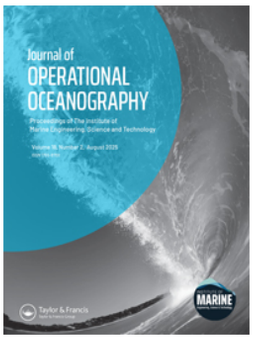

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# Effect of extreme rainfall events in the Mar Menor lagoon (SE, Spain): The use of a Smartbuoy for environmental monitoring

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**ABSTRACT**

Extreme climate events, now more frequent, are defined by the IPCC as occurrences outside typical weather ranges. Extreme rainfall, for instance, can lead to excessive freshwater inflow into saltwater environments, disrupting ecosystems like coastal lagoons. The Mar Menor lagoon in Spain faces issues like eutrophication and habitat loss due to changing water conditions. Monitoring water quality is crucial for managing these risks. While traditional sampling methods are valuable, real-time data from buoys enables quicker responses. This study focuses on data from sampling stations and a smartbuoy in the Mar Menor lagoon following rainfall events on October 6th and 10th, 2022. The goal was to assess how long the ecosystem took to recover. Results showed that the southern part of the lagoon had a delayed recovery compared to the northern region, with significant impacts on salinity, turbidity, and oxygen levels. Immediately after the rainfall, lower surface salinity was observed in the southern lagoon due to freshwater influx, while the northern region remained stable. Freshwater also affected bottom salinity along the western shore. By October 19th, salinity in the lagoon's center had increased but had not returned to pre-rainfall levels, with lower salinity still present in the southern region. Turbidity also increased along the western and southern shores due to runoff carrying nutrients and sediments, potentially disrupting local ecosystems. The continuous data from the smartbuoy offered detailed insights into hydrological changes, salinity, turbidity, and oxygen variations. This real-time data is essential for effective environmental management and conservation efforts in the lagoon ecosystem.

**ARTICLE HISTORY**
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## 1. Introduction

There is now strong scientific consensus that increased greenhouse gas emissions from human activities have led to changes in land and ocean temperatures (Ermolina et al. 2021), wind (Martinez and Iglesias 2024), and ocean currents (Harley et al. 2006; Doney et al. 2012). These changes impact the entire planet's geochemical cycle, creating more imbalances that negatively influence urban areas as well as ecosystems all over the world (Jacobs et al. 2021; Abbass et al. 2022; Akpuokwe et al. 2024; Vlasceanu et al. 2024). Impacts such as the spread of disease outbreaks (De Souza and Weaver 2024), decreased availability of food crops (Lee et al. 2024), and more extreme climatic events (Kreibich et al. 2022) have emerged worldwide.

Extreme climatic events are, according to the IPCC (2012):

> The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes'. (IPCC 2012)

Although extreme climatic events are (or used to be) considered rare in frequency, and there isn't enough historical data to allow for proper assessment of some kinds of events (e.g. droughts), observations from 1950 until now indicate a significant increase in extreme rainfall events in some global regions (IPCC 2012). An increase in global temperature of 2°C could double the damage done by floods worldwide (Kreibich et al. 2022).

That, combined with the increase in urbanisation rates in territories all around the world (Lin et al. 2020), leads to even higher intensification of rainfall due to microclimate changes in urban areas (IPCC 2023), further causing damage to the social, economic, and public health sectors (Guan et al. 2022).

In the case of extreme rainfall and floods, depending on the region, it is predicted that they promote an exacerbated

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freshwater inflow into saltwater environments. This higher freshwater discharge can influence physical aspects within the saltwater system, causing impacts on fauna and flora, and potentially affecting the survival of the whole ecosystem (Gillanders and Kingsford 2002).

Of all ecosystems subject to freshwater inflow, coastal lagoons are among the most susceptible to changes in the water column (Machado Toffolo et al. 2022). While being highly productive, they survive on a fragile equilibrium that is deeply influenced by climate change and urbanisation (Meredith et al. 2022). Due to their fragile nature, impacts such as habitat damage from eutrophication episodes, creating a state of hypoxia that in time leads to species depletion like seagrasses and macroalgae are not uncommon (Newton et al. 2014; Jones et al. 2018; Pérez-Ruzafa et al. 2019; Erostate et al. 2020, 2022; Machado Toffolo et al. 2022). These impacts can be prompted by high freshwater inflow from the water catchment area, which can be exacerbated by floods, diluting saltwater and thus creating variations in physical parameters throughout the water column (Pérez-Ruzafa et al. 2007; Sassi and Hoitink 2013; Honfo et al. 2024). This is exemplified by the Mar Menor, a highly productive shallow saltwater lagoon in the southeast of Spain, connected on one side to the Mediterranean Sea and presenting high mean temperatures (30°C), high salinity (43) and low precipitation (300 mm $year^{-1}$) (Pérez-Ruzafa et al. 2005a, 2005b, 2019; Ghezzo et al. 2015; Erena et al. 2019).

It is important to monitor an ecosystem to detect variations in environmental parameters and develop suggestions for the management of the territory whenever possible, but periodic sample monitoring is not sufficient anymore to respond to rapid changes when considering risk and environmental management. Hence, continuous monitoring is necessary (Trevathan and Johnstone 2018; Shukla et al. 2023). For that purpose, buoys present a valuable alternative, using multiple sensors to collect physicochemical as well as biological data in real-time for swift and reliable collection (Mills et al. 2003).

This study analysed data collected by the Smartbuoy, which has been active for 32 months. During this period, we selected 16 days between the 4th and 19th of October, 2022, during which 2 rainfall events occurred (6th and 10th of October). During this period, data from the Smartbuoy was verified with data collected from 11 sampling stations collected directly from the lagoon on 3 days over the same 16-day period (4th, 10th, and 19th of October). The goals were to ascertain whether the use of a Smartbuoy that collects continuous and quality data may contribute to understanding the lagoon's processes; to understand how parameters change according to meteorological events and how long it takes for the lagoon to reach homeostasis again; to support informing regional authorities on how to potentially proceed in management actions around the Mar Menor territory.

## 2. Methods

In order to acquire data on the amount of precipitation during both rainfall events, we utilised the Sistema de Información Agrario de Murcia (SIAM) database (Figure 1(a), available at: http://siam.imida.es/apex/f?p = http://101:41:2607332544415356).

