

## CORRECTED PROOF

## Management in Practice

**Rapid response to water hyacinth (*Eichhornia crassipes*) invasion in the Guadalquivir river branch in Seville (southern Spain)**

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## OPEN ACCESS

**Abstract**

A rapid response action carried out against the invasion of water hyacinth (*Eichhornia crassipes*) in the Guadalquivir River branch in Seville (Southern Spain) is described and analyzed. Removal was implemented and coordinated by the regional environmental Council, National security forces and public companies. Immediately after its detection, the distribution and abundance of water hyacinth, and the possible origin of introduction were assessed as the basis for selecting a feasible removal method. Plants were scattered across 110 ha and a perimeter of 8.4 km. A total biomass of 1,931 kg (fresh weight) was removed between May and December 2021 by combining manual removal from water using inflatable boats, floating booms, wetsuits and fishing waders, as well as removal from the shore. In total, the action cost ca. €22,500. Most biomass (83%) was removed during the initial control phase (one month). However, most of the efforts and costs (83%) were made in the following seven months, especially for monitoring and follow-up treatments. Rapid response avoided the growth, blooming and spread that could be expected in summer, coinciding with the optimal growing conditions. Moreover, rapid response reduced ca. 50 times the biomass and control costs with respect to a delayed action (i.e., after summer). Despite the fact that monitoring required a higher effort and cost than the initial control phase, it altogether represented a great cost saving as the invasion was kept at bay. The coordination between the regional Council, National security forces and public companies has taken advantage of the specific strengths of each one of them, achieving the shortest possible response time.

**Key words:** invasive plants, management, removal, monitoring, coordination, freshwater

**Introduction**

Water hyacinth (*Eichhornia crassipes* (Mart.) Solms) is one of the most dangerous invasive plants in the world (Gopal and Sharma 1981; Lata and Dubey 2010). Native to the Amazon basin, it has been used extensively for

ornamental purposes in warm temperate to tropical regions across the world. Water hyacinth causes negative impacts on the environment, water use and public health. For example, dense mats block light, reduce phytoplankton productivity and dissolved oxygen concentrations. Dense mats also increase evapotranspiration and sedimentation rates, reduce boating access, navigability and recreation and clog pipe systems used for agriculture, industry and water supply (Villamagna and Murphy 2010). These mats also create habitats for larvae of mosquitos, which are vectors of several diseases (Mack and Smith 2011). In Europe, the commerce of water hyacinth has been banned since 2013 according to national and European regulations (the Spanish Royal Decree 630/2013 that regulates the Spanish catalog of invasive alien species and the European Commission Regulation 2016/1141, that regulates the List of Species of Concern for the European Union).

