, and the lack of details on the function and identity of stakeholders (and reviewers) precludes an informed judgement on such biases. The selection and construction of the theoretical framework by AEA is also poorly justified and biased (see Supplementary Information).

Impacts of groundwater withdrawals on water quantity

Rebuttal to "Steps 3 & 4 Systematic evidence review and implications" – the 'detritic' aquifer and ecotones

AEA place emphasis on their literature search to review evidence systematically, yet searches in Web of Science or Google Scholar are not good at detecting publications such as those before

2000, or grey literature in Spanish, which are vital for establishing a baseline to measure impacts. Significant abstraction for agriculture began in the 1973-74 (Manzano 2001), so its impacts have been reported in grey literature for decades (Bea et al. 2021), and the Spanish media has reflected concerns among scientists and managers about impacts on water quantity and quality since the late 1970s (https://elpais.com/diario/1979/11/17/espana/311641209_850215.html).

AEA state that the Doñana aquifer is composed of four main groundwater bodies. In fact, in the recent hydrological plan (2016-2021), the Almonte-Marismas aquifer system was divided into six groundwater bodies (Fig. 1). The Confederación Hidrográfica del Guadalquivir (Guadalquivir River Basin Authority, CHG) is responsible for five of them (Almonte, Manto Eólico Litoral de Doñana, Marismas de Doñana, Marismas, Rocina), whereas Condado lies within the Hydrographic Demarcation (River Basin District) of Tinto, Odiel and Piedras rivers (TOP). AEA wrongly suggest there is an aeolian dune aquifer and a much deeper underlying detritic aquifer. In fact, both aquifers are detritic and highly interdependent, with a continuity of hydrogeological units between groundwater bodies (Custodio et al. 2009; CHG 2022a, 2022b, 2022c). As explained below and in Supplementary Information, their interpretations of the relationships between piezometer levels, rainfall, and well abstraction rates are incorrect. They severely understate the evidence for widespread reductions in groundwater levels due to abstraction, the extent of historical drawdowns (e.g. drawdowns up to >20 m shown in Fig.s S2 and S3), reductions of groundwater flow into ecotones, and the ecological damage that is a consequence.

AAE mention that groundwater extractions are about 100 hm^3/year, which exceeds sustainable limits. However, they do not mention the high uncertainty in this value, due to the failure to directly measure rates of pumping from the aquifer. This issue led the Court of Justice of the European Union to condemn Spain in 2021 for the absence of monitoring, and failure to act to avoid damage to the habitats in Doñana due to lowering of the water table. AEA stated that in many piezometers, groundwater levels are consistent with rainfall, but this is not consistent with the data. Not all piezometer levels are affected by decreases in rainfall in the same way. In areas farthest away from agricultural wells, such as the piezometers near the west ecotone or close to the dune ponds, levels during the most recent drought of 2021-2022 are higher than during the last drought of 1995. Fig. 2 provides examples from CHG data, and all piezometers show that, after the very wet year of 1996, there is a clear decreasing trend since 1997, with cumulative drawdowns ranging from 1 to 3 m. The magnitude of these drawdowns cannot be considered unimportant, and inevitably causes ecological damage. A 20 cm drop in the maximum annual level of the water table is sufficient to eliminate the appearance of surface water, and to keep capillary water out of the range for plant roots. Furthermore, a decrease in deeper aquifer levels has been detected by multilevel piezometers, indicating a switch from upward to downward gradients (see Palacio de Doñana and Marismillas in Fig. 2). This means that shallow aquifers are now losing water by feeding deeper aquifers. This in turn indicates a decrease in the deep aquifer water reserves due to abstraction, leading to feeding of these reserves from the upper aquifer levels.

AEA recognize that water tables in the north ecotone have declined by 10 m since the 1970s due to groundwater withdrawal, yet suggest no negative ecological impacts have been reported. Whether already explicitly documented in publications or not, impacts of the dramatic decline in groundwater levels (see also further details in Supplementary Information) are inevitable in the Mediterranean region and elsewhere, e.g. for stygofauna and vegetation (Camacho-Pérez and Puch-Ramírez 2006; Gibert et al. 2009). AEA mention the value of cork oaks *Quercus suber* in the ecotone, but do not report any evidence of damage. Cork oaks that are hundreds of years old are now dying quickly in Doñana National Park (8% loss since 2009, Singular Scientific-Technical Infrastructure of Doñana, ICTS-RBD, unpublished data) and losing leaf cover in response to the rapid drop in phreatic levels (Fig. 2), with mortality rates greatest in areas of higher altitude (i.e. where the distance to phreatic levels is greatest). Cork oak recruitment is virtually nil, largely due to the lowered water table resulting in high mortality during the seedling and sapling stages (Santamaría unpublished data). In addition, between 2002 and 2022 there has been a switch recorded in the scrub vegetation in the National Park towards drought tolerant xerophytic species, notably a reduction in the extent of heather *Erica scoparia* and *E. ciliaris* at the expense of gorse *Ulex australis* (Muñoz Reinoso et al. 2020; Díaz-Delgado et al. 2023; Díaz-Delgado in press). Scrub has now colonized the basins of many desiccated ponds (de Felipe et al. 2023).