Regarding environmental parameters, we then utilised data from 2 databases. The first set of data came from the SMARTLAGOON project's Smartbuoy (Figure 1(b), available at: https://www.wwt-platform.com/bgis/4926e69c-9ab2-41d0-926d-de905bbee8c9), which captures live data at 5 min-increments and sends it directly to the project's website server and can be accessed online. The Smartbuoy obtained measures of wind, depth, temperature, salinity, oxygen ($O_2$) concentration (later converted into $O_2$ saturation in %), and turbidity from the EE181temperature and humidity probe, 03101 wind Sentry anemometer, SeaBird ECO Dual Channel Fluorometer, and Aanderaa Oxygen Sensors.

The second set of data was obtained from the IMIDA (Murcian Institute of Agricultural Research & Development) field team, which since 2016 surveyed 11 different points covering all areas of the Mar Menor (Figure 1(b)). Values were obtained with the SBE 19plus CTD (Sea-Bird Electronics, WA, USA), equipped with additional sensors for oxygen and turbidity.

All 12 sampling stations were utilised for surface and bottom maps for the parameters temperature, salinity, turbidity, and $O_2$ concentration. Rainfall data was obtained from 7 stations covering the lagoon's catchment area (Figure 1(a)). Hourly precipitation values for each of the stations, reported in the SIAM database, were used to calculate the amount of rainfall during 6th and 10th October, 2022.

The parameters were elaborated using the Ocean Data View (ODV) [22] software. We analysed the distribution of parameter rates from hourly measurements from October 4th to October 19$^{th}$ as well as on the bottom and surface of the lagoon on 3 dates: October 4th, two days before the first event of October 6th, October 10th, right before the second event, and October 19th, 9 days after the second event of October 10th, to identify the changes in the lagoon following rainfall events.

## 3. Results

On October 6th, there was a rainfall rate of 237.8 mm, from 01:00 to 16:00, concentrated mostly between the

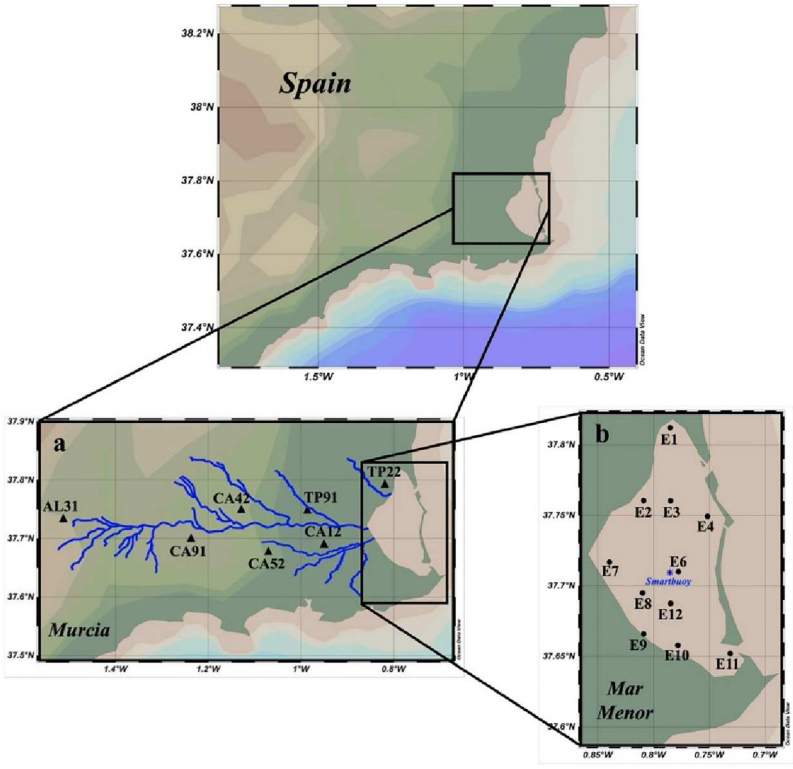


**Figure 1.** (a) Location of the Mar Menor rainfall data stations along the Rambla del Albujón basin (adapted from (Alcolea et al. 2019; Machado Toffolo et al. 2022). Stations: AL31: Lebor, Totana; CA12: La Palma, Cartagena; CA42: Balsapintada, Fuente Alamo; CA52: La Aljorra, Cartagena; CA91: Campillo Abajo, Fuente Alamo; TP22: Santiago de la Ribera, San Javier; TP91: Torre Pacheco, Torre Pacheco. b) Location of sampling stations within the lagoon territory and Smartbuoy (adapted from (Machado Toffolo et al. 2022)).

hours of 07:00 and 11:00 (Figure 2). October 10th saw a lower amount of rainfall, with 77.6 mm spread between 14:00 and 19:00, with the highest amount of rainfall at 17:00 (Figure 2).

Results from the Smartbuoy data show temperature ranged from 22°C to 24.5°C between the 4th and the 19th of October (Figure 3), with the lowest temperatures recorded on October 13$^{th}$, and the highest recorded on October 7th, 8th, and 10th. Temperature variations mostly coincide with day and night periods, and a slight decrease in temperature was observed following the October 6th and 10th rainfall.

Regarding the data from the sampling stations, on October 4th, the surface of the lagoon registered temperatures from 23.2°C to 23.6°C (Figure 4(a)). The bottom of the lagoon registered temperatures from 23.2°C to 23.9°C (Figure 4(b)). On October 10$^{th}$, 3 days after the first rainfall event, the surface of the lagoon registered temperatures from 22.6°C to 23.6°C (Figure 4(c)). The bottom of the lagoon registered temperatures from 23°C to 23.5°C (Figure 4(d)). On October 19$^{th}$, several days after both rainfall events, the surface of the lagoon registered the same temperatures of 23.2°C to 23.6°C (Figure 4(e)). The bottom of the lagoon registered temperatures from 23.3°C to 23.6°C (Figure 4(f)).

The Smartbuoy showed salinity rates decreased following the October 6th rainfall (42.5 to 41psu, Figure 5), increasing again in the following days, but not decreasing after the October 11$^{th}$ rainfall (42 to 41 psu). Higher salinity rates were observed at the 3 m range and lower rates at the surface and bottom (Figure 5). Salinity variations were observed to correspond to high and low tides during the period (Figure 5).

