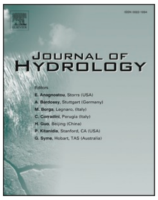
Journal of Hydrology 612 (2022) 128259

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Research papers

Effects of morphology and sediment permeability on coastal lagoons' hydrological patterns

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ARTICLE INFO

This manuscript was handled by Jiri Simunek, Editor-in-Chief, with the assistance of Jian Luo, Associate Editor

Keywords:
General Lake Model
Constructed coastal lagoons
Groundwater surface-water interaction
Lagoon morphometry
Lagoon water circulation
Salinity fluctuation

ABSTRACT

Mediterranean coastal lagoons are influenced from a wide variety of external factors such as surface and groundwater flows and climate dynamics. They are also vulnerable to human activities, which have caused a significant loss of these types of habitats. As a result, the EU habitat management have now prioritized restoration of natural wetlands. However, there is a lack of systemic studies on the mechanisms of coastal wetland degradation and ecohydrological processes that determine restored ecological functioning as an end goal, as well as a lack of reference sites to make comparisons. Furthermore, while lagoon morphometry and underlying sediment permeability have been studied extensively, combining these disciplines to evaluate lagoon hydrology and salinity dynamics is yet to be fully explored. The aim of this study was to analyze the hydrological dynamics of 4 newly constructed lagoons and compare them with 2 natural lagoons in the La Pletera salt marshes and evaluate the restoration and conservation efforts. We use the General Lake Model (GLM) to assess water volume fluctuations, salinity variability and lagoon water circulation (groundwater and surface water inflows, outflows and evaporation). We also combine data of the underlying lithological characteristics and lagoon morphometry, to compare and better understand the interplay of these parameters on the hydrological behavior of each lagoon. Results indicated that the older and natural lagoons exhibited more consistent patterns of confinement; with deeper morphologies, lower evaporation effect, lower water circulation, and more annual patterns of salinity fluctuation. The presence of low-permeability layers also resulted in less fluctuation of higher salinity levels. Conversely, three of the four new lagoons had similar, shallower morphologies and higher evaporation fluxes, but exhibited different water circulation patterns due to the presence or absence of low permeability layers. Also, their salinity fluctuations were more influenced by seasonal mixing than by evaporation, indicating more susceptibility to climatic influence in their annual hydrological pattern than in the natural lagoons. This could prove important when constructing and restoring lagoons according to predetermined morphology and underlying sediment patterns, as it could ultimately limit or enhance the success of set objectives and overall ecological functioning in a flooding – confinement driven lagoon ecosystem conditioned by irregular and unpredictable climatic events.

1. Introduction

Coastal lagoons are diverse in their geomorphological and hydrological characteristics and have a wide variety of influences from external factors such as freshwater and saltwater inputs, tidal regimes and climate dynamics (Basset et al., 2013; Guelorget and Perthuisot, 1983; Kennish and Paerl, 2010; Kjerfve, 1986; Pérez-Ruzafa et al., 2005; Nidzieko et al., 2014). Coastal lagoons within the Mediterranean region are influenced more by storm events than by tidal regimes and their surface connection to the sea and freshwater sources are limited for most of the year. These types of lagoon ecosystems (defined as confined coastal lagoons) are typically shallow (<5m), and their salinity regimes fluctuate significantly according to the amount of freshwater input, the climate, and the level of connectedness to the sea (Ridden and Adams, 2008; Trobajo et al., 2002; Tyler et al., 2001). Furthermore, these lagoons have also been described as surface representations of shallow

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https://doi.org/10.1016/j.jhydrol.2022.128259
Received 22 April 2022; Received in revised form 7 July 2022; Accepted 21 July 2022
Available online 28 July 2022

aquifers and only recently have groundwater processes been recognized as significant contributors to their hydrological behaviors and biogeochemical compositions (Casamitjana et al., 2019; Menció et al., 2017; Slomp and Van Cappellen, 2004; Windom et al., 2006). As a result, they are vulnerable to minor changes in catchment and groundwater hydrology (Chikita et al., 2015; Menció et al., 2017; Rodellas, et al., 2018; Sadat-Noori et al., 2016). Also, it has been shown that both freshwater inputs and morphological characteristics can control biological roles and determine the level of impact of confined lagoons (Basset et al., 2006; Cancela da Fonseca et al., 2001; Cañedo-Argüelles and Rieradevall, 2010; Félix et al., 2015). It is therefore important from a management perspective to understand the hydrology of these ecosystems, and to quantify the level of impact they may endure due to changes in surface and groundwater inputs.

While coastal wetlands and lagoons are well documented as being the most fluctuating and productive ecosystems in the world, it is also well documented that coastal wetlands are severely threatened due to climate change or shifts in land use (Cvetkovic and Chow-Fraser, 2011; Gabler et al., 2017; Newton et al., 2012; Wingard and Lorenz, 2014). In addition, coastal wetland deterioration can contribute to climate change due to reduced carbon storage capabilities (DeLaune and White, 2012). UNEP/MAP and Plan Bleu (2020) noted a 48 percent reduction in natural wetland habitats between 1970 and 2013 in the Mediterranean basin alone. Thus, the EU habitat management has prioritized restoration and recovery of the ecosystem services of these habitats, which is why projects such as Life Nature have awarded financial assistance for restoration purposes on some Mediterranean coastal lagoons (Quintana et al., 2018). While this is a great step in mitigating coastal lagoon degradation, aquatic habitat restoration can be challenging and ecological functioning as an end goal is not always fulfilled due to a lack of integrated understanding of the ecosystem being restored (Hobbs and Harris, 2001). Also, comparison of restoration efforts with other natural sites is not always possible, due to a lack of reference sites or pre-existing studies (Anton-Pardo et al., 2013). While the majority of wetland restoration projects usually focus on eutrophication control, vegetation restoration or water quality improvement, the mechanistic understanding of coastal wetland degradation and ecohydrological processes, especially large scale hydrological and biological connectivity, is still

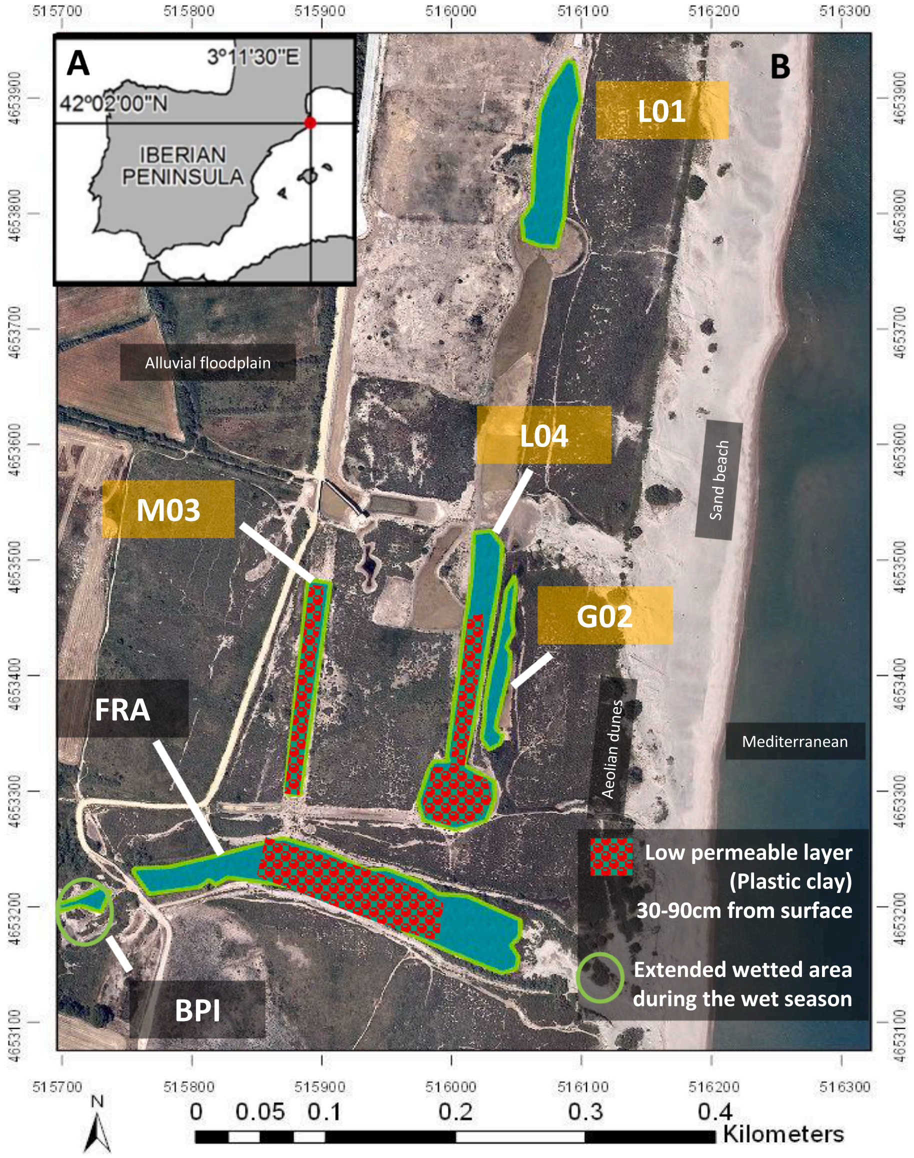

Fig. 1. (A) Geographic location of the La Pletera coastal lagoon system map of the study area with, (B) the six studied lagoons. Yellow labels indicate newer constructed lagoons (2016) and an older constructed lagoon (G02 in 2002), black labels indicate natural lagoons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not fully understood (Cui and Yang, 2006; Harttera and Ryan, 2010; Scheffer et al., 1993). In case of the flooding-confinement pattern of Mediterranean coastal lagoons, it has been shown that community structure dynamics are dependent on nutrient dynamics and the variability of water volume and salinity fluctuations (Gascón et al., 2005; Quintana et al., 2006). While lagoon morphometry and underlying sediment permeability have been studied extensively, combining these disciplines to evaluate lagoon hydrology and salinity dynamics is yet to be fully explored. Therefore, a multidisciplinary approach in understanding these ecohydrological processes will help to evaluate overall ecological functioning within these ecosystem types.