Reduction of groundwater levels in the northern areas of Doñana has led to the disappearance of many ponds and shallow lagoons. Manzano (2001) identifies a drop in water table there of up to 20 m between 1972 and 1992. She also notes the disappearance of many wetlands visible in historical documents, including the map of Castroviejo (1993), in the area of northern ecotone most affected by the drop in water table, largely due to rice irrigation. Examples of water bodies now almost permanently dry include the Juan Sardina, Charco del Cura, Charrán and Lengua ponds, as well as the Bochicao and Galvija *lucios* (shallow lakes) (see abstraction cone in Fig. S1).

A decrease in the water table in all ecotones is shown clearly by the CHG report (2022e) (see also Supplementary Information). The decreases in water table, although smaller in magnitude than the decrease in the deep aquifer, are important enough to cause ecological damage to wetlands and terrestrial habitats. There are springs in the ecotone that have stopped upwelling (i.e. they have dried up) and have undergone an inversion of the hydraulic gradient, such that the shallow aquifer now recharges the deep aquifer. Parallel behaviour of shallow and deep levels in all piezometers measuring at different depths proves the direct connexion between superficial and deeper aquifer sub-systems (see Supplementary Information). This is clear evidence that the Doñana wetlands are impacted by abstraction from the deep aquifer, contradicting AEA. These changes have been observed in all the areas bordering the marsh, not just at isolated localities (see Supplementary Information). Thus, we disagree with AEA's statement that "ecotones may be at risk from abstraction of the detritic aquifer but impacts seem to vary locally". Likewise, abstraction has had a clear impact on ponds across different parts of the National Park (de Felipe et al. 2023, see below).

AEA highlighted Spanish government plans to restore the aquifers to Good Status (Berbel et al. 2012) by reducing abstraction and by substituting groundwater irrigation supplies with surface water from dams within other catchments. However, AEA only provided a superficial assessment of the measures being implemented in the area, considering them "appropriate", without referring to alternative pathways and measures, the risks of maladaptation to climate change, or reflecting the lack of implementation of Spanish River Basin Management Plans and other investment plans. Hence there are significant gaps in how AEA evaluate the Response part of the DPSIR framework. They refer to the approval of the supply of 20 hm^3 $year^{-1}$ from the Guadiana basin in 2018, yet only a total of 7 hm^3 $year^{-1}$ has yet reached Doñana, and the proposed law has yet to complete the parliamentary process. These proposals may be unrealistic given the limited volume of surface water available and climate model predictions for the southern Spain. In practice, it will be hard or impossible to transfer water from other, neighbouring catchments, which are all now suffering the consequences of a severe drought period and would experience similar drops in surface runoff with the decreased rainfall forecast for the region (Amblar-Frances et al. 2017). In addition, 20 hm^3 is only 21% of the current volume (95 hm^3) legally extracted each year from the aquifer for irrigation (CHG 2022d). Thus, we do not agree with AEA when they suggest that in the longer term, the total replacement of pumping by surface water supplies would allow total closure of the wells. Furthermore, the supply of surface water from other watersheds could facilitate biological invasions and promote further eutrophication associated with expansion of irrigated crops, as recorded in the Mar Menor wetland in south-eastern Spain (Martínez 2001).

Rebuttal to "Steps 3 & 4 Systematic evidence review and implications" - marshes

Although they do not provide a definition of what they mean by "marshes", we deduce that AEA refer to the natural, seasonal marshes protected within Doñana National Park, excluding the transformed or semi-natural marsh habitats (such as extensive fish ponds, Walton et al. 2015) found in other parts of Doñana Natural Space (see Green et al. 2018).