Regarding the data from the sampling stations, on October 4th, Salinity ranged from 42.6 psu to 43.4 psu, with higher rates around the centre and north of the lagoon, and lower around the southern and eastern shores (Figure 6(a)). On the bottom, Salinity showed a peak of 43.5 psu, with lower values (42.7 psu) observed around the southern shore of the lagoon (Figure 6(b)). On October 10th, Salinity ranged from 40.5 to 43.2 psu, with higher rates around the centre and north of the lagoon (42–43 psu), and lower around the western and southern shores (42–41 psu, Figure 6(c)). On the bottom, Salinity showed a peak of 43 psu, with lower values (41.5–42 psu) observed around the western and southern shores (Figure 6(d)). On October 19th, Salinity rates peaked at 42.6 psu, with higher rates in the centre and northern parts of the lagoon, and lower rates in the southern parts of the lagoon and at the eastern shore (Figure 6(e)). Salinity ranged from 42.6 to 42.7 psu in the

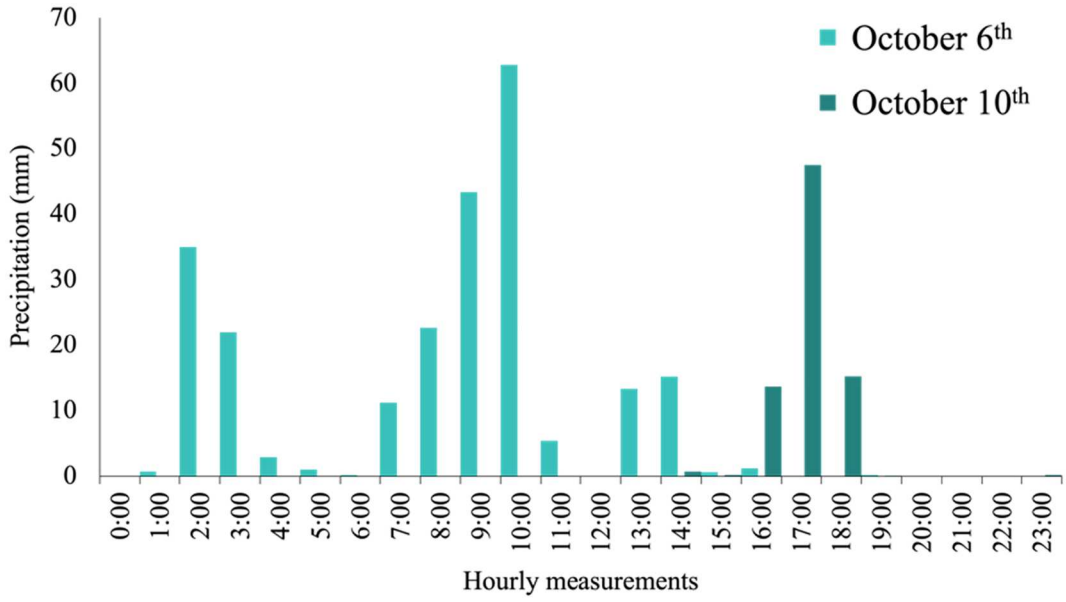


**Figure 2.** Precipitation values observed throughout the 7 stations during October 6th (237.8 mm) and October 10th (77.6 mm), 2022 (315.4 mm in total).

northern part of the lagoon, and from 41.9 to 42.3 psu in the southern part of the lagoon (Figure 6(f)).

The Smartbuoy showed that turbidity rates peaked following the 6th October rainfall (5 NTU), decreasing rapidly in the following days (1.5 NTU), and turbidity did not increase during the October 11th rainfall (Figure 7).

Results from the sampling stations showed that on October 4th, Turbidity showed low rates (0–3.5 NTU) throughout the lagoon, with higher rates (3.5 NTU) around the connection of the Mar Menor to the Rambla del Albujón watershed (Figure 8(a)). Turbidity showed low rates (0–3 NTU) throughout the lagoon, with higher rates (4–7 NTU) around the Rambla del Albujón (Figure 8(b)). On October 10th, turbidity showed low rates (0–1.5 NTU) throughout the eastern part of lagoon, with higher rates (2–5 NTU) on the southern and western part of the lagoon, peaking at the Rambla del Albujón entrance (Figure 8(c)). On the bottom, turbidity showed low rates (1–2 NTU) throughout the eastern part of the lagoon, with higher rates (3.5–12 NTU) around the Rambla del Albujón (Figure 8(d)). On October 19th, turbidity showed low rates (0–0.5 NTU) throughout the eastern part of lagoon, with higher rates (1.5–4 NTU) on the western part of the lagoon (Figure 8(e)). On the bottom, tremained low throughout the lagoon (0–2 NTU), with a 5 NTU peak at the Rambla del Albujón entrance (Figure 8(f)).

The Smarbuoy data showed that $O_2$ saturation rates decreased following the October 6th rainfall (under

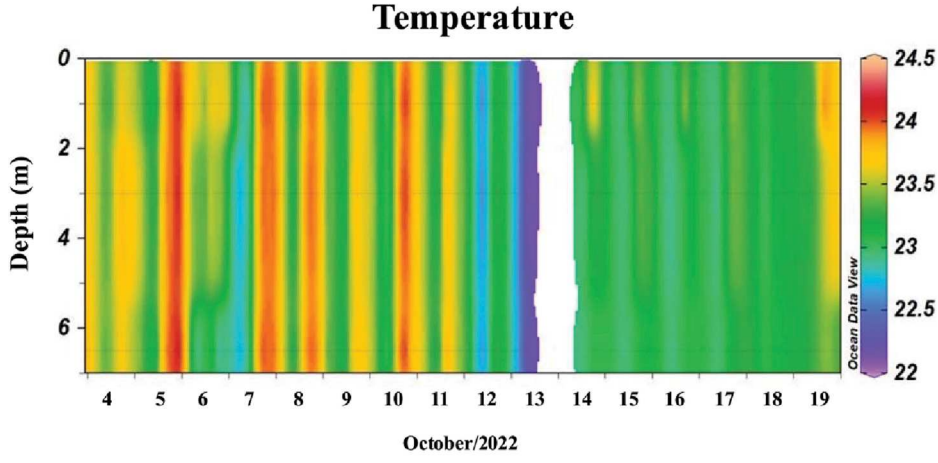


**Figure 3.** Temporal distribution of temperature (°C) recorded by the Smartbuoy in the water column (0–6 m). Blank spaces are from defective data and therefore not considered.