The La Pletera salt marshes is an example of a coastal wetland system affected by a failed urbanization project and was awarded financial assistance from the Life + project (http://lifepletera.com/es/life-pletera/), which aimed to restore this protected area and to recover its ecological functioning by dismantling unused urban features. Various studies were conducted to assess several structural and functional indicators of restoration of the salt marsh. Among these studies, two were focused on the salinity fluctuations and groundwater dependence of two natural lagoons (BPI and FRA) and one constructed lagoon (G02) in 2002 (see Menció et al. (2017) and Casamitjana et al. (2019)). In 2016, three new lagoons (L01, L04, and M03) were created under the second phase of the Life project, and they were constructed by excavating the sediment below sea level, while also considering the underlying sedimentary pattern to ensure the conservation of low-permeability layers present (GEOSERVEI, 2016). The aim was to facilitate higher salinity conditions by decreasing an efficient connection with the aquifer during periods of confinement, to increase favorable refuges for the endangered Iberian toothcarp fish (*Aphanius iberus*) (Alcaraz et al., 2008; Badosa et al., 2006). These conditions are important to reduce the competition of the invasive mosquitofish (*Gambusia holbrooki*), which is more adapted to freshwater flooding conditions and less salinity variability (Alcaraz & Garcia-Berthou, 2007; Rincón, 2002; Ruiz-Navarro et al., 2011).

The aim of this study was to analyze the overall hydrological dynamics of the new lagoons (including G02), along with their dependence on groundwater circulations, and compare them with natural lagoons, to assess the restoration efforts of increasing salinity fluctuations (higher salinity during the dry period) and ecological functioning. We used the one-dimensional General Lake Model (GLM) to assess water volume fluctuations, salinity variability, and lagoon water circulation (groundwater and surface water inflows, rainfall, outflows, and evaporation) to assess how the lagoons' hydrological behaviors and their dependence on groundwater and surface water fluxes contribute not only to their salinity fluctuations but their total water budgets. We also combine data of the underlying lithological characteristics and the overall morphometry of the natural and new lagoons, to better understand the interplay of such parameters on the hydrological behavior of each lagoon individually and in comparison with each other.

2. Site description

The study was carried out in the La Pletera salt marshes, which is located in the Baix Ter wetlands in the northeast of Catalunya (Fig. 1A) and south of the urban center of L'Estartit (Torroella de Montgrí, Girona). The climate is sub-humid Mediterranean, and has mean temperatures of 25 °C in summer and 10 °C in winter. The average rainfall is 590 mm/year, with the highest rainfall periods in spring (140 mm) and autumn (200 mm; Estartit meteorological station, 1966–2021 period; Pascual, 2021)). The La Pletera lagoon system consists of six permanent lagoons, two of which are natural (FRA and BPI, Fig. 1 B), which run perpendicular to the coastline, and are remnants of an abandoned river channel. The other 4 lagoons (G02, L01, L04, and M03, Fig. 1 B) were constructed and restored under two LIFE projects (2002 and 2016) and run parallel to the coastline behind an Aeolian dune system (Fig. 1B). A shallow subterranean plastic clay layer (30–90 cm in depth) is present in the SSW of the salt marshes (Fig. 1B; Table 1).

The underlying lithological characteristics of the lagoons were analyzed by GEOSERVEI in 2016. The presence of marsh silts predominates in the areas of the natural lagoons in layers above sea level, while the presence of alluvium and sands are more common in the new lagoons. BPI is the only lagoon with low-permeability clay layers above sea level. At sea level, the presence of a plastic clay layer becomes evident and extends across the central area of the FRA lagoon, the entire area of the M03 lagoon, and three-quarters of the area of the L04 lagoon; which then tapers away towards the north. The layer reaches a depth of around 90 cm below sea level, especially in FRA (Table 3 and Fig. 1C.). G02 does not show a record of a low-permeability layer. At a depth deeper than 1 m below sea level, permeable fine sands form the underlying base of the lagoon systems, except for FRA - which still shows the presence of the low-permeability plastic clay layer. Fine sands, however, predominate the deeper sediment profiles of all the lagoons.

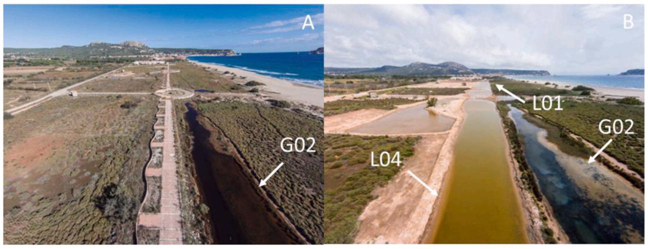

Fig. 2. Aerial view of the restored area in La Pletera (Baix Ter wetlands) before (A) and after (B) the restoration in 2016. G02 was constructed in 2002. Figure adapted from Quintana et al. (2018).

Table 1
Lithological characteristics of the La Pletera lagoons according to the geological survey conducted by GEOSERVEI in 2016. The relative permeability of the unconsolidated deposits are listed according to Lewis et al. (2006) and Freeze & Cherry (1979).

Height m.a.s.l.	BPI	FRA	G02	L04	L01	M03	
>0m	Marsh Silt/Fluvial Clay	Marsh Silt/Alluvium	Marsh Silt	Sandy Silt	Alluvium	Medium Sands	
0m	Fluvial Clay	Alluvium	Alluvium	Plastic Clay	Alluvium/Fine Sands	Alluvium	
< 0m > -1m	Fluvial Clay/Fine Sands	Plastic clay/Alluvium	Alluvium/Fine Sands	Plastic Clay/Fine sands	Fine Sands	Plastic Clay	
< -1m	Fine Sands	Plastic Clay/Fine Sands	Fine Sands	Fine Sands	Fine Sands	Fine Sands	
Lagoon Bottom	−0.5m	−1.5m	−1m	−0.3m	−0.2m	−0.3m	
Relative sediment permeability							
Sediment	Marsh silt	Fluvial clay	Plastic clay	Alluvium	Medium sands	Sandy silt	Fine sands
Relative Permeability	Moderate-low	Low-very low	Very low	High-low	High-low	Moderate-low	High-moderate

During the survey, L01 had no low-permeability layers detected throughout its sediment profile. In summary, the lagoons with underlying low-permeability layers are BPI, FRA, M03, and part of L04, while L01 and G02 has higher permeability layers throughout its sediment profile.

2.1. *Historical background*

As is the case in other Mediterranean regions, this area has been affected by high anthropic pressure and the salt marsh was subjected to partial urbanization with alterations to its landscape and hydrology during the late 1980s. This project was later discontinued in the 1990s. Years later, efforts were underway to recover the areás ecological functioning and two LIFE Nature restoration projects (http://lifepletera.com/en/life-pletera/) were implemented. The first project in 2002 created the lagoon G02. To ensure water permanency, the lagoon was excavated below sea level during construction (Fig. 2 A). The second project in 2016 dismantled the remaining urban features (promenade, accesses, filling material, breakwaters and debris, Fig. 2 A) and was substituted by a set of new lagoons (L01, M03, L04) with varying depths and shapes to produce lagoons with different salinity levels and permanency characteristics (Fig. 1; Fig. 2 B; Quintana et al., 2018). Quintana et al. (2018) go on to explain that, among different criteria for the restoration, the design of the topographic distributions of the lagoons were intended to be a reminder of the failed urbanization process, with the old accesses and promenades converted into lagoons, while the old roundabouts separate the permanent lagoons. The intention was to create a recovered area, with restored ecological functioning, and not a pristine salt marsh. This was because the old morphology was strongly altered and impossible to replicate.

2.2. *Hydrology*

The hydrology of the La Pletera lagoons is characterized by the absence of continuous surface freshwater or seawater inflows. It has a micro-tidal regime, with a spring tidal range of about 0.15 m. The water bodies are located behind a foredune, with surface water exchanges occurring mainly during winter sea storms or intense rainfall events (Pascual, 2021). These cyclonic storm events associated with strong easterly winds (known as *llevantades*) can cause sea level rise of more than 1 m (Marquès et al., 2001). During these periods, sea waves may enter the saltmarshes, and together with the freshwater surface flow (overland flow), sub-surface flow (lateral percolation through the topsoil) and groundwater inputs, can cause a 0.3–0.9 m increase in the level of the salt marsh. Therefore, the hydrology is strongly influenced by the sea, with sudden sea storm flooding, followed by extended periods of decreasing water levels and increasing salinity during confinement (Badosa et al., 2007; López-Flores et al., 2006; Quintana et al., 1998, 2018).