AEA suggest there is no evidence that groundwater extraction impacts the hydroperiod of the Doñana marshes, based on their Fig. 4, and an apparent absence of a long-term trend in the maximum annual flooded surface area of the marshes according to remote sensing from 1994 to 2014 (although the study they cite provides hydroperiod data from 1974 to 2014, Díaz-Delgado et al. 2016). Their underlying assumption that maximum flooded area can be used as a reliable indicator of impacts of groundwater abstraction on marsh hydrology is seriously flawed (as is the same assumption made by Acreman and Salathé 2022), especially due to fundamental changes in the size of the marsh and the nature of the inflows over that time period. The size of the potential area to be flooded was increased through the restoration of marsh areas that were previously lost by drainage projects in the 1960s, notably the Caracoles estate in 2005 whose incorporation increased the area of natural marsh in Doñana National Park by 10% (Fig. 4, Almeida et al. 2020, Coccia et al. 2021). Furthermore, restoration projects since 1998 (mainly in response to the Aznalcóllar mine spill that year) have recovered some of the surface water inputs to the marsh lost decades before, allowing water to drain into the National Park at new entry points both from the north (*marisma Gallega*) and north-east (*caño Travieso*). Therefore, if groundwater abstraction had no impact on the marsh, AEA should have observed a significant *positive* trend in the maximum flooded area of marsh in their Fig. 4. resulting from these restoration projects. The lack of such a trend is in fact evidence for a loss of pre-existing surface water inputs to the marsh due to groundwater abstraction. Importantly, the hydrochemistry of these restored inputs is different to that of the lost groundwater inputs (Espinar and Serrano 2009).

Any reduction in flow rates of surface water into the marshes can be expected to have an ecological impact, especially in a dynamic, Mediterranean wetland system where freshwater inputs are limiting. Contrary to AEA, there is strong evidence that abstraction has a major impact on flow rates, especially since the Partido and Rocina streams originally provided a major fraction of the water supply to the marsh, and the flow of groundwater discharge into these streams and their tributaries has been strongly reduced by extraction. According to Castroviejo (1993), the Rocina and other streams formerly contributed 20-140 hm^3/year to the marsh system, compared to 70-190 hm^3/year from direct precipitation.

Apart from precipitation, Rocina and Partido stream basins themselves receive water inputs from the aquifer where mean historic (1975–1997) discharges were estimated at 34 and 11 hm^3 $year^{-1}$ respectively (Guardiola-Albert and Jackson 2011), although flows have since been reduced due to groundwater extraction (Arambarri et al. 1996; Manzano et al. 2005). Data from the Rocina gauging station (at El Rocío village), although fragmentary, allow an approximation to the evolution of the flows circulating through the Rocina stream, by comparing two periods before and after 2004 (periods of 93 and 91 months, with similar average annual rainfall of 480 and 463 mm respectively). These data show a decrease in surface flows of 62% (from 775 l/s to 292 l/s) (CHG 2022d), linked to piezometric decrease. Models of groundwater flow in the Rocina suggested a 25% decrease between 1975 and 1997 (Guardiola-Albert and Jackson 2011), which has since been exacerbated by the major expansion of greenhouse crops in the Rocina catchment since 1997 (approximately a threefold increase by 2016, Paredes et al. 2021a). Manzano (2001) noted that groundwater discharge to the Rocina (as well as in ecotones) was twice as high in 1970 than in 1994, and that groundwater abstraction is a major cause of this change (which pre-dates the time series for maximum annual flooded surface area of the marshes presented by AEA in their Fig. 4). Further evidence of ecological impacts comes from the temporary ponds along the Rocina stream catchment that showed a clear decline in hydroperiod between 1985 and 2014 (Fig. 7 in Bustamante et al 2016). Furthermore, the reduction in groundwater discharge explains changes in dominant species in riparian forests of this area, with a progressive decline of *Salix* (more water dependent) and increase of *Fraxinus* (less water dependent) from 2004 to 2021 (Rodríguez-González et al. 2017), with additional effects on tree-ring growth (Rodríguez-González et al. 2021).

There are other reasons why data on the annual maximum marsh flooded area (in Fig. 4 of AEA) should not be used as evidence against an impact of groundwater extraction on the marsh. The maximum flooded surface area is not an adequate proxy for hydroperiod, or for the volume of water entering the marshes, for two main reasons. Firstly, the maximum flooded area per flooding cycle in the marshes is only weakly correlated with the more relevant mean hydroperiod (i.e. average length of time flooded averaged across the marsh area, Díaz-Delgado et al. 2016). For the period 1974-2021, the relation between maximum flooded area and mean hydroperiod is relatively weak (r^2=0.46, p<0.05, n=46; data available as Supplementary Information). A spatially explicit Teil-Sen slope shows a statistically significant decline in hydroperiod for southern areas of the marshes from 1974-2014 (Fig. 8 in Díaz-Delgado et al. 2016), as well as for a longer updated series of 1974-2022 (Fig. 3, see also Díaz-Delgado in press). The surface area within Doñana National Park with a significant negative trend exceeds that with a positive trend (Fig. 3), and has grown since 2014 (Díaz-Delgado et al. 2016).