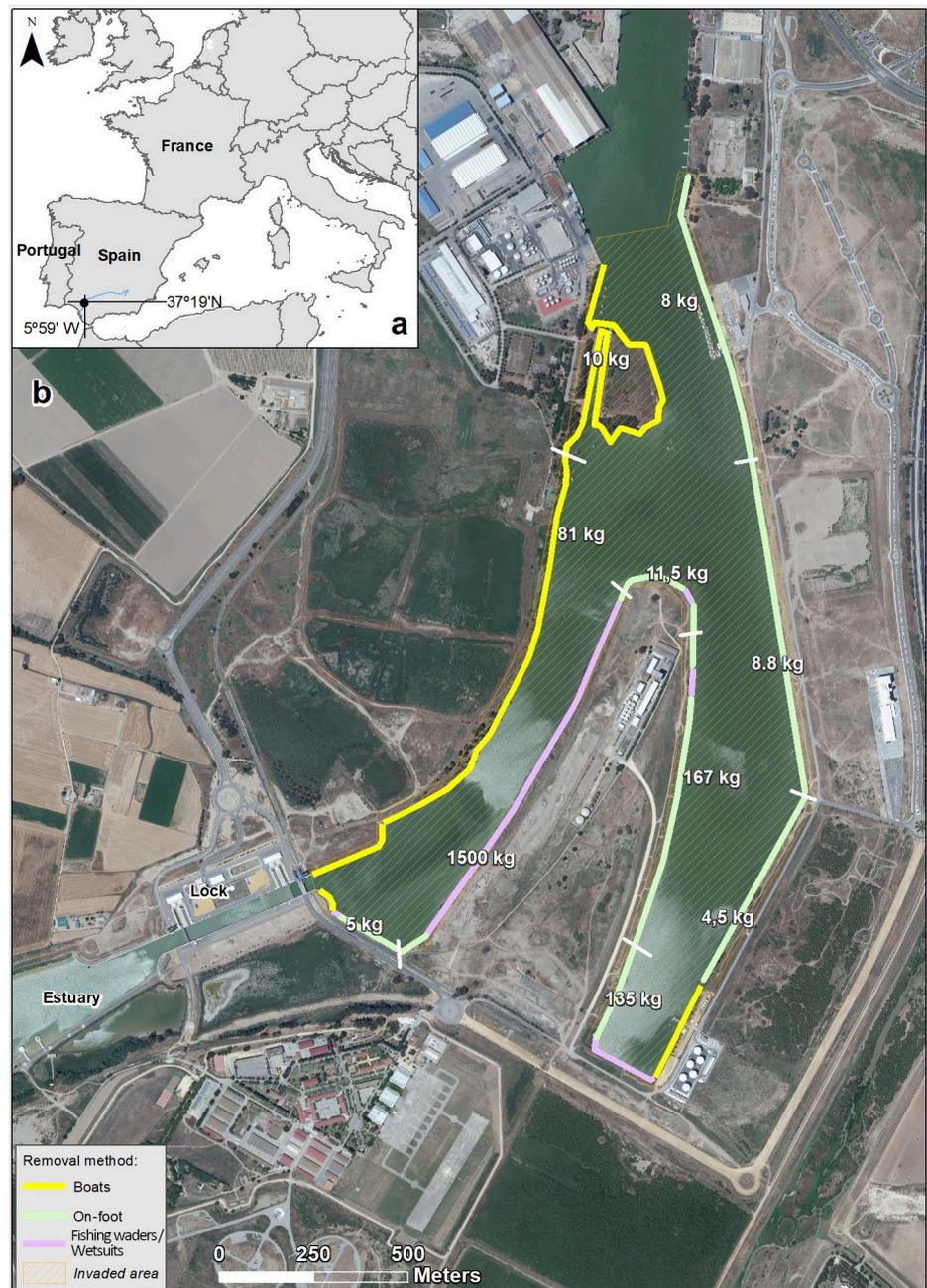
In the case of large, extensive invasions (i.e, large rivers and lakes), the eradication of water hyacinth is hardly feasible due to (i) the longevity of its seeds (Matthews et al. 1977; Sullivan and Wood 2012); (ii) the large amount of biomass accumulated (e.g., Lwasa and Mwanje 2002; Opande et al. 2004; Brundu et al. 2012); (iii) a high dispersion capacity mediated by water flow and wind (Coetzee et al. 2017; Miskella and Madsen 2021) and (iv) the difficulty of detecting and removing all plants and stands among the riverside vegetation (García-de-Lomas et al. 2021). Control actions have been developed worldwide, most of them dealing with extensive water hyacinth invasions in large lakes, rivers and reservoirs, and these have involved massive costs. At a large-scale, different methodologies have been documented, including mechanical removal (excavators, harvesters, push boats, etc.), herbicides, brine spraying, biological control, manual removal, containment with floating booms or a combination of some of these (e.g., Chu et al. 2006; Laranjeira and Nadais 2008; Tipping et al. 2017; Robles and Martínez 2021; Karouach et al. 2022). However, not all of them have been effective, neither to control the invasive species nor to recover the damage caused to the ecosystem (e.g., Mangas-Ramírez and Elías-Gutiérrez 2004; Waltham and Fixler 2017). The failures in the management of this species mainly rely on reproduction from seed (once the water hyacinth completes fruiting, reinvasion is assured), the lack of continuity in the control tasks, insufficient or discontinuous financing, or procedures not adapted to the size of the invasion (e.g., Williams et al. 2005; Cacho et al. 2006; Albano et al. 2011; Brundu et al. 2012).