In hydrogeological terms, the La Pletera salt marsh area is connected to the shallowest level of the quaternary sediments that fill the regional basin (Menció et al., 2017). As an unconfined aquifer with a thickness of 10–30 m, this unit was formed by recent alluvial deposits which becomes marsh and coastal deposits near the coastline (Montaner, 2010; ICGC, 2011a; Icgc, 2011b). This results in permanent water levels in the lagoons and contributes up to 80 % of the summer water exchange when surface exchanges are scarce (Menció et al., 2017). Furthermore, Menció et al (2017) also concluded through hydrochemical and isotopic

A

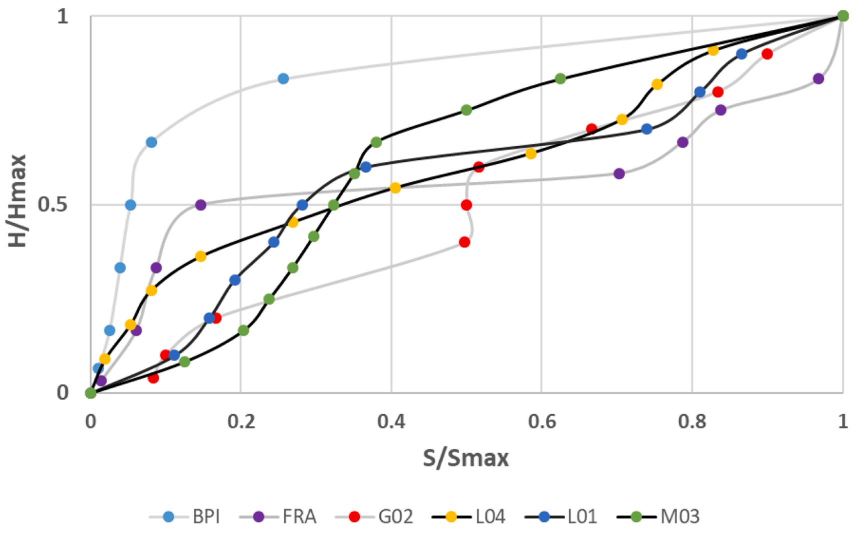

Fig. 3. (A) Bathymetric profiles of the six lagoons normalized by their respective maximum heights and surface areas. The newer lagoons are shown in darker lines and the natural and older lagoons in lighter lines. (B) Rate of change of area with respect to volume (m^2/m^3) and the average depths of all the lagoons. Red indicates summer average depths that correspond with the depth column value and blue indicates all year round. N/A implies the rate of change is very high and non-applicable at this depth. Depths are estimates and can be above or below the indicated level within 0.1 m-0.2 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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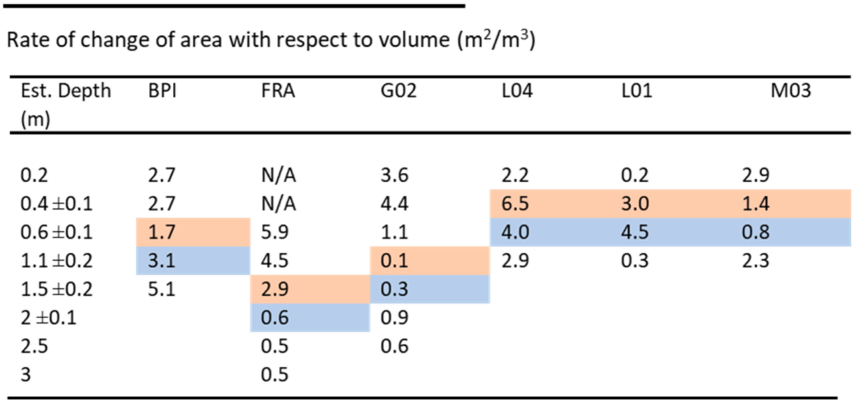

Rate of change of area with respect to volume (m^2/m^3)

Est. Depth (m)	BPI	FRA	G02	L04	L01	M03
0.2	2.7	N/A	3.6	2.2	0.2	2.9
0.4 ±0.1	2.7	N/A	4.4	6.5	3.0	1.4
0.6 ±0.1	1.7	5.9	1.1	4.0	4.5	0.8
1.1 ±0.2	3.1	4.5	0.1	2.9	0.3	2.3
1.5 ±0.2	5.1	2.9	0.3			
2 ±0.1		0.6	0.9			
2.5		0.5	0.6			
3		0.5				

analyses that the water salinity of the lagoons is determined by two main processes: freshwater and seawater mixing (in the lagoon and aquifer) and evaporation. The resulting fluctuations of physical and chemical parameters, such as salinity levels, allow for just a few euryhaline species to establish significant populations in these lagoons.

3. Methods

3.1. Morphometry, lithological and physical characteristics

Bathymetric data were used to calculate the physical characteristics and morphometry of the lagoons. Morphometric parameters such as mean depth, relative depth, and volume development were calculated based on the methods by Hutchinson (1957). This included calculations of the rate of change of area with respect to volume. The geomorphological profiling and geological analysis were conducted in combination with drilling boreholes in the lagoon pre-construction phase (Geoservei, 2016). The main characteristics of the lagoons were estimated from the bathymetric data that were incorporated into AutoCAD LT® software to estimate surface areas, volumes, lengths, and widths.

3.2. Hydrological dynamics

Schlumberger water level data loggers (accuracy ± 0.02 m) were used to determine daily water levels from November 2014 to September 2017 (Fig. 3). Water levels in 2018 and 2019 were obtained biweekly from depth gauge boards installed in the lagoons. A CTD profiler (Sea & Sun Technology) was used to measure biweekly values for temperature and salinity. Daily-average relative humidity, precipitation, and maximum and minimum temperatures were obtained from the ĹEstartit meteorological station, 2 km from the lagoons (Pascual, 2021). This was used to determine the evaporation and precipitation in these lagoons. Data for solar radiation was obtained daily from Mas Badia (La Tallada, ~10 km from the La Pletera) in 2016 and 2017 and in situ in the La Pletera with radiation sensors in 2018 and 2019.

3.3. The General Lake Model (GLM) and application

The now well-documented GLM is an open-source model developed as an initiative of the Global Lake Ecological Observatory Network (GLEON) with several publications documenting simulations using the model (Bueche et al., 2017). Briefly, it is a one-dimensional open-source code designed to simulate the hydrodynamics of lakes, reservoirs, and wetlands (Hipsey et al., 2019) and integrates a Lagrangian layer structure similar to other 1-D lake model designs (Hamilton and Schladow, 1997; Imberger and Patterson, 1981). By integrating the effects such as inflows and outflows, mixing, as well as surface heating and cooling, the model computes vertical profiles of temperature, salinity, and density (Casamitjana et al., 2019). The GLM was applied in the La Pletera lagoons in previous studies to analyze the groundwater influence in the salt marsh (see Menció et al., 2017) and the water circulation patterns and salinity fluctuations (see Casamitjana et al., 2019), and provided, to our knowledge, the first of its application in small water bodies that do not exceed 3 m in depth. This study is a continuation of the work conducted by Casamitjana et al. (2019) and follows the same methodology in the application of the GLM. This study however extends the period of the natural and old lagoons (BPI, FRA, and G02) to 2019 and introduces 3 new lagoons (L01, L04, and M03) constructed in 2016. The selected study period was from March 2016 to September 2019, due to the availability of data from the M03 lagoon, as it was constructed later than the other lagoons. The methodology of applying the GLM will be explained briefly below. However, for a full description of the governing equations of the GLM, the chosen outlet point depths to model the best fit for salinity and temperature, as well as observed meteorological data, see *Data in Brief*.

Inflow and outflow measurements were estimated from the water levels of the lagoons. From the bathymetry data, water volume at any

Table 3
Summary of the main characteristics and morphometry of the studied lagoons during the studied period March 2016 to September 2019. Salinity (‰) is in parts per thousand. Mean Depth (z) is the average depth of the lagoon. Relative depth (Z_r) is the ratio of the maximum depth as a percentage of the mean diameter of the lagoon at the surface. Volume Development (D_v) is the ratio of the volume of a lake to the volume of a perfect cone with the same surface area and maximum depth. According to Hutchinson (1957), Dv values higher than 1 indicate a typical conical depression shape and easily eroded geology. Lake number (calculated by GLM) is the dimensionless quantitative index of the dynamic stability of the water column, defined as a ratio, at the moment of stabilizing force due to gravity to the moment of turbulence destabilizing forces.

Lagoon	BPI	FRA	G02	L04	L01	M03
Origin	Natural	Natural	2002	2016	2016	2016
Max Depth (m)	1.5	3	2.2	1.6	1.2	1.6
Max Volume (m$^{3)}$	1295	22,956	2999	4231	4168	3723
Max Surface area (m^2)	5387	17,290	2991	9878	8657	8007
Average Surface Salinity (‰)	43.38	38.74	25.04	21.7	17.01	32.53
Average Bottom Salinity (‰)	77.91	54.49	25.23	22.53	17.26	33.47
Average Surface Temp (°C)	19.08	19.41	18.78	18.08	19.07	18.93
Mean Depth z (m)	0.24	1.33	1	0.43	0.48	0.46
Relative Depth Zr (%)	1.93	2.02	3.56	1.43	1.14	1.55
Volume Development (Dv)	0.48	1.32	1.36	0.8	1.2	0.89
Lake Number	536	843	1378	179	107	359

Table 4
Model performance assessments using the root mean relative square error (RMSRE) and Nash-Sutcliffe efficiency (NSE) for the lagoons BPI, FRA, G02, L04, L01, and M03.