Secondly, the marsh does not have a stable depth profile (Fig. 4), and the volume required to fill the marsh is likely to decrease over time. Depth is reduced by sedimentation, and sedimentation rates have accelerated in recent decades due to soil erosion (Rodríguez-Ramírez et al. 2005). This soil erosion is more intense due to stream canalization and agricultural expansion, with run-off from greenhouses concentrating erosive water flow in certain parts of stream catchments, eroding sandy soils which are then deposited downstream in the marsh (Borja et al. 2009). Hence, to some extent, ongoing siltation reduces marsh depth and means that hydroperiod might remain stable even when the volume of water entering has been reduced. Results from the long-term monitoring program at a landscape scale have shown a change in marsh topography in general (Fig. 4), including the north-west area of the marsh (ICTS-RBD 2010). Loss of depth over the past century has an important ecological impact, and although long-term monitoring data for most fauna are lacking, waterbirds act as bioindicators for the resultant changes (Amat and Green 2010). For example, this explains the disappearance of diving ducks such as the white-headed duck *Oxyura leucocephala* and ferruginous duck *Aythya nyroca*, which formerly bred in the marsh (Valverde 1960, Mañez 1991). These birds were associated with permanent or semi-permanent channels where they nested in *Typha* stands that disappeared many decades ago. Similarly, the Eurasian Pochard *A. ferina*, another diving duck that was particularly common in the marsh (Amat 1982), has declined markedly as a breeding bird since the 1980s (Fox et al. 2016).

AEA state that areas of marshes adjacent to Rocina entry stream have not been reduced, and that no negative ecological impacts were found for this area. The Rocina enters the marshes at El Rocio village in an area where the hydroperiod has locally been extended artificially since agricultural expansion began in the Partido catchment, due to a dam effect caused by sands deposited by this stream in its mouth, just to the east of El Rocio, due to upstream erosion (Borja et al. 2009, Mintegui-Aguirre et al. 2010, Huelin-Rueda et al. 2015). However, negative impacts are now obvious in the Rocina area, which is to be expected given the reduced flow rates and increased nutrient loads associated with abstraction, often making conditions impossible for aquatic fauna, and promoting harmful algal blooms (Paredes et al. 2021a).

Thus, the statements by AEA that the inundation of the marshes is not affected by groundwater abstraction are unsupported, and overlook several types of major ecological damage. Additional concerns about the interpretation by AEA of annual variation in rainfall and marsh area are explained in Supplementary Information.

Rebuttal to "Steps 3 & 4 Systematic evidence review and implications" – the ponds

Doñana National Park includes over 3000 temporary ponds (vernal pools, Gomez-Rodriguez et al. 2011) that extend over the aeolian sands (but not only in the dunes close to the coast, contrary to AEA). These Mediterranean temporary ponds are a priority habitat according to the EU Habitats Directive (Camacho et al. 2009), and are especially sensitive to small changes in water levels, which can readily be caused by abstraction. The only impact recognized by AEA is the damage to dune ponds caused by water abstraction for tourist use in the Matalascañas beach resort, and the irrefutable evidence that this abstraction impacts what they call the dune aquifer, as well as the hydroperiod of temporary ponds (Gómez-Rodríguez et al. 2010). AEA underestimated the impacts to these ponds from the pumping from the deep aquifer (see Supplementary Information). Furthermore, a recent analysis by de Felipe et al (2023) has found that 59 % of ponds in Doñana dried out completely between 1985 and 2018, and that expansion of greenhouses since 1995 had a statistically significant impact on desiccation rates after controlling for climatic effects. These impacts were widespread, occurring not only in the dune ponds but also in central and northern areas of the National Park. Hence this new analysis from remote sensing data (de Felipe et al. 2023) supports the conclusion of earlier studies (see above) that groundwater abstraction has been causing extensive ecological damage to Doñana ecosystems for decades.

On the other hand, the agricultural impacts become more complex when considered at a landscape scale. Water abstraction from the aquifer for agriculture and urban use has reduced the hydroperiod of temporary ponds and other surface waters inside the National Park, or even dried them out completely (de Felipe et al. 2023). However, agriculture has also created an artificial increase in surface area and hydroperiod of some other ponds outside the National Park (but inside the UNESCO Biosphere Reserve). This is driven by the creation of irrigation ponds for storing groundwater, after it has been extracted from the aquifer (Bustamante et al.

2016). Even some natural ponds are affected in this way, as some ponds are used as storage reservoirs, or receive surplus irrigation water (e.g. Laguna de Mimbrales). Thus, the groundwater withdrawal leads to "artificialization" of an important part of the Doñana system in which availability of surface water becomes uncoupled from precipitation, leading to a loss of both spatio-temporal variability and ecological quality (Bustamante et al. 2016).