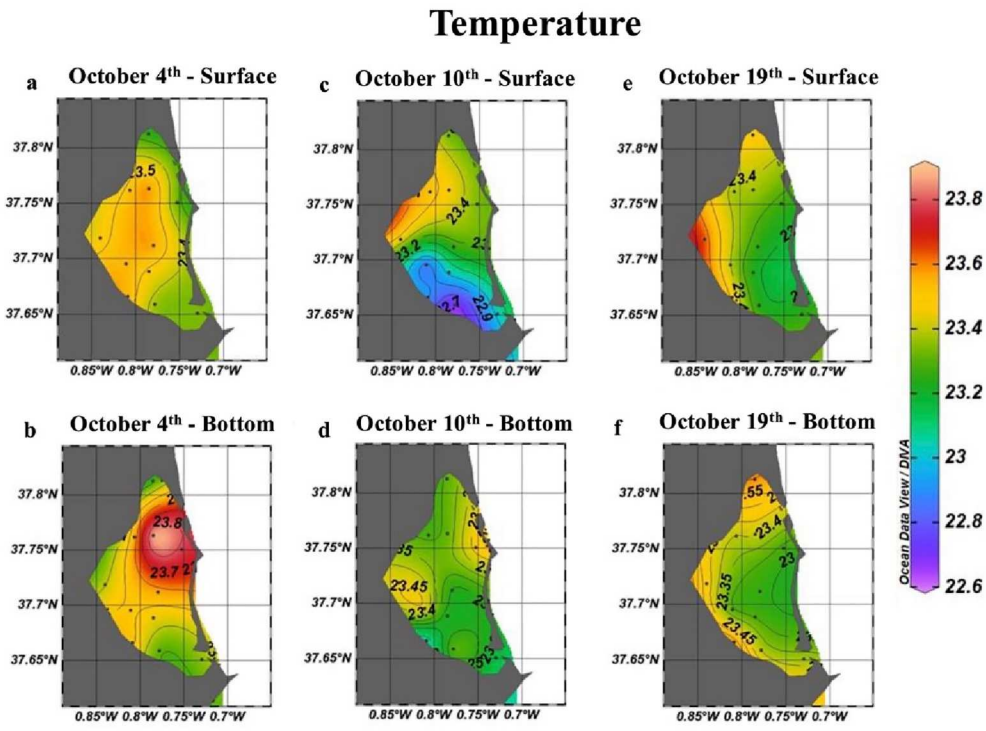


**Figure 4.** Horizontal distribution of surface (a, b, c) and bottom (d, e, f) temperature (°C) for the 3 sampling days: October 4th, October 10th and October 19th, 2022.

100%), peaking during the October 11th rainfall (175%), and decreasing on the following days (under 125%), with variations correspondent to day and night periods (Figure 9).

Results from the sampling stations showed that on October 4th, $O_2$ saturation ranged from 95 to 135%, with higher saturation rates coming from the centre of the lagoon and peaking around the El Ventorillo canal (Figure 10(a)). On the bottom, $O_2$ saturation showed higher values (135–140%) in the centre of the lagoon, with lower values (115–120%) being observed in both southern and northern regions (Figure 10(b)). On October 10th, $O_2$ saturation ranged from 110 to 145%, peaking at the south of the lagoon, with higher rates around the northern part (Figure 10(c)). On the bottom, $O_2$ saturation peaked (140%) in the north of the lagoon, with lower values (130–110%) in the western and southern parts (Figure 10(d)). On October 19th, $O_2$ saturation ranged from 100% to 135%, peaking in the south of the lagoon, with lower rates on the shores and higher in the centre (Figure 10(e)). On the bottom, $O_2$ saturation peaked at 145% in the centre of the lagoon, with rates from 105 to 135 around the lagoon area (Figure 10(f)).

## 4. Discussion and conclusions

The October 19th figures show the southern part of the lagoon had not yet reprised hydrological conditions from before the rainfall events of the 6th and 10th of October, while the northern part was less influenced. The results indicate that the rainfall entering the lagoon had an impact on salinity, turbidity, and $O_2$ saturation.

Lower salinity rates were observed on the lagoon's surface, in the southern region, right after October 6th, which is to be expected as there was a higher inflow of freshwater into the lagoon. Meanwhile, the northern part remained fairly unchanged, following the lagoon's current distribution patterns (Figure 11). The freshwater inflow changed the salinity also at the bottom along the western shore of the lagoon, while the rest of the bottom remained unaffected. This can be explained by the speed of freshwater inflow (Pérez-Martín 2023), which together with the lagoon's current patterns, distributed freshwater within the water column, decreasing salinity rates from surface to bottom. In 1975, the lagoon's overall salinity decreased from 50 to 42–46 psu due to the opening of a channel with the Mediterranean Sea to facilitate the transit of recreational boats, changing numbers of native populations and allowing Mediterranean species to enter the lagoon (Álvarez-Rogel et al. 2020). In addition to freshwater inflow, other physical processes such as direct precipitation, evaporation, and water depth variations may have contributed to the observed salinity patterns (Mosley et al. 2023). Direct rainfall over the lagoon surface can reduce salinity, especially in shallow areas where