	BPI	FRA	G02	L04	L01	M03
NSE						
Volume	0.95	0.96	0.94	0.95	0.97	0.98
Salinity	0.71	0.70	0.70	0.71	0.71	0.65
Temp	0.71	0.71	0.68	0.70	0.70	0.65
RMSRE						
Volume	0.17	0.10	0.07	0.18	0.11	0.11
Salinity	0.25	0.17	0.19	0.17	0.15	0.18
Temp	0.22	0.25	0.23	0.24	0.23	0.23

Table 2
Polynomial fit ($V(x) = Ax^5 + Bx^4 + Cx^3 + Dx^2 + Ex + F$) for the lagoons BPI, FRA, G02, L04, L01, and M03 where V(x) is the volume in m^3 and × the height above sea level in m. R^2 is the coefficient of determination.

	A	B	C	D	E	F	R^2
BPI	1551.5	627.73	−411.33	77.365	284.6	99.208	1
FRA	−170.88	−577.28	1659.9	6279.7	6811.5	32370.4	0.9992
G02	0	0	20.952	550.22	1205	667.4	0.9998
L04	0	0	−2491.1	7216.7	−2131.7	203.94	0.9913
L01	0	0	0	1887.8	1048.5	190.94	0.9719
M03	0	0	2236.7	−1646.6	1002.4	288.27	0.9981

single depth was estimated using a polynomial fit; with values of R-squared (R^2) that indicate the goodness of fit. (Table 2). This was then followed by the net daily inflow and outflow calculations to fit the volume fluctuations. The modeled inflows and outflows were then set from the net daily inflow and outflow calculations. The modeled volumes were then compared to the observed water volumes. As rain fluxes and evaporation are modeled separately from the inflows and outflows, differing volumes emerged. Through an iterative process, the inflows and outflows were adjusted until the modeled and real volume, temperature, and salinity values showed the smallest possible differences. Many inflows and outflows were compatible with a single water level, due to estimations from the inflows and outflows. However, we followed the hypothesis that there is either inflow or outflow but not both at the same time for a certain day (especially in summer and autumn). Indeed, the real inflow can be higher than the estimated inflow into the lagoons in some situations, especially in periods of heavy autumn rains with small estimated times for water renewal (<10 days). Nevertheless, this analysis determined the minimum inflows necessary to accurately model the observed volume levels. Simulation performance was assessed using the commonly applied root-mean-square relative error (RMSRE) and Nash-Sutcliffe efficiency (NSE) (Table 4.).

3.4. Data analyses

Bivariate Pearson's correlation coefficient was used to analyze whether a statistically significant linear relationship existed between variables influencing lagoon salinity and volume levels (salinity, volume, evaporation, total inflow, total outflow, inflow salinity, rain, and surface temperature) and to assess the strength of this relationship within the lagoons. Due to highly seasonal patterns, linear mixed models were used to allow for both fixed and random effects within the analysis and aggregate the hierarchical data based on the month and year on lagoons which showed no significance in annual patterns. Stepwise multiple regression models for hydrological parameters affecting salinity and volume were used to analyze the variance among lagoons grouped according to their features: 1) new lagoons (L01, L04, M03, G02), 2) old lagoons (BPI, FRA), 3) presence of low-permeability layers (BPI, FRA, L04, M03) and 4) absence of low-permeability layers (L01, G02). Statistical analyses were done with R software (version 4.1.2; R Project for Statistical Computing, Vienna, Austria) and The jamovi project (2021) (*jamovi* Version 2.2.2, Computer Software, retrieved from https://www.jamovi.org). Uncertainties for empirical and modeled mean values in this study were quantified by the standard coefficient of variation following the methods by (Håkanson, 2005). The CV-value within lagoon variability (CVw) is calculated from time-series data and is related to hydrological and physical conditions. Variations within and among lagoons were analyzed using the standard coefficient of variation, CV, to quantify parameter uncertainties as illustrated by Håkanson (2005).

4. Results

4.1. The main characteristics and morphometry of the lagoons

Table 3 shows the main characteristics and morphometric features of the six lagoons in the La Pletera salt marsh. The new lagoons (L01, L04, M03) were more homogeneous in their main characteristics and showed similarities in their volumes, surface areas, and mean depths. They also had little stratification in their surface and bottom salinity levels. L01 was the shallowest of all 6 lagoons and 2.5-fold shallower than FRA. L04 and M03 were similar in their volume development values at ~ 0.80, while L01 had a value similar to the natural lagoons at ~ 1.2–1.36, indicating a typical conical depression shape and easily eroded geology. The new lagooń relative depths were similar and lower than 2 %.

In contrast, the natural lagoons and G02 were more heterogeneous in terms of their volumes and surface areas, with notable stratification in surface and bottom salinity levels in BPI and FRA. G02 showed little stratification in salinity levels despite being the second deepest lagoon. The natural lagoons and G02 also differed in their mean depths, with BPI showing a notably lower mean depth level in comparison with all the lagoons. BPI also had the lowest volume development value, indicating that it has less of a uniform bottom and is more of a localized deep hole. The FRA and G02 lagoons, however, showed more similarity in terms of their mean depths and have the highest volume development values. They were also the deepest lagoons with higher relative depths (including BPI) in comparison with the other lagoons, with G02 above 3.5 % (Table 3).

When comparing all the lagoons together, little differences in their average surface temperatures were observed. BPI, FRA, and M03 showed 1.5 to 2-fold higher surface salinity levels than the rest of the lagoons. BPI and FRA had the biggest contrast in terms of the volume capacity of all the lagoons, with FRA having a 20-fold greater volume capacity than BPI. L01 showed the lowest surface salinity levels with nearly a 1.5 to 2.5-fold lower difference than the rest of the lagoons. FRA and G02 had the highest lake number values followed by BPI, suggesting more water column stability in these lagoons than the new lagoons L04, L01, and M03.

Fig. 3 A shows the normalized bathymetric profiles of the six lagoons and illustrates their respective surface to height ratios. The respective heights and surface areas were normalized by their maximum height and surface area values. The new lagoons were similar in their bathymetric profiles (shown as darker lines). In contrast, the natural lagoons and G02 showed differences in their profiles, with BPI having the biggest surface area over height change the deeper the lagoon becomes. L04 had a slightly higher surface area change with respect to its height. The natural lagoons had more of a conical depression shape (as can be seen with the volume development ratios in Table 3) with FRA showing more increase in height over its surface area at around 50 % of its height with only an increase of ~ 15 % of its surface area (Fig. 3 A).

Fig. 3 B shows the calculated rate of change of area with respect to volume. Values highlighted in red indicate estimated average depths in summer (June to September). Blue indicates the estimated average depths of the lagoons for the rest of the year (that excludes summer). For the convenience in representation and due to the nature of the bathymetric data and varying depths of each lagoon, depth are estimates that can either be above or below the indicated level within 0.1 m-0.2 m. L04, L01, and M03 had similar average water depths and were shallower than the natural lagoons and G02 both in summer and for the rest of the year. The difference in the new lagooń water levels in summer compared with the rest of the year is ~ 0.2 m-0.3 m. In contrast, the natural lagoons and G02 showed a ~ 0.5 m difference in their water levels from summer to the rest of the year. The rate of change of area with respect to volume shows that the new lagoons had a higher surface area rate of change than the natural lagoons and G02 at shallower depths (Fig. 3 B). This can be seen in the similar bathymetric profiles and steady increase in surface area over the heights illustrated in the darker lines in Fig. 3 A. FRA and G02 had a less rate of change of area as the lagoons get deeper (Fig. 3 B). This can also be seen in the increase in the height over surface area the deeper the lagoons become (Fig. 3 A). However, BPI showed the opposite trend where the rate of change of area increases as the lagoon gets deeper. G02 showed a 65-fold lower rate of change of area compared with L04 in the summer - which also had the highest rate of change on average out of all the lagoons.

4.2. Water volume fluctuations

Fig. 4 shows relative water volumes of all six lagoons normalized by their initial water volume on the 1st of October, with the hydrological period beginning in October the previous year. The year 2015–2016 was evaluated from April to October of the same year due to the availability of data. Similar patterns of mixing and desiccation can be seen in all the lagoons, with levels increasing from the initial volume in autumn and