Impact on water quality

Since our principal concern and that of AEA is with "ecological damage", two critical questions are: 1) does groundwater extraction reduce the volume of water entering the marsh and ecotones, and 2) does it affect the quality of water entering the marsh and ecotones? These two aspects are interdependent. The former is clearly the case (see above). The latter is also true since extraction is coupled with contamination through agrochemicals and urban activities, and a reduced flow rate leads to further increases in concentrations of contaminants, and increased salinity through higher evaporation rates (Paredes et al. 2021a). Nevertheless, AEA pay scant attention to water quality issues, which were excluded from their DPSIR framework (i.e. their Fig. 1). Since the methodology advocated by AEA is not strictly limited to water availability, it would be appropriate to pay full attention to the major problems of water quality and eutrophication, especially since any change in water quantity has a direct effect on quality (Corrales-González et al. 2019).

Concerns about surface water quality in Doñana have long been raised (e.g. Serrano et al. 2006, Camacho-Muñoz et al. 2010; Contreras 2012), and phosphorus loading has increased sharply since 2000 (Espinar et al. 2015). Increased P loading has in turn favoured the expansion of the invasive aquatic fern *Azolla filiculoides* across the marsh and some ponds (García-Murillo et al. 2007; Espinar et al. 2015), negatively impacting macrophytes and amphibians (Piñero-Rodriguez et al. 2021). Concentrations of many pharmaceuticals (e.g. ibuprofen, antibiotics) recorded inside the National Park demonstrate the entry of domestic wastewater into the system, and often exceed levels known to have toxic effects on fauna (Camacho-Muñoz et al. 2010). Regarding groundwater, AEA stated that "the quality of aquifer water is generally good", but the data do not support this statement. Widespread areas underneath irrigation zones are polluted with agrochemicals which are transported within groundwater and discharged into the Doñana wetlands. Pollution in the Doñana aquifer due to agricultural and urban activities dates back to initial expansion of irrigation in the 1970s (see Supplementary Information). Deterioration of groundwater quality has been recognized by the Water

Authorities, and Groundwater Bodies of 'Condado' and 'La Rocina' (Fig. 1) have been declared to be in bad chemical status for their high nitrate contents according to their basin plans.

Therefore, AEA attempt to separate two intimately related direct impacts of abstraction, i.e. those on water quantity and on quality. Red fruit crops for which water is abstracted are heavily dependent on agrochemicals, which in turn are transferred to ground and surface water. The aquifer is particularly vulnerable to this pollution, given the thinness of the unsaturated zone and its sandy nature (see details in Supplementary Information). Recent data show extremely high nutrient loads in streams affected by groundwater pumping for agriculture (Paredes et al. 2021a, 2021b). Expansion of greenhouses based on abstraction has contributed to eutrophication to the extent that fish life is impossible in long stretches of these streams (Paredes et al. 2021a). Hyper-eutrophication is partly due to poor treatment of urban wastewaters, but it even occurs in the Rocina stream, which does not have urban centres or wastewater treatment plants (WWTPs) in its catchment (Paredes et al. 2021a). Stable isotopes of nutrients and vegetation indicate that fertilizers are a major cause of eutrophication (Paredes et al. 2019, 2020).

Conflicts of interest

AEA's statement regarding a complete lack of competing interests is surprising, since the article addresses a Ramsar Site and a UNESCO World Heritage Site, and all three authors work for, or were paid by, the Ramsar secretariat, the UNESCO World Heritage Centre, or the IUCN World Heritage Programme. Arguably it may be in the interest of those working on behalf of these international institutions to demonstrate that their programmes lead to adequate site protection. The statement of competing interests in a closely related publication by Acreman and Salathé (2022) therefore seems more appropriate. It is noteworthy that Doñana has been included in the Montreux Record of the Ramsar Convention (for Ramsar sites where changes in ecological character have occurred, are occurring or are likely to occur) since 1990 due to "over-exploitation of regional aquifers, leading to a drop in groundwater levels and a reduction in the extent and duration of seasonal flooding in the marshes".

Conclusions

Contrary to AEA, there is strong scientific evidence that groundwater abstraction has already caused major ecological damage to Doñana, and that this damage is increasing over time. We conclude that the methodology advocated by AEA to analyse the eco-hydrological scientific knowledge was incomplete and misapplied by them. Many important studies providing evidence for a negative ecological impact of water abstraction (including major impacts through eutrophication) were overlooked or misinterpreted. We suggest this is linked to insufficient involvement of the numerous scientists from different disciplines with local knowledge, as well as inadequate procedures for stakeholder involvement and participation. In a place as complex as Doñana, the methodology should be applied by a multi-disciplinary team with extensive experience in the study area and in the use of participation techniques. Urgent measures are needed to substantially reduce the levels of groundwater extraction for agriculture and tourism (Camacho et al. 2022; de Felipe et al. 2023).