The feasibility of specific control methods for water hyacinth is context-dependent. Factors such as the resources available, environmental features (e.g., temperature regime, nutrient concentration), human uses, size and age of the invasion, presence of an upstream invasion, accessibility, or the presence of harmful animals will determine the feasible strategy for water

hyacinth (Alamu et al. 2002; Osmond and Petroeschovsky 2013; Dana et al. 2019; Karouach et al. 2022). Prevention, early detection and rapid response actions (preferably before plants flower and set seed) are encouraged to avoid large, dense infestations and huge costs (e.g., Wilby 2007; Brundu et al. 2013). For invasions characterized by sparse individuals or occurring in hard-to-reach areas, methodologies based on excavator, push boats, harvesters, herbicides or biological control may not be effective when applied alone. These methodologies overlook small stands that are hidden in the riverside vegetation or deposited on the banks, posing a risk of reinvasion and investment loss (Brundu et al. 2012; MITECO 2019a). Manual removal is labor intensive but also highly selective and effective only for minor invasions (Labrada 1995; Pan et al. 2011; García-de-Lomas et al. 2021; Karouach et al. 2022). In invasions characterized by sparse individuals or occurring in hard-to-reach areas, manual removal is more selective and allows a higher significant reduction of plant biomass than chemical treatments (Robles and Martínez 2021). Even in large-scale invasions, manual removal can be combined with other methods to remove small stands hidden along the banks (Lwasa and Mwanje 2002; Ayanda et al. 2020).

In Europe, extensive invasions of water hyacinth have occurred in Spain, Central Portugal, Sardinia, and Corsica and these involved massive costs (Coetzee et al. 2017). In the river Guadiana (SW Spain), water hyacinth has invaded a stretch of up to 160 km, and ca. €50 million have been spent in recurring control actions between 2004–2020 (MITECO, <https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-camalote-est%C3%A1-controlado-en-todos-los-tramos-del-r%C3%ADo-guadiana/tcm:30-520159>). In Sardinia, actions aimed at controlling this species in the river Mare'è Foghe cost ca. €167,000 in 2010, but the river was reinvaded on a large scale (Brundu et al. 2012). Although a number of casual records of water hyacinth have been reported in ponds and streams (e.g., Brundu et al. 2013; Peña-Bretón and de la Cruz 2014; Gil-López 2016; García-de-Lomas et al. 2021), the information on management practices and outcomes is scarce. Reporting particular site-specific methodologies and management results can provide planners and managers with effective solutions to prevent extensive invasions of this species.

At the end of April 2021, agents of the National Security Forces (Spanish Civil Guard) detected scattered plants of water hyacinth in the Guadalquivir river branch in Seville during routine rescue diving practices (García-Murillo et al. 2021). In this work, we evaluated the different management options and the decision taken. We report the rapid response action performed just after detection and key management results obtained over eight months after detection. Particular advantages and limitations of the implemented rapid response action are discussed.



**Figure 1.** Study area, showing the removal method followed according to the characteristics of the riverbank and distribution and amount of biomass removed in the period May–December 2021.

## Materials and methods

The water hyacinth invasion was detected in the Guadalquivir river branch in Seville ( $37^{\circ}14'27''\text{N}$ ,  $5^{\circ}58'42''\text{W}$ ; Figure 1). The branch length is 13 km and hosts the Port of Seville, which is separated from the main channel of the Guadalquivir River Estuary (total length = 110 km) by a lock. Both the Estuary and the river branch are crossed daily by freighters and yachts. The climate is Mediterranean, with hot summers and mild winters. Mean annual temperature is  $19.2^{\circ}\text{C}$  and mean annual rainfall is 539 mm (AEMET, <http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?l=5783&k=undefined>). In the study region, water hyacinth