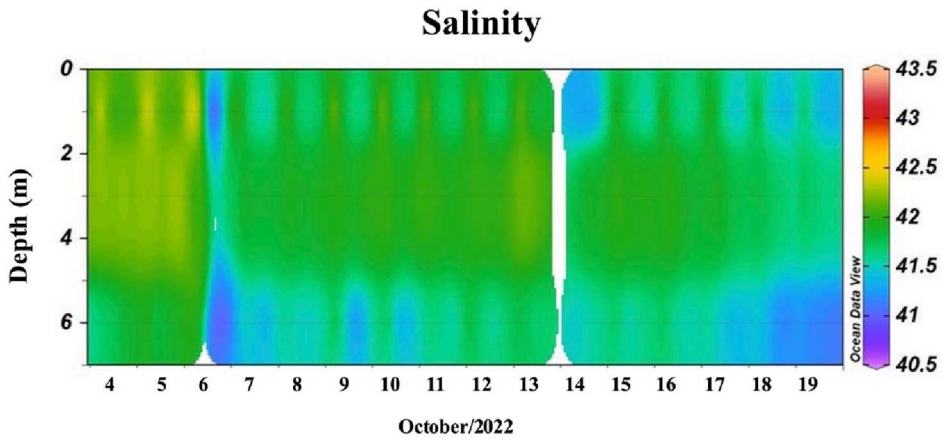


**Figure 5.** Temporal distribution of salinity recorded by the Smartbuoy in the water column (0–6 m). Blank spaces are from defective data and therefore not considered.

dilution effects are more pronounced. Conversely, evaporation, which is significant in the Mar Menor due to its semi-arid Mediterranean climate, acts to increase salinity, particularly in periods following precipitation events when skies clear and solar radiation increases (Pérez-Ruzafa et al. 2005b; Umgiesser et al. 2014; Pérez-Ruzafa et al. 2019). Furthermore, shallow areas of the lagoon are more sensitive to these processes due to their reduced water volume, while deeper areas respond more gradually (Meredith et al. 2022). These factors, combined with wind-driven mixing and limited tidal exchange, shape the spatial and temporal variability of salinity and temperature across the lagoon (Fabião et al. 2016).

Regarding the temporal salinity distribution (Figure 5) and horizontal surface salinity distribution (Figure 6) observed on October 19th, there was an increase in salinity at the centre of the lagoon, although it had not yet returned to pre-rainfall rates, while the southern part of the lagoon remained still low in salinity. A

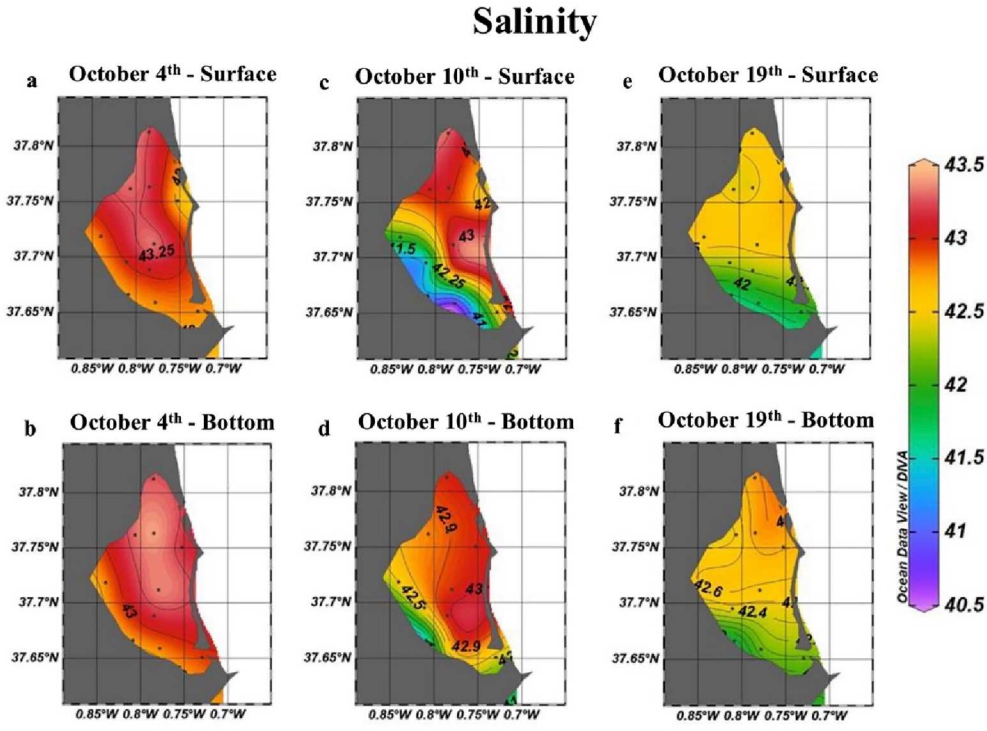


**Figure 6.** Horizontal distribution of surface (a, b, c) and bottom (d, e, f) salinity for the 3 sampling days: October 4th, October 10th, and October 19th, 2022.

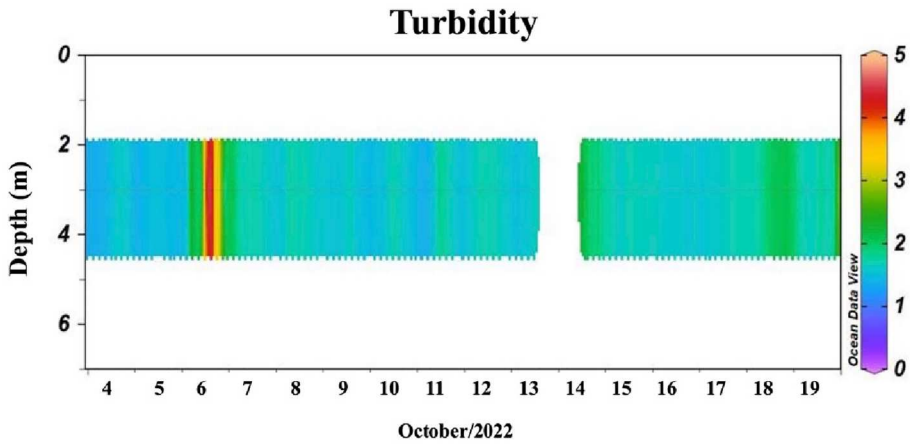


**Figure 7.** Temporal distribution of turbidity (NTU) recorded by the Smartbuoy. Turbidity values were obtained for the 3 m range. Blank spaces are from defective data and therefore not considered.

similar pattern was observed at the bottom of the lagoon, with higher salinity rates in the centre and northern parts of the lagoon, and lower rates in the southern parts, indicating that the freshwater from the rainfall events was still present. This could be explained by the increase in aquifer recharge, brought on by the escalation in irrigation from agriculture, enhancing groundwater discharge that transformed ephemeral water courses, the so-called *ramblas,* into permanent ones that flow directly into the lagoon (Figure 1; Álvarez-Rogel et al. 2020). While surface freshwater inflow can vary salinity values throughout the lagoon, previous studies suggest that brackish water present in the aquifers can help maintain lower salinity rates at the bottom of the lagoon even long after rainfall events (Domingo-Pinillos et al. 2018; Álvarez-Rogel et al. 2020; Tragsatec 2020).