In summary, key ways to improve the application of the methodology used by AEA in Doñana in relation to the five steps they identify would be: Step 1, be more inclusive, rigorous and transparent when consulting interested and knowledgeable parties; Step 2, give water quality the necessary attention; Step 3, include historical and grey literature, especially those not written in English; Step 4, interpret data with help from local scientists who can provide up to date, unpublished data; Step 5, be transparent about peer review, and seek verification from reviewers without conflicts of interest (e.g. exclude those responsible for administering protected areas, or their water supply). These recommendations may be helpful when considering the impacts of groundwater extraction in many other protected areas around the world (Huggins et al. 2023). We hope this article will contribute to the growing body of evidence supporting management initiatives to restore groundwater and surface water quantity and quality in Doñana.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception. Fig. 3 and Fig. 4 were prepared by Ricardo Díaz-Delgado. Additional figures were prepared by José Antonio Serrano Reina and Carolina Guardiola-Albert. The first draft of the manuscript was written by Andy J. Green, Carolina Guardiola-Albert, Ricardo Díaz-Delgado and Javier Bustamante. Later drafts included extensive writing by Antonio Camacho, Luis Santamaría and Guido Schmidt. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

Data supporting the results reported in this article can be found by following the enclosed hyperlinks, notably the piezometer data of CHG (2022e). The dataset used for Fig. 3 is included in Supplementary Information. The dataset generated for Fig. 4 is available from the corresponding author on reasonable request.

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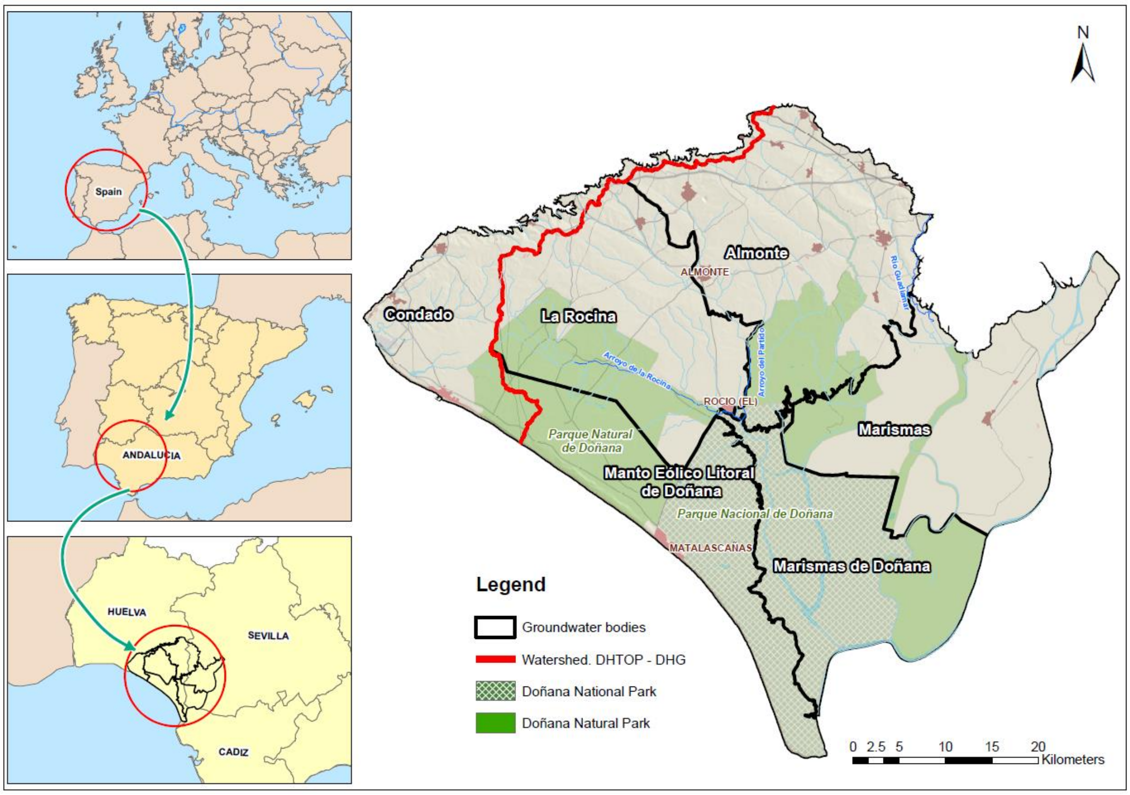

Fig. 1. The Almonte-Marismas aquifer system underlying Doñana, the division between six groundwater bodies, and the areas protected within Doñana National and Natural Parks (which, combined, make up “Doñana Natural Space”).