flowers mainly between June and September, however, this period can be extended to between April and November if conditions are favorable (MITECO 2019b). Freezing events are extremely rare (3 days/year), thus water hyacinth can persist through the winter, unlike other regions with colder winters, where the water hyacinth behaves as an annual species. Water conductivity varies between 1–2 mS cm<sup>-1</sup> depending on rainfall and water inputs from the estuary. Turbidity is high (Secchi depth < 0.5 m) and nutrient concentration reported (Rivero 2016) is typical of eutrophic to hypertrophic conditions (Carlson 1977). Shore characteristics included: (i) gentle shores with breakwater rocks and scarce vegetation that is easily accessible on foot (total length = 3.80 km); (ii) steep shores with dense riverside vegetation (mainly *Typha domingensis* Pers., *Phragmites australis* (Cav.) Trin. ex Steud., *Rubus ulmifolius* Schott, *Tamarix* sp.) and depths ≤ 1.70 m accessible from water using waterproof fishing waders and neoprene wetsuits (1.39 km); and (iii) steep shores with dense riverside vegetation and depths > 1.70 m accessible only by boat (3.17 km) (Figure 1).

Immediately after the first detection (on 26 April 2021), a preliminary inspection was carried out to evaluate the extent of the invasion (distribution and abundance) by two inflatable boats (4 and 9 meters in length) over the entire catchment area (perimeter = 50 km) (Figure 2a). No flowering plants were observed during our initial inspection. Thus, the main objective of implementing a rapid response was to eradicate the population. Also, one specific objective of implementing a rapid response action was to prevent the spread of water hyacinth across the Guadalquivir estuary and its tributaries. Thus, the connected estuary within a radius of 20 km was also inspected in search of possible spread. Following this inspection, the feasibility of five different management options were evaluated according to Dana et al. (2019). The considered management options were: (a) chemical treatment, (b) use of heavy machinery, (c) search from the water and manual removal using boats, (d) search from the shore and manual removal, and (e) manual removal combining search from the shore, and search from the water using boats and wetsuits (Table 1). For each method, particular attention was paid to legality, response time (including time required for the acquisition of supplies, services, materials, workers and permits), accessibility, and the effort needed (working days) (Table 1). The method best adapted to the invaded habitat and the minimum response time was chosen. The use of herbicides in open aquatic environments is illegal in Spain. Moreover, a safety band of at least 5 m must be left around surface waters, unless special permits are given, and it is not allowed to apply herbicides at wind speeds above 3 m/s (Royal Decree 1311/2012). Heavy machinery and searches from the shore alone did not allow to access the entire invaded area. Thus, only two methods were considered to be feasible options to manage the invasion, since they allowed accessibility to the entire invaded area: (i) a search from the water and manual removal using boats, and (ii) manual



**Figure 2.** a) Inspection using inflatable boats; b) search from the water in gentle banks and manual removal using wetsuits; c) manual removal in gentle banks, using floating booms and fishing waders; (d) small plants (red arrow) hidden in the riverside vegetation; e) a cargo ship crossing the invaded area during removal operations. Photos by J.M. Martínez, J. Borrero and J. García-de-Lomas.

**Table 1.** Various management options assessed for a rapid response action against water hyacinth in the Guadalquivir estuary (southern Spain). \*Effort was estimated as the number of workers  $\times$  the approximate number of working days required. \*\*for the Environmental Council (requires hiring an external company); \*\*\*for the National Security forces.

Method	Legal?	Expected response time (days)	Accessibility to the entire invaded area?	Estimated effort* (days)
Herbicides (from the shore, using wetsuits)	No	10	No	30
Herbicides (from the water using boats)	No	30	Yes	30
Heavy machinery	Yes	30-50	No	20
Search from the shore and manual removal	Yes	2	No	120
Search from the water and manual removal from boat	Yes	50** or 4***	Yes	160
Manual removal combining search from the shore and water using boats and wetsuits	Yes	4***	Yes	192