Following rainfall, higher turbidity rates were observed along the western and southern shores of the lagoon (Figures 7 and 8), as runoff from the Rambla de Albujón carried nutrients, sediment, and particulate organic matter from the whole catchment (Pérez-Martín 2023). Bottom turbidity results indicate that sediments remained in the water column close to the Rambla del Albujón but were not widely distributed by the currents in the whole lagoon, instead settling along the western shore of the lagoon. When this nitrate-rich groundwater discharges into the lagoon, it can stimulate the growth of phytoplankton and microbial communities due to the increased nutrient availability. Such primary producer proliferation may lead to the release of organic matter and the aggregation of particulate material, both of which contribute to increased turbidity levels (Álvarez-Rogel et al. 2020). Given that high turbidity rates disrupt photosynthetic potential and create impacts on benthic macrophytes (Ruiz-Fernández et al. 2022), this might cause damage to the local organism communities, in addition to pollution from inorganic and organic compounds. Recent studies have demonstrated that microbial communities in the lagoon and ICOLL systems are highly sensitive to stormwater and sewage inflows following rainfall events, which can alter bacterial assemblages more strongly than natural physicochemical parameters alone. For example, Williams et al. (2025) reported that faecal contamination, rather than variables such as salinity or temperature, was the primary driver of shifts in bacterial community structure in intermittently open lagoons during high rainfall events, leading to increased abundance of potential pathogens and antibiotic resistance genes (ARGs). In Venice Lagoon (Italy), sewage-associated and faecal bacteria were found to significantly contribute (up to 6% of total microbial populations) especially in particle-attached fractions near urban centres after rainfall, emphasising the strong influence of urban runoff on microbial community composition (Basili et al. 2022). Similarly, in an Ivorian lagoon, increased suspended particulate matter following rainfall events was strongly correlated with increased concentrations of enteroviruses and organic load, demonstrating the role of runoff in enhancing viral persistence and microbial contamination in lagoon environments (Momou et al. 2017). In Yundang Lagoon (China), an extreme precipitation event (132 mm) caused a dramatic rise in ARGs and mobile genetic elements, largely originating from wastewater treatment plant discharges and combined sewer overflows. These contaminant levels peaked one day after the storm and remained elevated for several days, highlighting the role of stormwater as a vector for microbial pollutants and ARG loading (Hou et al. 2022). Such alterations in microbial community structure, combined with sediment resuspension and nutrient loading, likely contribute to ecosystem stress and pose potential health risks for both aquatic organisms

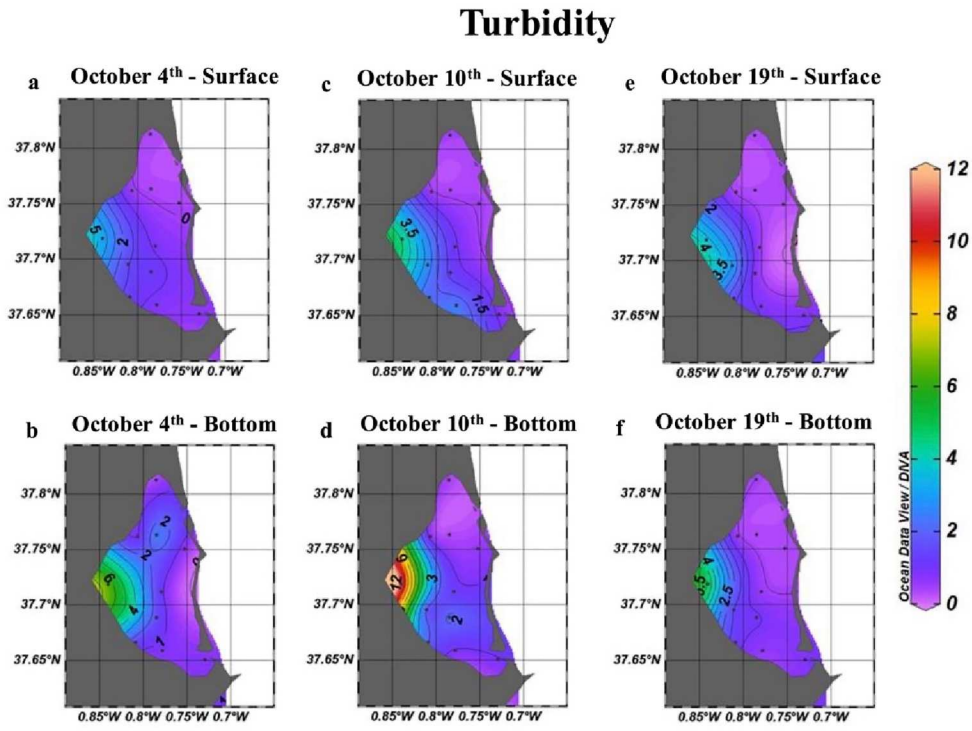


**Figure 8.** Horizontal distribution of surface (a, b, c) and bottom (d, e, f) turbidity (NTU) for the 3 sampling days: October 4th, October 10th, and October 19th, 2022.

and human users of these coastal systems. Even 10 days after rainfall events, turbidity rates remained high close to the Rambla, although decreased at the bottom (Figure 8), indicating no significant redistribution of sediments and associated microbial communities, which could further impact the local benthic and pelagic community.