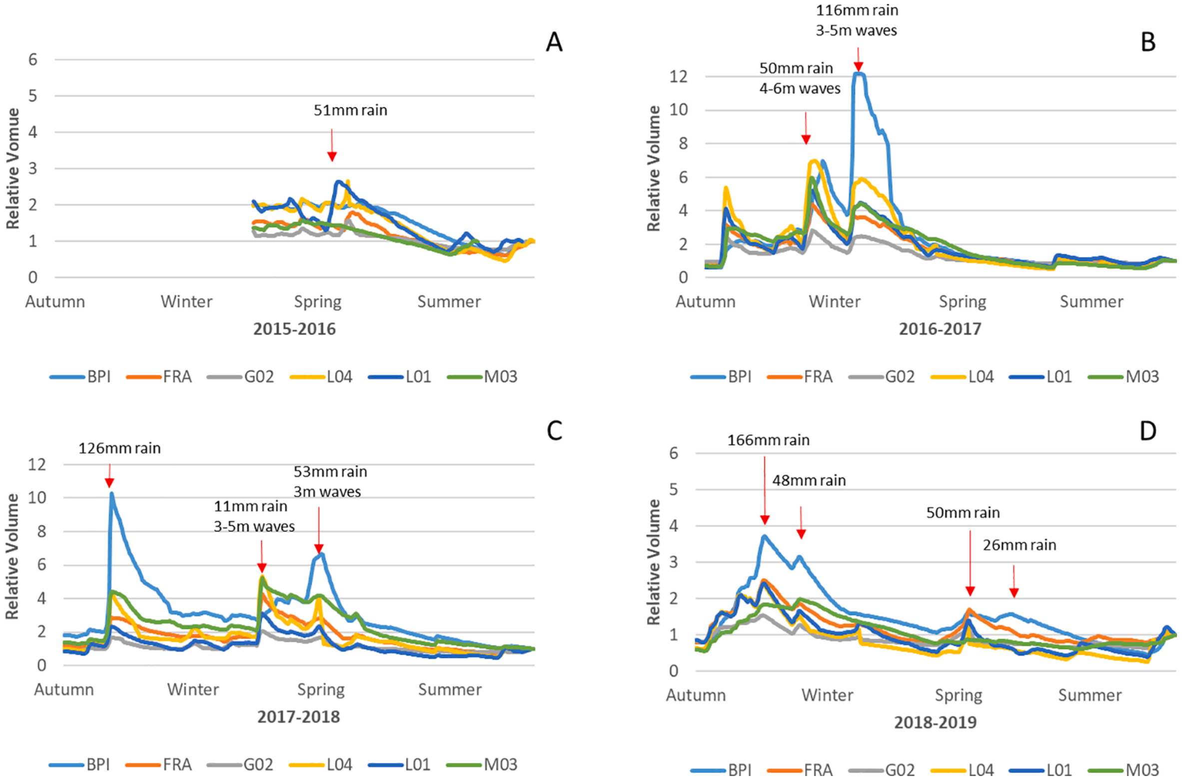

Fig. 4. Relative water volumes (normalized by the initial volume of the respective lagoons on the 1st October of the year 2016, 2017, 2018 and 2019 to show periods of mixing through to periods of desiccation in summer (end of September). The hydrological period is from October of the previous year to October of the following year. The year 2015–2016 was evaluated from April to October due to availability of data. Red arrows indicate inputs from either rainfall and/or seawater from sea storms (wave heights higher than 3 m). Note the relative volume axis maximum unit measurement change in 2017 and 2018 (Fig. 4B and C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

returning to the initial volume level towards the end of summer (Fig. 4). The year 2015–2016 and 2018–2019 had no influence of storms and only significant rainfall events (Fig. 2 A, D), with 2018–2019 showing the most significant rainfall events and changes in volume levels in all the lagoons. All lagoons behaved similarly in 2015–2016, with more fluctuation of volume levels in L01 than in the other lagoons (Fig. 2 A). The year 2016–2017 and 2017–2018 showed significant storm events with waves higher than 3 m on all occasions combined with significant rainfall in 2017 (11 mm − 126 mm) (Fig. 2 B, C). When evaluating the individual responses of the lagoons to rainfall and/or seawater inputs, the higher rainfalls (above 100 mm) affected BPI more with a 6-fold increase in its relative volume in 2016–2017 and 2017–2018. L04 showed high fluctuations in its volume levels from both rainfall and seawater inputs. Overall, G02 had a lower response in its relative volumes from rainfall and seawater inputs over the 4-year study period. The newer lagoons (L04, L01, and M03) showed a 3 to 9-fold increase in their relative volumes due to seawater inputs and a 2.5 to 3.5-fold increase with significant rainfall events. In contrast, G02 and FRA only had a 1.5 to 3.5-fold increase during similar events.

4.3. *Calculated GLM water circulation and surface area fluxes*

Simulation performance was assessed using the commonly applied Nash-Sutcliffe efficiency (NSE) and root-mean-square relative error (RMSRE) (Table 4). For the 4-year study period, the NSE values on average for volume were ~ 0.95 and ~ 0.7 for salinity and temperature. The values for RMSRE were ~ 10 % for volume, ~20 % for salinity, and ~ 23 % for temperature. Modeled vs observed data graphs are shown in the *Data in Brief*.

Fig. 5 shows the modeled fluxes per unit of water volume of the lagoons, calculated during the study period from 2016 to 2019. These fluxes are calculated in cubic meters per day per lagoon volume and are together categorized as water circulation within the lagoons (Inflow/V, Outflow/V, Evaporation/V, Rain/V). For the convenience of representation, calculations are converted to cubic millimeters per day, except for surface area. The selected time includes the periods of mixing which occur in October, after the autumn rains, and subsequent desiccation that occurs towards September in the summer and illustrates the overall average hydrological behavior of each lagoon. Inflow and outflow were modeled as a singular occurrence and did not occur concurrently. Also, due to the nature of the hydrological activity in Mediterranean lagoons, the sensitivity of mean calculations was considered representative. Modeled results of inflow, outflow, evaporation, and rain were normalized by their respective lagoon volumes at each time step to best represent the overall circulation of each lagoon relative to other lagoons. Surface area flux calculations were also normalized by their respective water volumes and included to compare with evaporation fluxes.

Differences in mean water circulation between the lagoons can be seen across the 4-year study period. Despite M03 and BPI having similar mean evaporation (7.69 mm^3 day^{-1} and 7.49 mm^3 day^{-1}, respectively), L04 showed a higher surface area per volume that corresponds with higher evaporation per volume (Fig. 5 C, E), while G02 had the lowest corresponding surface area and evaporation fluxes, indicating a positive relationship between the surface area to volume ratio and evaporation for all the lagoons combined (Pearsońs correlation, $p = < 0.001$, $R^2 = 0.79$, Supplementary Table 1). The new lagoons L01 and L04 showed higher circulation with higher mean evaporation, inflow, and outflow in comparison with M03 and the natural lagoons BPI, FRA, and G02 (Fig. 5 A, B, C). L01 and L04 had a 1.8-fold higher difference in mean inflow in comparison with M03 (12.9 mm^3 day^{-1}, 12.7 mm^3 day^{-1}, and 7.01 mm^3 day^{-1}, respectively), while L01 showed a nearly 2.5-fold increase in mean outflow compared with MO3 (8.64 mm^3 day^{-1} and 3.53 mm^3

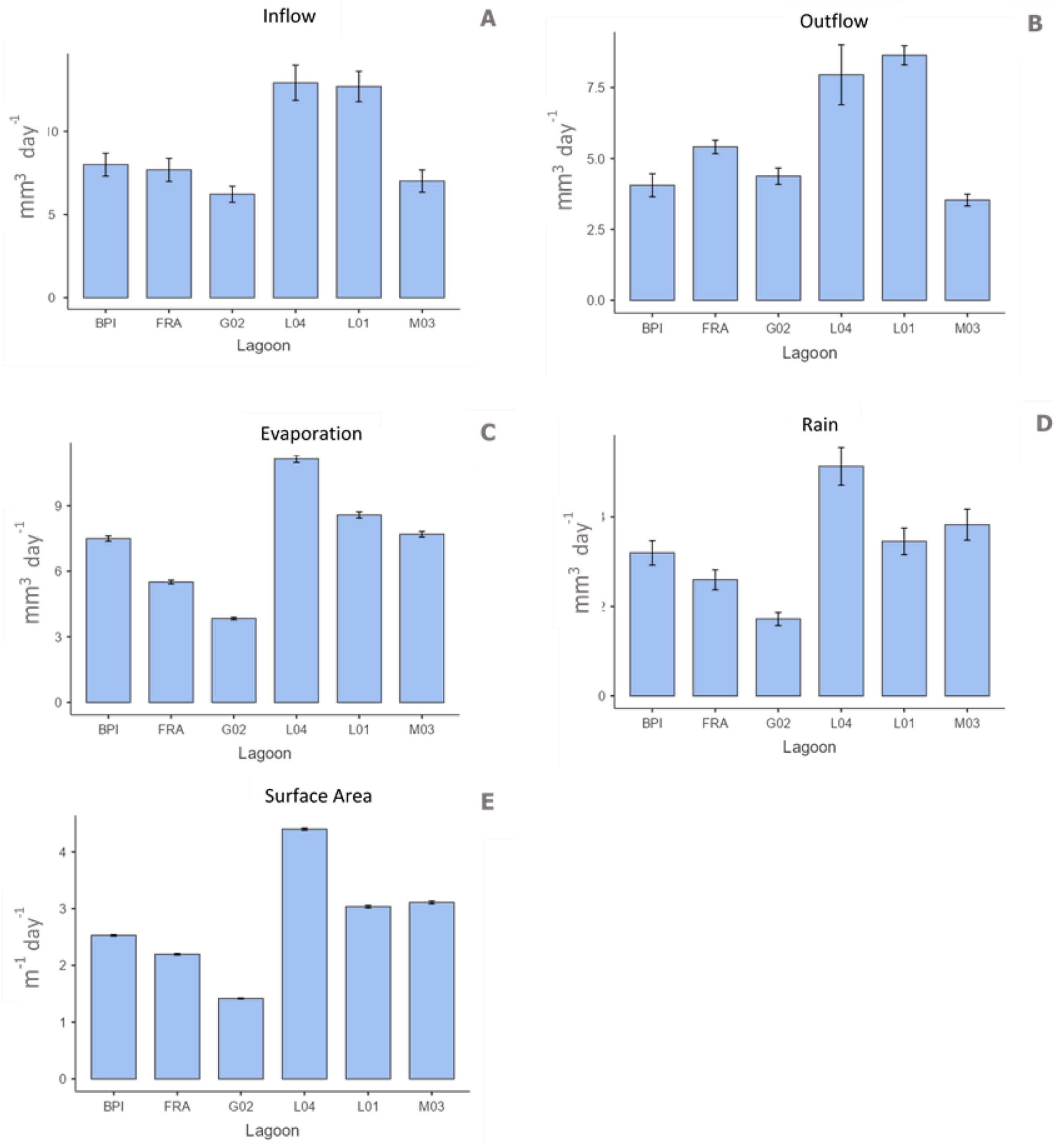

Fig. 5. Bar plots with error bars of mean lagoon circulation of the GLM water budget for all the lagoons BPI, FRA, L04 (n = 1309), G02 (n = 1292), L01 (n = 1300) and M03 (n = 1266) for the study period from 2016 to 2019. Modeled results of (A) Inflow, (B) Outflow, (C) Evaporation, (D) Rain and (E) Surface Area are normalized by their respective daily lagoon volumes. Calculations are in cubic meters per day per lagoon volume and converted to cubic millimeters per day. All parameters are categorized as water circulation within the lagoons (Inflow/V, Outflow/V, Evaporation/V, Rain/V. Evaporation and outflow represent the removal of water. Surface area over volume included to compare the effect of lagoon surface area on evaporation.