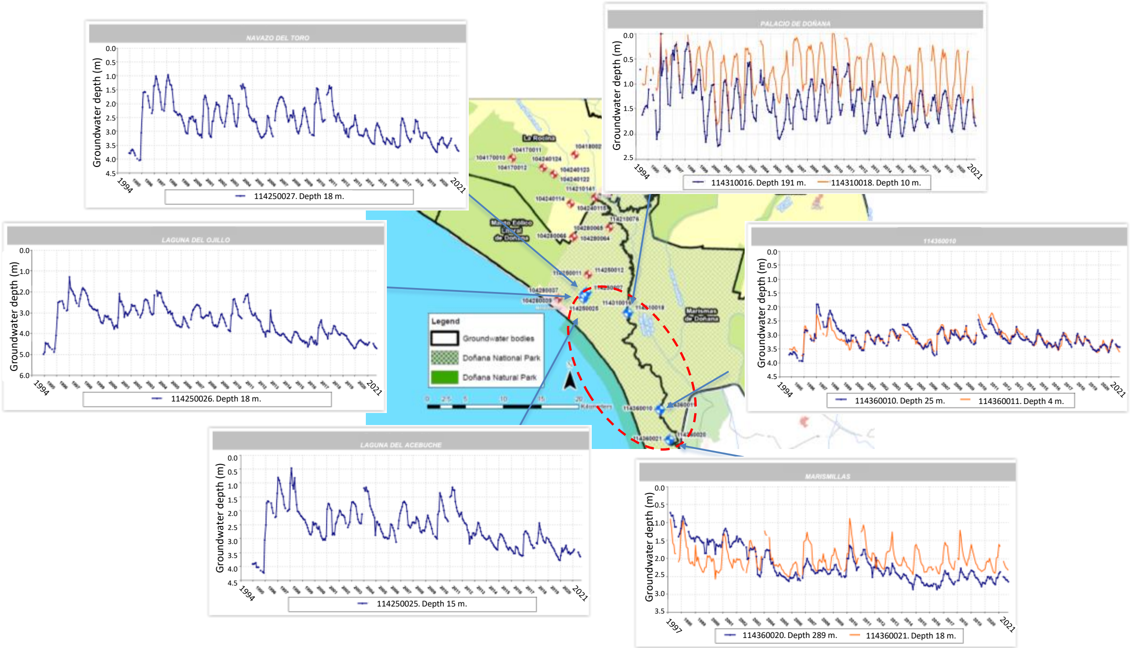

Fig. 2. Temporal piezometric evolution of groundwater levels in the dune ponds (left side) and west ecotone (right side) in Doñana. The declines in depth shown in each graph are stronger in those piezometers closer to areas of groundwater extraction for agriculture and urban uses. Information from the annex of CHG (2022e).