Nutrient inflow (30–45 mg/L N-$NO_3^-$closer to the coastal area) (Álvarez-Rogel et al. 2020) could also explain the increase in $O_2$ saturation rates following the October 6th rainfall event, particularly near the Rambla and in the northern and southern parts of the lagoon. The influx of nutrient-rich freshwater following the rainfall events likely stimulated increased primary productivity, particularly among phytoplankton and benthic macrophytes, leading to elevated oxygen production through photosynthesis (Álvarez-Rogel et al. 2020). Although a decrease in surface oxygen saturation was observed by October 19th, values remained high both at the surface and bottom of the lagoon, especially in the centre area with reduced water circulation where

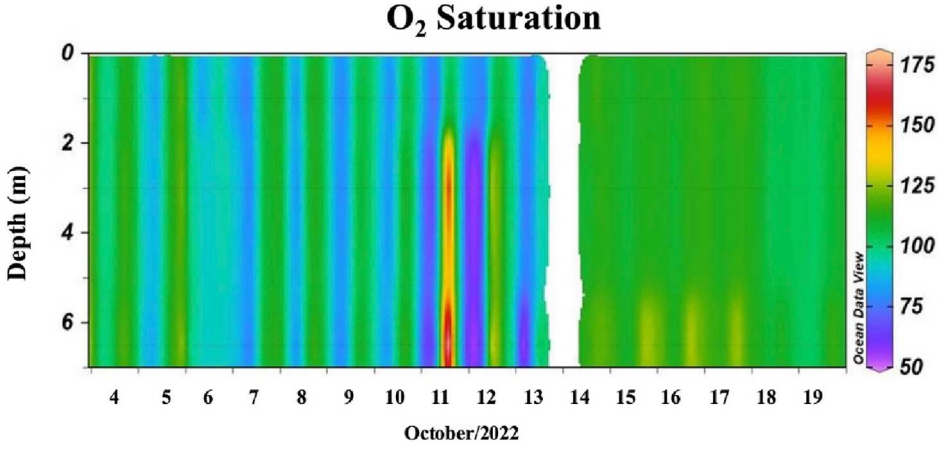


**Figure 9.** Temporal distribution of $O_2$ saturation (%) recorded by the Smartbuoy in the water column (0–6 m). Blank spaces are from defective data and therefore not considered.

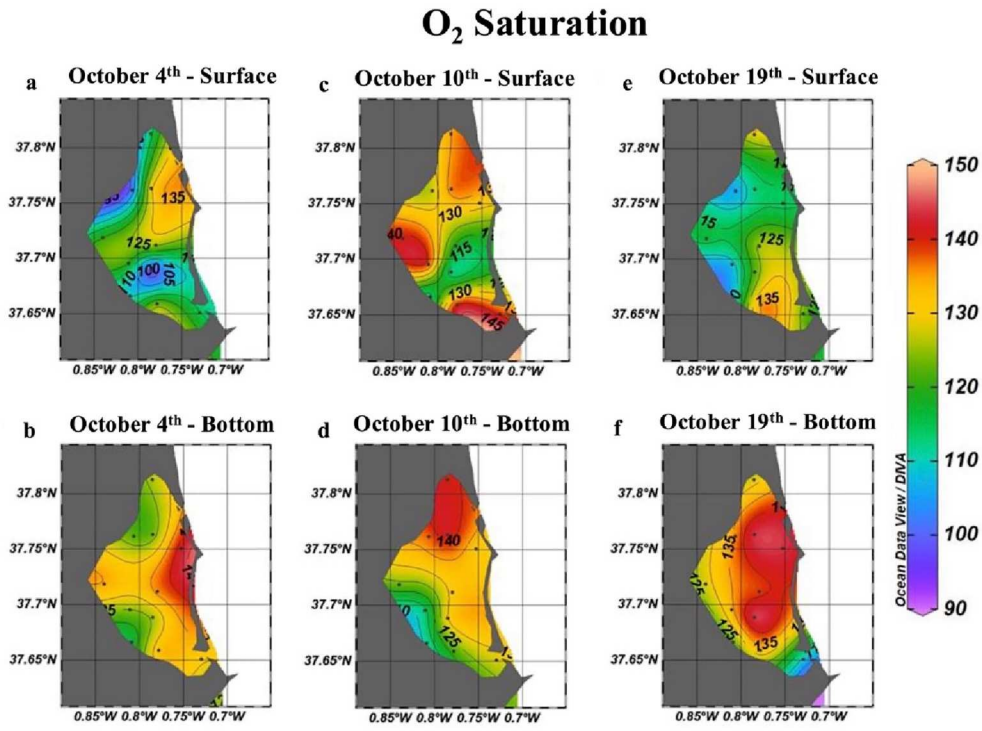


**Figure 10.** Horizontal distribution of surface (a, b, c) and bottom (d, e, f) $O_2$ saturation (%) for the 3 sampling days: October 4th, October 10th, and October 19th, 2022.

there was less water mixing (Machado Toffolo et al. 2022). This suggests that the system had not yet returned to equilibrium. Elevated oxygen saturation levels may have been sustained in part by photosynthetic activity from submerged macrophyte communities, which are known to influence oxygen dynamics in shallow ecosystems (Antunes et al. 2012).

Besides the environmental parameters analysed in this study, the discharge of nutrient-rich freshwater into the Mar Menor lagoon can also have consequences that extend beyond immediate physical changes. Runoff from the surrounding basin can also transport a variety of pollutants such as pesticides, heavy metals, and polycyclic aromatic hydrocarbons (PAHs). These substances can accumulate in the sediment or in benthic organisms (Marín-Guirao et al. 2005; Marini and Frapiccini 2014; Moreno-González and León 2017), causing damage at cellular and tissue levels (Tchounwou et al. 2012), impairing physiological processes such as photosynthesis (Fulke et al. 2024), and potentially biomagnifying through trophic networks with implications for human health (Pérez-Ruzafa et al. 2000; Han et al. 2022). Furthermore, the freshwater inflow can also carry faecal matter from urban wastewater, inserting microbial pollution into the ecosystem, that can survive for up to 72 h (Romei et al. 2021; Manini et al. 2022; Penna et al. 2023). In heavy rainfall conditions, this contamination can persist for extended periods in lagoons, as they are enclosed regions with low water exchange (Pascual-Benito et al. 2020; Johnston et al. 2024; Williams et al. 2025). These conditions compromise bathing water quality, suspend fishing efforts, and interrupt touristic activities, affecting aspects like public health and hindering the local economy (Romei et al. 2021; Penna et al. 2023).