day^{-1}, respectively). The mean effect of rain over volume was greatest in L04 and lowest in G02 with a 3-fold difference between them (5.13 mm^3 day^{-1} and 1.72 mm^3 day^{-1}, respectively), and follow a similar mean pattern to that of the surface area over volume measurements.

4.4. *Modeled salinity inflows*

Table 5 shows the modeled salinity inflows of the lagoons. To match observed salinity levels, inflow salinity values were manually entered into the GLM on a daily basis for each lagoon. BPI, FRA, and M03 salinity levels were set above Mediterranean Sea salinity levels (37 ppt) in 2016, 2017 (only for BPI), 2018 and 2019 (only in M03). This occurred mainly in the summer and autumn periods, with M03 showing high inflow salinity across the seasons, except in 2017 and the autumn of 2019. G02 registered higher salinity only in the summer of 2018. L04 and L01 showed no inflow salinity greater than sea salinity, with L01 showing the lowest inflow salinities of all the lagoons during summer and autumn. Overall, 2019 showed lower salinity inflow levels in all the lagoons, while 2016 and 2018 had the highest levels (Table 6).

4.5. *Variations among and within lagoons*

The within-lagoon variations for all variables, except surface area, mainly depend on seasonal climatic changes such as desiccation in summer and seawater intrusions from winter cyclonic storms. The CV expressing variations among lagoons, CVa, is defined from the

Table 5

Model inflow salinity (ppt) averaged by the season (4 months) for the 4-year study period. Asterisk and highlighted values indicate salinity levels above the Mediterranean Sea salinity (37ppt).

Year	Season	BPI	FRA	G02	L04	L01	M03
2016	Winter - Spring	**48***	36	21	17	16	**49***
	Spring - Summer	**60***	27	19	11	5	**39***
	Autumn - Winter	25	**44***	23	31	28	**43***
2017	Winter - Spring	18	25	25	15	10	10
	Spring - Summer	**40***	35	23	14	7	28
	Autumn - Winter	28	27	16	15	8	21
2018	Winter - Spring	26	34	21	27	19	**43***
	Spring - Summer	**50***	**45***	**45***	12	3	**60***
	Autumn - Winter	25	**49***	20	26	21	**60***
2019	Winter - Spring	22	33	13	20	13	**60***
	Spring - Summer	22	25	13	20	8	**40***
	Autumn - Winter	22	21	15	20	5	5
	Average	32	33	21	19	12	38

coefficient of variation of mean monthly values from different lagoons. Both CVw and CVa were calculated from March 2016 to September 2019.

As expected, there were no significant differences between CVw and CVa for surface temperature, with variation around 20 % and driven by seasonal temperature changes. Significant differences in morphological features (surface area and volume) can be seen within and among the lagoons, with BPI showing the greater variance of both within the lagoon and G02 showing the lower variations within. The largest variations among the lagoons were in their volume and surface areas. Circulation parameters among the lagoons showed variation at ~ 30 % for Inflow/V, Outflow/V, Evap/V, and Rain/V, however, the circulation parameters within the lagoons had high variation (due to occasional daily zero values) in Outflow/V, with L04 having a 3-fold higher variation than L01. Salinity variation within the individual lagoons was 1.5-fold lower in both L01 and FRA compared with the rest of the lagoons and 3-fold lower than BPI. The natural lagoons (BPI and FRA) showed the lowest inflow salinity variations, while the new lagoons had a 1.5–2-fold higher variation than the natural lagoons.

4.6. Variables influencing salinity and volume levels

To assess the relationship between variables that influence volume and salinity levels within the lagoons, a series of Pearson product-moment correlations were performed (Table 7). When assessing the relationships influencing salinity, the volume levels were negatively correlated with salinity in all the lagoons except for L01, where its total inflow was associated with salinity levels. Evaporation was associated with salinity in the natural lagoons and G02, where it was negatively correlated with salinity in BPI and positively correlated in the FRA and G02 lagoons. Evaporation, however, had no significant correlation with salinity in the new lagoons. Also, inflow salinity was associated with salinity levels only in BPI. As expected, the total inflow calculated by the GLM was positively correlated with volume levels in all the lagoons. Evaporation was negatively correlated with volume levels in FRA and G02. However, evaporation was positively correlated with volume levels in BPI and L04. Inflow salinity was positively correlated with volume levels in L04 and L01.

Table 8 shows the analysis of variance among lagoons grouped according to their features using stepwise multiple regression models for hydrological parameters affecting salinity and volume. The lagoons are categorized as new lagoons (L01, L04, M03, G02), old lagoons (BPI, FRA), presence of low-permeability layers (BPI, FRA, L04, M03) and absence of low-permeability layers (L01, G02). G02 was removed from Table 8 C & D to improve consistency in lagoon morphology. The new lagoonś salinity fluctuations were explained more by total inflow and outflow than by rain and evaporation in the regression models (A & C), while volume levels explained more of the variance in the old lagoons (E). A similar effect on salinity was seen in lagoons with low-permeability layers, where volume had a bigger influence (G). However, a combination of inflow salinity and volume helped to explain more of the variance in salinity fluctuations in lagoons without low-permeability layers (I). Total inflow and outflow affected the volume fluctuations more in the new lagoons (D), while rain and evaporation explained nearly all of the variance in the old lagoons (F). A similar result was obtained in lagoons with the presence of low-permeability layers, where rain and evaporation explained nearly all of the

Table 6

Coefficient of variation (CV = SD/MV; SD = standard deviation, MV = mean value) within, CVw, and among, CVa, the lagoons from the study period 2016 to 2019.

	Volume	Surface Area	Surface Temp	Salinity	Inflow Salinity	Inflow	Outflow	Evaporation	Rain
Coefficient of variation within Lagoons (CVw)									
BPI	0.85	1.19	0.26	0.71	0.25	3.13	3.51	0.62	3.20
FRA	0.48	0.18	0.24	0.26	0.21	3.37	1.61	0.58	3.28
G02	0.30	0.12	0.24	0.34	0.50	2.84	2.33	0.55	3.19
L04	0.68	0.48	0.26	0.37	0.41	3.11	4.66	0.53	3.10
L01	0.53	0.34	0.25	0.27	0.47	2.56	1.42	0.60	3.16
M03	0.56	0.32	0.23	0.39	0.40	3.43	2.08	0.59	3.25
Coefficient of variation among Lagoons (CVa)									
CVa	1.27	1.04	0.06	0.34	0.31	0.32	0.38	0.34	0.35

Table 7

Correlation Matrix of Pearson correlation coefficients for all the seasons combined to assess the relationship of hydrological parameters (Evaporation, Total Inflow, Total Outflow, Inflow Salinity, Rain and Surface Temperature) influencing lagoon volume and salinity. Values averaged monthly.

Lagoon	BPI	FRA	G02	L04	L01	M03	BPI	FRA	G02	L04	L01	M03
	Salinity						Volume					
Volume	−0.55*	−0.77*	−0.43*	−0.33*	0.07	−0.67*	–	–	–	–	–	–
Evaporation	−0.36*	0.35*	0.49*	−0.17	0.27	0.13	0.89*	0.32*	−0.57*	0.6*	−0.01	0.08
Total Inflow	−0.24	−0.1	0.07	0.15	0.45*	−0.07	0.62*	0.57*	0.58*	0.6*	0.52*	0.53*
Total Outflow	−0.37*	−0.63*	−0.38*	−0.21	0.21	−0.51*	0.85*	0.95*	0.87*	0.85*	0.91*	0.88*
Inflow Salinity	0.5*	0.11	0.2	−0.03	0.19	0.04	−0.26	−0.04	0.17	0.34*	0.45*	−0.1
Rain	−0.3	−0.41*	−0.15	−0.17	0.13	−0.38*	0.77*	0.6*	0.64*	0.72*	0.71*	0.6*
Surface Temp	0.6*	0.76*	0.64*	0.64*	0.27	0.63*	−0.59*	−0.7*	−0.73*	−0.69*	−0.69*	−0.67*

Asterisk indicates correlation is significant $p < 0.05$.

Table 8
Stepwise multiple regression models for hydrological parameters affecting salinity and volume according to new lagoons (A, B, C*, D*), old lagoons (E, F), presence of low-permeability layers (G, H) and absence of low-permeability layers (I, J). Asterisk indicates G02 was removed from the new lagoons category due to conflicting morphology. Adjusted r^2 values and the inclusion of parameters at each step are shown. r^2 asterisk indicates significance with a *p*-value below 0.05.