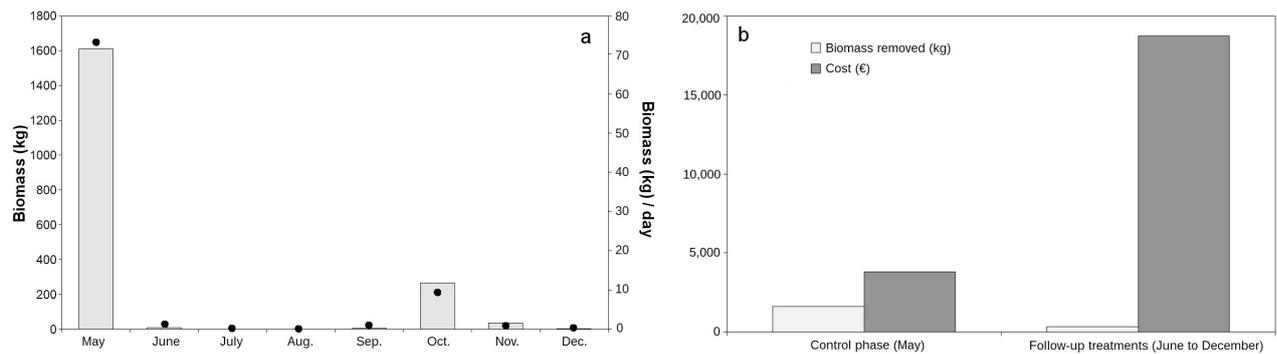
removal combining a search from the shore and a search from the water using boats and wetsuits. In addition, for the latter option, the coordination between administrations would allow the fastest possible response time (4 days) (Table 1).

In May 2021 (just four days after the first detection), a rapid response action was carried out due to the high risk of water hyacinth escaping to the Guadalquivir estuary and its tributaries. In this stage, we combined the search from the water using boats (on steep banks with a depth of  $>1.70$  m, two working days), wetsuits (in shallower areas with a depth of  $\leq 1.60$  m) and the search from the shore using fishing waders (on gentle shores with a depth of  $\leq 1.15$  m) (Figure 2). Removal from the boats was carried out with nets, with the removed biomass being deposited in drums or baskets, while workers with wetsuits and fishing waders used big-bags to facilitate collection and transport of the plant through the invaded area (Figure 2b, c). During the removal, floating booms were also used (Figure 2c) in order to facilitate aggregation and extraction of dense stocks and to prevent their wind dispersal. These barriers were built with polyethylene foam cylinders (noodles) and had a 30 cm depth PVC net below the noodles (mesh size = 1 cm) that prevented the escape of small plants under the barrier (Figure 2c). The filled bags were dragged out of the water by jeeps. Once out of the water, the biomass was transferred to Environmental Council facilities for drying and waste disposal.

The use of the invaded area by large ships (Figure 2e) required special permissions for the use of boats with a professional skipper who was not available at short notice. Thus, control and monitoring were developed mainly by a search from the shore and a search from the water using wetsuits and fishing waders (Figure 2b–e). However, the involvement of National Security Forces allowed the use of boats during the early inspection. The early inspection included removal of water hyacinth found throughout steep shores with dense riverside vegetation and depths of  $> 1.70$  m. Monitoring (periodic reviews) were carried out in the early hours of the day, mainly due to a massive colonization of stony shores by wasp nests (*Vespula* spp.). The use of wasp-protective suits was ruled out due to risk of dehydration for workers (maximum air temperatures of the area were  $> 30$  °C). Workers used mosquito repellents due to the outbreak of West Nile neuroinvasive disease in 2020 throughout the Guadalquivir estuary (García San Miguel et al. 2021). Weekly reviews were developed between May and July, whereas biweekly reviews were developed between August and December.

## Results

Water hyacinth was highly scattered throughout the invaded area (110 ha, perimeter = 8.9 km) (Figure 1). Plants and stands were either intermingled with the shore vegetation, stranded along the shore or hidden in riparian



**Figure 3. 3.** (a) Water hyacinth biomass removed monthly (bars) during the rapid response action and subsequent follow-up treatments. Black circles indicate the monthly yield per unit effort (kg/day). (b) Total biomass and cost for each management phase (control vs. follow-up treatments).

holes (Figure 2d). No flowering plants were observed during our initial inspection. The total effort, including preliminary inspection, initial control stage and monitoring, took 150 days. Five to seven people were needed during initial inspection tasks by boat, whereas two or three workers carried out further removal and biomass disposal tasks. The total biomass removed was 1,931 kg (fresh weight) and the total cost of the action was ca. €22,500. Most biomass (1,612 kg, 83%) was removed during the first control phase (May 2021) and the rest during subsequent monitoring and follow-up treatments (from June to December 2021) (Figure 3). In contrast, most of the effort and cost invested (€18,700, 83%) related to monitoring and follow-up treatments (Figure 3b). The yield per unit effort varied from 73.3 kg/day during the initial control phase (May) to an average ( $\pm$  SD) of  $1.8 \pm 3.4$  kg/day during the monitoring phase (June–December,  $n = 7$ ). The biomass distribution was highly heterogeneous, showing an aggregation (1,586 kg) in the SW sector of the invaded area (Figure 1). In total, the cost/biomass ratio was €11.6/kg and the cost/surface ratio €205/ha. The maximum yield per unit coincided with the removal of the biggest stands with the highest density. During the inspections carried out, no water hyacinth was detected in the Guadalquivir estuary.