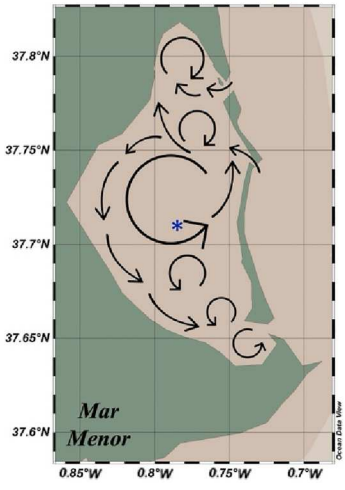


**Figure 11.** Current patterns around the lagoon and from the Mediterranean Sea and Smartbuoy position. Adapted from Machado Toffolo et al. (2022).

While the surface and bottom maps provided valuable snapshots of specific moments before, during, and after the October rainfall events, the continuous

data collected by the Smartbuoy offered a more nuanced view of the lagoon ecosystem throughout that period, allowing for the observation of subtle changes in various hydrologic parameters, contributing to a more comprehensive understanding of how the lagoon's properties behave over time. It was possible to observe how salinity distributes and fluctuates through the water column, indicative of the flow exchange between the Mar Menor and the Mediterranean Sea, with constant salinity found over the 3 m range due to the gyre circulation in this central area of the lagoon (Figure 11). We could also pinpoint the time of the rainfall event of October 6$^{th}$ due to the extreme increase in turbidity, with subsequent recovery and stabilisation of turbidity rates. Finally, we observed the changes in $O_2$ saturation, correspondent to the periods of day and night; higher rates correspond to the day period, where there is light and consequently photosynthesis, whereas during the night there is no $O_2$ production but consumption, resulting in the decrease of $O_2$ saturation rates. This type of data is extremely useful when planning for or adapting to environmental changes, enabling researchers and decision-makers to make informed decisions that align with the dynamic nature of the ecosystem. Additional data points could improve representation of the conditions and behaviour of the lagoon, thus improving the evaluations of lagoon processes and promoting improvement interventions for the management of the territory.

Extreme rainfall events can have profound impacts on coastal lagoons, leading to immediate disruptive effects that require extended periods for the ecosystem to reach homeostasis again (Dittmann et al. 2015). Although different organisms adapt to the conditions of aquatic ecosystems, extreme variations in salinity could alter the habitat conditions, creating stress for many aquatic species (Dittmann et al. 2015; Lam-Gordillo et al. 2022; Mosley et al. 2023). Increases in turbidity, caused by sediment runoff, along with elevated oxygen saturation levels, can further destabilise the ecosystem, leading to ecological imbalances that impact the entire biological community. When these changes persist for too long, they can lead to catastrophic consequences, such as the loss of biodiversity and the collapse of essential ecological processes. During extreme rainfall events, the influx of pollutants poses a significant threat to the survival of native organisms within coastal lagoons (León et al. 2017). Runoff can carry both organic contaminants, such as PAHs and pesticides (León et al. 2017), and inorganic pollutants, such as fertilisers and heavy metals (Álvarez-Rogel et al. 2006) which accumulate within the lagoon. This bioaccumulation disrupts essential ecological processes, negatively impacting the health of the biological community (Marín-Guirao et al. 2005). As these toxins move up the food chain, they significantly impact higher trophic levels, leading to declines in predator populations and contributing to further imbalances in the ecosystem (Martínez-Gómez et al. 2023).

This study highlights the complementary nature of high-frequency data from the Smartbuoy and the discrete, spatially resolved data obtained through traditional sampling methods. While traditional monitoring provides valuable insights into the spatial heterogeneity of the lagoon, its lower temporal resolution may overlook short-term fluctuations driven by transient events such as rainfall.

In contrast, the Smartbuoy continuously captures variations in key physicochemical parameters such as salinity, temperature, turbidity, and dissolved oxygen at high temporal resolution. This real-time monitoring capability was crucial in detecting the rapid changes occurring immediately after rainfall events, including sudden freshwater inputs and associated shifts in oxygen saturation and turbidity, which could not have been fully resolved by conventional methods alone. For example, while traditional sampling revealed the spatial distribution of salinity changes across the lagoon, the Smartbuoy recorded the temporal dynamics of salinity recovery, indicating delayed normalisation in certain areas of the lagoon. By integrating both approaches, this study demonstrates that Smartbuoy data enhances the interpretative power of traditional methods, offering a more complete picture of the lagoon's response to environmental perturbations. This combination is particularly relevant for environmental management and early warning systems in coastal lagoons, where rapid changes can have significant ecological and socio-economic consequences.

The observations conducted in the lagoon through periodic monitoring at designated stations, alongside the deployment of a Smartbuoy that collects real-time data from throughout the water column, can significantly enhance the knowledge of the local population residing within the hydrographic basin and its surrounding areas. This knowledge may enhance awareness regarding the protection of the lagoon and encourage active participation in its conservation through the adoption of better practices within the territory.

To enhance the resilience of the Mar Menor and mitigate the impacts of extreme rainfall events based on the present study results, our findings indicate a need to better manage catchment runoff, in particular freshwater inflow entering the lagoon at different points, mainly the Rambla del Albujón. This is helpful to adopt

sustainable management strategies, such as tanks for the collection and storage of rainwater, helping in capturing rainwater that might otherwise enter the lagoon and disturb environmental parameters, sewage treatment plants for control and management of wastewater, urbanisation and tourism strategies to avoid overconsumption of resources, decrease in fertiliser use by agriculturists (Conesa and Jiménez-Cárceles 2007). Furthermore, conducting long-term monitoring of the ecosystem, and promoting interdisciplinary collaboration by making the data available to all stakeholder groups, such as the continuous data provided by the Smartbuoy, can aid in the creation of management strategies where policymakers and the general population can work together for a common goal, the conservation of the ecosystem and availability of natural resources. Additionally, more effective climate adaptation policies, like investing in regulations, incentives, and capacity building aimed at controlling the impact businesses and citizens have on natural resources, incentivising best practices for ecosystem conservation, and creating opportunities for awareness raising regarding environmental issues (Ulibarri et al. 2022), will be crucial for protecting the ecological functions and biodiversity of the lagoon system.

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