Step	Parameter		r^2	Step	Parameter		r^2
New Salinity (L01, L04, M03, G02)		A		New Volume (L01, L04, M03, G02)		B	
1	Rain		0.03*	1	Rain		0.36*
2	Evaporation		0.04	2	Evaporation		0.39*
3	Total Inflow		0.05*	3	Total Inflow		0.39
4	Inflow Salinity		0.36*	4	Total Outflow		0.73*
New Salinity (L01, L04, M03)		C*		New Volume (L01, L04, M03)		D*	
1	Rain		0.03	1	Rain		0.44*
2	Evaporation		0.05	2	Evaporation		0.45
3	Total Inflow		0.06*	3	Total Inflow		0.45*
4	Inflow Salinity		0.24*	4	Total Outflow		0.80*
Old Salinity (BPI, FRA)		E		Old Volume (BPI, FRA)		F	
1	Rain		0.02*	1	Rain		0.66*
2	Evaporation		0.09*	2	Evaporation		0.95*
3	Total Inflow		0.10*	3	Total Inflow		0.95*
4	Volume		0.45*	4	Total Outflow		0.97*
Presence Salinity (BPI, FRA, L04, M03)		G		Presence Volume (BPI, FRA, L04, M03)		H	
1	Rain		0.04*	1	Rain		0.56*
2	Evaporation		0.06*	2	Evaporation		0.89*
3	Total Inflow		0.08*	3	Total Inflow		0.89
4	Volume		0.30*	4	Total Outflow		0.93*
Absence Salinity (L01, G02)		I		Absence Volume (L01, G02)		J	
1	Rain		0.01	1	Rain		0.35*
2	Evaporation		0.03	2	Evaporation		0.46*
3	Total Inflow		0.05	3	Total Inflow		0.47
4	Volume		0.26*	4	Total Outflow		0.70*
5	Inflow Salinity		0.33*				

variation, despite the inclusion of lagoons L04 and M03 (H). However, the model improved greatly when total outflow was added to lagoons without low-permeability layers.

5. Discussion

Recent method and technology improvements in data collection has seen a deluge of data generation, and environmental modeling is a way of observing systems coherently with large data sets (Farley et al., 2018; Porter et al., 2012). As with all models, choosing the level of resolution and complexity within a generic model structure, that is both accessible and can confidently predict system process is challenging at best (Bruce et al., 2018; Hipsey et al., 2019). Stress testing the GLM over a global network by Bruce et al. (2018) identified a range of limitations that included warm or cold biased estimations and larger mean errors of temperature, depending on the frequency and location of meteorological data collected. Accurate light extinction coefficients (K_W) and wind speed measurements, as well as the parameterization and classification to physical characteristics were also emphasized to improve model performance. Furthermore, to increase the applicability of the GLM to a wide variety of systems, it was proposed to adopt a Bayesian hierarchical calibration framework and increase the flexibility of assumed globally common parameter values for the core hydrodynamic parameters. Our investigation into shallow coastal lagoons is one of the first (to our knowledge) to model these types of systems that don't exceed 3 m in depth. While it was found that shallow, well-mixed lakes performed better overall during stress testing (Bruce et al., 2018), this study contributes to an ever-increasing list of diverse system types modeled by the GLM, and provides insights into shallow, well mixed lagoon systems with higher salinity fluctuations. Also, the diversity of morphologies of the new and natural lagoons, combined with underlying lithological characteristics and different hydrological parameters modeled separately has provided an opportunity to not only quantitatively assess the success of restoration, but also to analyze factors that contribute to lagoon circulation and water volume fluctuations (Section 5.1), as well as lagoon salinity variability (Section 5.2).

5.1. Shallower lagoon morphometry and lack of low-permeability layers can increase overall water circulation and volume fluctuation

5.1.1. Lagoon circulation and morphometry

Our results indicate differences in the hydrodynamics of the lagoons when assessing overall water circulation and volume fluctuations, in conjunction with differing lagoon morphometry and the presence or absence of low-permeability layers. Differences between the lagoons start with their lithological characteristics and permeability, shown in Table 1, and are defined by their temporal and spatial distributions. Firstly, the accumulation of decomposing plant and organic matter in marsh silts is found at the sediment–water interface in the natural lagoons and not in the new lagoons, due to insufficient time for decay and accumulation (Table 1, Boadella et al., 2021; GEOSERVEI, 2016). The new lagoons have mostly sandy silts and alluvium deposits at the sediment–water interface. As unconsolidated deposits, the permeability of these sediments differ with marsh silts having moderate to low permeability in the old lagoons, and high to low permeability in alluvium and medium sands in the new lagoons (Freeze & Cherry, 1979; Lewis et al., 2006). The underlying fine sands for all the lagoons have a high to moderate permeability (Freeze & Cherry, 1979; Lewis et al., 2006). Also, the plastic clay layer is distributed in the South and South West of the study site, which represents significantly lower permeability (Freeze & Cherry, 1979; Lewis et al., 2006) for the affected lagoons (Fig. 1) and reduces the efficiency of groundwater input in FRA, M03, and part of L04. Although BPI didńt register the presence of this layer, its lithological characteristics are nevertheless dominated by low-permeability silts and clays (Table 1). Also, the decision to emulate the new lagoons (L01, L04, and M03) to previous urban developments, such as promenades and rotundas, as well as to preserve the shallow underlying low-permeability layers, provided a guideline during construction and resulted in similar and shallower mean depths and bathymetrical profiles (Table 3 and Fig. 3 A). This led to different morphometric features as well as lithological characteristics between the new and the natural lagoons, resulting in differences in the hydrological patterns between them. The new lagoons have similar summer and yearlong water levels, higher rate of change with respect to volume, and higher surface to volume ratios (Surface/V) in comparison with the old lagoons (Fig. 3 B, Fig. 5 E). Therefore, the new lagoons have a higher evaporation flux in comparison with the old lagoons (Fig. 5 C). A higher Surface/V ratio results in higher evaporation (Casamitjana et al., 2019; McJannet et al., 2008). This is also observed in the rate of change of area with respect to volume (Fig. 3 B), where the new lagoons' surface areas increase with lower water volume.

The strength of the one-dimensional GLM to differentiate inflows, outflows, mixing and surface mass fluxes allows for the distinction of different circulation patterns within the lagoons. This includes inflows separate from rainfall and outflow from evaporation. Due to the nature of the hydrological activity in Mediterranean lagoons, the occurrence of extreme values for inflow, outflow, and rain was common and concurrent with episodes of non-occurrence (i.e. either inflow or outflow occurred, and periods of no rain). This resulted in highly skewed data in its distribution (Supplementary Fig. 1 A, B, C, D, E, F; Supplementary Fig. 2 A, B, C, D, E). Nevertheless, the NSE and RMSRE values indicate reasonable adjustments despite the sudden changes in volumes (Table 4.) Also, the sensitivity of mean calculations was considered convenient and representative, as the occurrence of both extreme values and the non-occurrence of daily parameters are equally important in water circulation representations. Distinguishing circulation parameters allowed for two contrasting patterns to emerge between the natural lagoons and G02 and the new lagoons L04 and L01. The circulation is higher in L01 and L04 than the natural lagoons and G02 in all parameters calculated by the GLM (Fig. 5 A, B, C, D). This also coincides with differences in the morphometric features, where mean depth and relative depth are greater in FRA and G02 (Table 3), and their variation of surface area and volume was lower (Table 6). Both features indicate the deepness of the lagoons and Hutchinson (1957) and Wetzel and Likens (1991) note that those that have a higher relative depth (approaching 4 %) usually have smaller surface areas and exhibit greater resistance to mixing. This idea is strengthened with the higher lake numbers for FRA, G02, and BPI (Table 3). Also, despite no observation of low-permeability layers in G02 (Table 1), the response to inputs is more moderate and only increases once above 2 times its relative volume after the dry period (Fig. 4), suggesting water column stability due to deeper lagoon morphometry and resistance to high volume fluctuation as a result of higher relative and mean depths. This can be seen in Table 8, where most of the variance is explained for volume fluctuations in the new lagoons when including total inflow and outflow (D*), whereas most is explained in the old lagoons through evaporation and rainfall, with little affect from total inflow and outflow (F). Combining all these factors has led to two main findings that could be explained by lagoon morphometry. First, the less effect of water volume fluctuations in FRA and G02 can be attributed to more water column stability, due to variations in density with depth and lower evaporation effect due to smaller surface/V ratio; and second, the new lagoons shallower profiles are sensitive to water inflows and outflows due to lower volume capacity and are subject to higher evaporation effect by the higher surface/V ratio. The result is higher water turnover for L04 and L01 and a quicker response to external drivers, such as winter cyclonic storms or long dry periods.