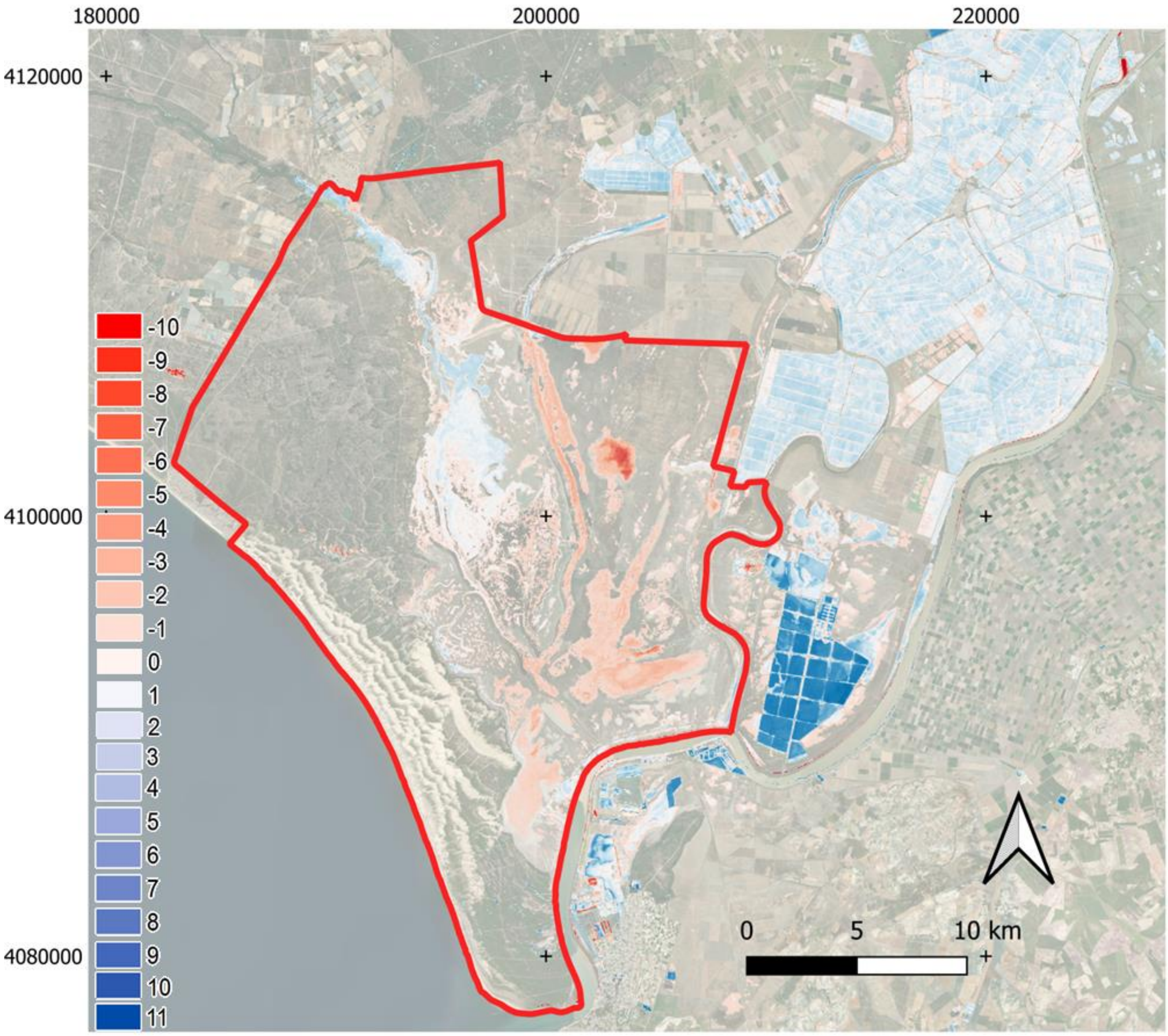

Fig. 3. Theil–Sen slope in days/year showing the hydroperiod trend from 1974 to 2021. Red indicates consistent and significant decreasing trend in hydroperiod, while blue indicates the opposite (methods from Díaz-Delgado et al. 2016). The boundary of Doñana National Park is shown in red.

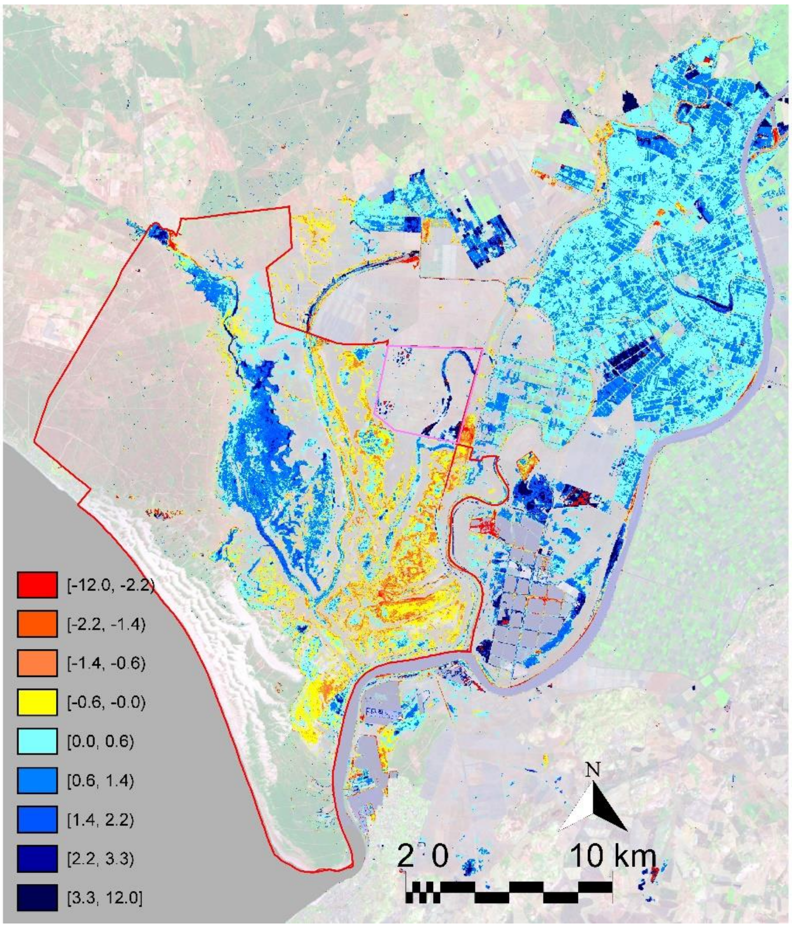

Fig. 4. Trends in maximum depth of the water column over the period 1984-2021, calculated via the Theil-Sen slope. Water depth was estimated for every Landsat image available by applying the water depth model of Bustamante et al. (2009). Much of the natural marsh of Doñana National Park has been affected by a loss of depth that suggests sedimentation and transformation processes. Other areas (especially ricefields) have undergone depth increases. In the north-east corner, a former agricultural area (Caracoles estate identified by the pink line) was restored into marsh in 2005 and incorporated into the National Park, producing a local increase in water depth and expansion of the potential maximum flooded area.