During monitoring and follow-up treatments, some plants appeared in places that already had been assessed in recent weeks. Surprisingly, up to 267 kg appeared in October 2021 and 35 kg in November 2021 (Figure 3a), thus breaking the four-month trend with virtually no water hyacinth being detected. This record occurred after winds rolled from the southwest (the dominant direction in the study area) to the north-northeast (Supplementary material Appendix 1). During the course of the action, no flowers were detected.

## Discussion

The invaded area showed water characteristics that are highly favorable for the development of water hyacinth, i.e., stagnant waters with high concentration of nutrients and high temperatures (Wilson et al. 2005). The origin of water hyacinth in the study area remains unclear since this

species has been banned in Spain since 2013. The total biomass removed and the heterogeneous distribution of biomass throughout the invaded area suggest that the invasion may have remained unnoticed for some time before the first detection. The restricted public access to the invaded area due to port activities supports this assumption. Curiously, the person who discovered the water hyacinth had previous experience with this species in other regions of Spain. This fact highlights the importance of providing adequate training or expert support to key partners in order to promote early detection (Genovesi et al. 2010). In the present study, the prior evaluation of different control methods and approaches led to the selection of a viable strategy adapted to local conditions. The involvement of the regional Council, National security forces and public companies has allowed to take advantage of the specific strengths of each one of them, achieving the shortest possible response time. The coordination with National security forces was essential according to National standards on *Eichhornia crassipes* management (MITECO 2019b) as it allowed to quickly initiate some basic, key actions (e.g., initial inspection) without having to apply for multiple permits that are mandatory for the operation of other public or private entities. In fact, the required permissions for certain management actions (e.g., access to the port, biomass removal, boat use) are given by different authorities with jurisdiction in the invaded area. Such a labyrinth of governmental agencies can present an additional challenge for implementing a rapid response action (Kraus and Duffy 2010). A more flexible and effective response model (e.g., comparable to firefighting) should be provided for highly invasive species, e.g., aquatic species, invading unconfined habitats, estuaries and rivers, or showing high seed longevity.

The rapid response action may have prevented the spread of water hyacinth across the Guadalquivir estuary and its tributaries. This is a mesotidal estuary, ca. 110 km long and covering an area of 185,000 ha, with complex tidal dynamics, freshwater inputs and river discharges, and multiple uses involved (including the irrigation of over 40,000 ha of rice fields) (Losada et al. 2017; MAPAMA, [https://www.mapa.gob.es/es/agricultura/temas/producciones-agricolas/distribuperf\\_prodarrozenespanaporcaa\\_tcm30-135393.pdf](https://www.mapa.gob.es/es/agricultura/temas/producciones-agricolas/distribuperf_prodarrozenespanaporcaa_tcm30-135393.pdf)). The Guadalquivir estuary is also connected with the Doñana National Park. This Natural Area is of particular importance for the conservation of unique wildlife and constitutes one of the most significant wetland in Europe of special importance as a major stepping-stone for birds migrating between Africa and Europe (García-Novo and Marín-Cabrera 2006). Taking this into account, the management of a possible invasion of water hyacinth in the estuary would be extremely complex and practically impossible to tackle in the short term with the available resources. Also, we tried to avoid massive flowering that, at this latitude, occurs in summer, coinciding with higher temperatures (MITECO 2019b). The emergence of 267 kg of biomass in October suggests that some

flowering must have taken place during summer time, but no flower spikes or dry flowers were observed in these stands. Due to the longevity of its seeds, long-term resources must be available to prevent an extensive reinvasion. The emergence of water hyacinth stands after the first control phase also suggests that small plants and stands could have been overlooked, hidden in the riverside vegetation (Brundu et al. 2012; García-de-Lomas et al. 2021). The emergence of “fugitive” stands (even in places already reviewed in previous weeks or months) may come from poorly checked areas from where it was later dispersed by the wind. This fact demonstrates the need to increase the frequency of water hyacinth searches by boat, preferably during periods of active growth (temperatures  $> 8\text{ }^{\circ}\text{C}$ ; Wilson et al. 2005), to prevent reinvasion (Osmond and Petroeschovsky 2013).

Most of the effort and cost invested (83%) related to monitoring and follow-up treatments. In terms of yield per unit effort, monitoring seems relatively inefficient compared to the initial control phase. However, rapid response and monitoring reduced the absolute costs related to controlling extensive, higher density invasions of water hyacinth (see below). In the absence of periodic follow-up treatments, the area would be reinvaded. Using ratios such as the yield per unit effort, cost/biomass or cost/surface can be useful to assess the performance of a management action (compared to similar actions) but is less suitable to assess the management effectiveness. Such ratios may vary depending on the size of the invaded area, plant density, the spatial aggregation pattern, accessibility, or the specific target (e.g., eradication or containment). For example, Peña-Bretón and de la Cruz (2014) reported €6.45/kg for a sparse water hyacinth invasion and €0.39/kg for a highly aggregated pattern in eastern Spain. In addition, the cost/biomass ratios for manual removal are much higher than the ratios obtained by using heavy machinery, e.g., €0.026/kg–€0033/kg in a Sardinian river and the Guadiana river, respectively (Brundu et al. 2013; MITECO, <https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-camalote-est%C3%A1-controlado-en-todos-los-tramos-del-r%C3%ADo-guadiana/tcm:30-520159>). Whatever the €/kg ratio, water hyacinth reinvasion will continue since it must be taken into account that, in most cases, there will be a long-lived seed bank.

Past experience with water hyacinth management demonstrates the importance of rapid response actions. A rough economic analysis supports this claim. Considering the local environmental conditions ( $\text{NO}_3^- > 10\text{ mg/L}$ , mean temperatures ranging from 21–28 °C between May and September, salinity = 1 g/L), a growth rate of ca.  $0.06\text{ g g}^{-1}\text{ day}^{-1}$  could have been expected (Wilson et al. 2005). Therefore, with the initial plant density of  $0.0015\text{ kg/m}^2$  found in the area, the growth model reported by Wilson et al. (2005) suggests that if the action was delayed for four months (i.e., start removal after the summer), the density of water hyacinth and the total biomass would have been ca. 50 times greater (i.e., up to 80 tons). Consequently, and given the impossibility of using heavy machinery, a commensurate

increase in management costs (from €22,500 to €1,125,000) could have been expected. This delay would also have provoked massive blooming, increasing the risk of spreading to the adjacent estuary and associated impacts on navigation. The total cost of the rapid-response action here reported is much lower than the costs required to manage large water hyacinth invasions. For instance, in Louisiana (USA), ca. \$124 million (€108 million) was spent on water hyacinth control between 1975–2013, affecting 16,600 ha. In Spain, ca €50 million was spent between 2004–2020 in the Guadiana river, where water hyacinth initially covered ca. 200 ha, but then expanded over a length of 185 km along the river (total perimeter affected = 630 km) (MITECO, <https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-camalote-est%C3%A1-controlado-en-todos-los-tramos-del-r%C3%ADo-guadiana/tcm:30-520159>). Therefore, whenever possible from an administrative and technical viewpoint, rapid-response actions and continued follow-up treatments are much more cost-effective than managing advanced water hyacinth invasions (Wainger et al. 2018).

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### Authors’ contribution

JGL, ED: research conceptualization, data analysis and interpretation, writing – original draft; JGL, JB and JMM: data collection, sampling design and methodology; JY, AC, JMB, FJC and CR-H: sample design and methodology, data collection, funding provision and writing – review; FV: writing – review and editing, funding provision and ethics approval.

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### Supplementary material

The following supplementary material is available for this article:

**Appendix 1.** Wind roses.