5.1.2. *Influence of low-permeability layers on water circulation*

Notable differences in the circulation patterns of M03 are observed in comparison with the other new lagoons. Despite sharing similar morphometric features, M03 has different inflow, outflow, and evaporation patterns from L04 and L01 (Fig. 5 A, B, C). Also, the total coverage of underlying low-permeability layers in M03́s wetted area is unique, where all other lagoons (except for BPI) have a combination of low permeable and permeable layers underlying the wetted area (Fig. 1 and Table 1), and the more inland topographical location suggests this lagoon is subject to more confinement than the rest of the lagoons. Furthermore, in the absence of sea storms and with rain inputs only, M03 showed minimal fluctuation in water volumes in comparison with L01 and L04 (Fig. 4 A), indicating a smaller influence of rising groundwater. Also, sea storm inputs and high rainfall can increase all the lagoonś water volume 2–12 times the initial volume in autumn. However, there is a lag in declining water volume levels after such events in M03, while L04 and L01′s volume levels decline quicker (Fig. 4 B, C, D). A similar pattern of lag can also be seen in FRA. M03 and BPI showed similar evaporation patterns over their respective volumes (Fig. 5 C), despite having similar surface area fluxes with L01 - which has no low-permeability layers (Fig. 5 E, Table 1). Furthermore, a large part of the variance of volume fluctuations in lagoons without low-permeability layers is explained with the inclusion of total outflows (Table 8 J), whereas inflow and outflow contribute only a percentage of the total fluctuations in the presence of these layers (Table 8 H). This suggests the underlying low-permeability layers overall effect on hydrological behavior, which influences inflows, outflows, and evaporation patterns, resulting in a more elevated confinement pattern of circulation due to a less efficient connection with the aquifer. Therefore, low-permeability layers and lagoon morphometry can influence water circulation and volume fluctuations, and the interplay of both can create similar hydrological behavior. This is the case with BPI and M03, which behaved similarly in terms of lag in response to both inflows and outflows, yet can have high increases in their relative volumes due to their lower mean and relative depths (Table 3).

5.2. *The presence and absence of underlying low-permeability layers influence lagoon salinity variability.*

5.2.1. *Presence of low-permeability layers*

In conjunction with the presence of underlying low-permeability layers (Table 1 and Fig. 1), BPI, FRA, and M03 show higher surface and bottom average salinity levels (Table 3). Furthermore, to fit the GML results to the experimental data when modeling salinity, the inflow salinity levels were set to values higher than sea salinity (Mediterranean salinity ~ 37ppt), mainly during the summer and autumn seasons (Table 5.). A similar observation was made by Casamitjana et al, (2019), who suggested that these salinity values are similar to those at the bottom of the lagoons (or have a higher salinity with little stratification, as is the case in M03, Table 3). The study concluded that differences in water input amounts and water salinity may be attributable to the composition and permeability of the lagoons' sediment. While that study showed this effect in the natural lagoons (BPI and FRA having higher salinity inflows, while G02 lower), this was also observed in the new lagoon M03, showing high salinity levels in its inflows, mainly during the summer-autumn period (Table 5). Although indirect, these results suggest that there is a less efficient connection occurring with the aquifer, which minimizes groundwater inflows and outflow circulations (Fig. 5) and therefore more water confinement. This idea is supported by a strong negative correlation between volume levels and salinity (Table 7), particularly in BPI, FRA, and M03, as well as a negative correlation of total outflows and salinity levels, indicating that outflows are more restricted by the low-permeability layers. This has an effect of increasing overall lagoon salinity when water levels decrease. This idea is strengthened when volume is included in the multiple regression models that affect salinity levels in the presence of low-permeability layers (Table 8 G). However, when groundwater levels increase, mostly during autumn and winter cyclonic storm events (Fig. 4), the groundwater inflows into these lagoons have salinity similar to summer salinity levels. Additionally, some of the inflowing surface waters can have higher salinities because they flow through small salt deposits formed due to the evaporation of small ponds in between the lagoons and the sea (Casamitjana et al., 2019). These results support similar findings by Sadat-Noori et al. (2016), who observed inputs of shallow brackish hypersaline pore water into the lagoons when groundwater levels rise. Also, Rodellas et al. (2020) observed that the increased hydraulic gradient favors the upward advection of deep hypersaline pore waters in periods of shallow lagoon water depths. Zarroca et al. (2011) went further to explain that textural and mineralogical characteristics condition the retention of salts in sediment, as the low permeability of clays as well as the high capacity of adsorption and absorption contribute to the increase of ion concentrations.

5.2.2. *Absence of low permeability layers*

While higher salinity levels seem to correspond with the spatial distribution of low-permeability layers, lagoons with lower overall salinity levels (L01, L04, and G02) also correspond with the absence or partial presence of low permeability layers. During rainy and stormy periods (mostly in spring and autumn), the inflow is estimated to be a mixture of groundwater and surface water, while for the rest of the year inflow is mostly from underground sources (Menció et al., 2017). L01 showed significant freshening during the summer period (Table 3), with higher salinity inflows of seawater entering during autumn storm events. This suggests freshwater is the main input from the aquifer, possibly due to freshwater stratification on top of a saltwater wedge (Menció et al., 2017). Although L04 had the low permeability layer conserved, the partial distribution of this layer has resulted in some connection with the underlying aquifer and as a consequence more freshening and water circulation (Table 5, Fig. 5 A, B). In seemingly contrasting behavior to the presence of low permeability layers, there were no or weak correlations found for volume levels and salinity in L01 and L04, and outflow had no effect on their salinity levels - suggesting the more efficient connection to the shallow aquifer and susceptibility to the influence of circulating waters (surface and groundwater inflows), despite having the highest evaporation flux of all the lagoons. This idea is further strengthened by the lowest coefficient of variation for inflow and outflow in L01 in Table 6. This finding is in agreement with Rodellas et al. (2018), who determined that water recirculating through permeable sediments in a coastal lagoon could account for more than 60 % of the total recharge. In our case, this kind of circulation may explain a significant amount of the water flow that occurs at the beginning of the autumn.

It is long been held that in a flooding-confinement hydrological pattern coastal lagoon surface waters would be more susceptible to evaporation, and salinity would increase as water levels decrease. When analyzing the annual hydrological pattern, there is a positive correlation of evaporation with salinity levels in the natural lagoon FRA and G02 but does not correlate with salinity levels in the new lagoons (Table 7) (BPI had a negative correlation due to a smaller surface area at lower volume levels). However, when aggregating the data by seasons using mixed linear models (i.e. Winter, Spring, Summer, and Autumn), evaporation is positively correlated with salinity levels between the winter and summer seasons in both L04 and M03 ($r = 0.44$ and 0.57 respectively; $p < 0.05$; Supplementary Table 2.), but not for L01, where its increasing salinity is more dependent on annual total inflows as well as inflow salinities (Table 7, $r = 0.45$; $p < 0.05$) due to sea water inputs. Furthermore, a third of the variance in new lagoonś salinity can be explained by including inflow salinity, while evaporation is not significant in the multiple regression models (Table 8 I). These results imply two findings. First, while evaporation affects the salinity levels in the lagoons, the new lagoonś salinity is controlled more by seasonal inputs. Second, the absence of low-permeability layers limits salinity variation in a confined lagoon system. It is well documented that evaporation plays a role in changes in salinity levels (e.g. Lécuyer et al., 2012; Abd Ellah and Hussein, 2009). Also, many studies have focused on Submarine Groundwater Discharge (SGD) through permeable sediments and its influence on nutrient loadings and salinity of surface water bodies (Anschutz et al., 2009; Liefer et al., 2013; Rodellas et al., 2015). However, few have quantified parameters affecting salinity fluctuations with known sedimentary patterns and their influence on the overall hydrological pattern from surface and groundwater flows, both from land to sea and vice versa. Our results show that there is an overall influence of low-permeability layers on lagoon salinity variability, despite the strong influences of external hydrological patterns. This can be seen in the similarity of the morphometric features in L01, L04, and M03, where all are relatively shallow and have a high evaporation flux with low water levels in summer, yet their salinity variability varies widely with M03 showing the highest fluctuations with lower circulation (Fig. 5 and Table 5). Similarly, FRA and G02 show similar hydrological behavior with similar morphometric features (Fig. 5 and Table 3) but with different salinity levels. The results of this study show that the new lagoons (especially L01) seem to be more influenced by annual mixing than by evaporation, and possibly due to underlying low-permeability layer distributions that influence the efficient connection with the aquifer. This is supported by Menció et al. (2017), who found that groundwater contributions could be as high as 80 % in the dry season. Therefore, lagoon salinity flux is not only limited by lagoon morphology or by evaporation fluxes, but also by the extent of connection with the aquifer and circulating waters.

5.2.2.1. A lesson learned: The case of G02. As mentioned before, G02 was excavated below sea level to ensure water permanency all year round. However, the underlying lithological characteristics were not taken into consideration and any presence of low-permeability layers

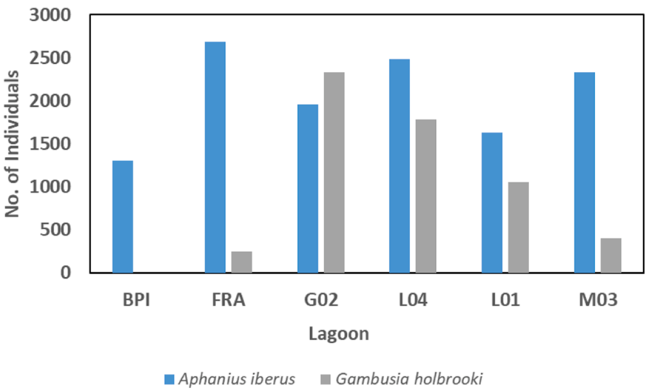

Fig. 7. Species abundance for *Aphanius iberus* and *Gambusia holbrooki* from 2018 to 2019. Large numbers were capped at 100 for each trap during the census. *Aphanius iberus* was introduced into the new lagoons between 2016 and 2018.

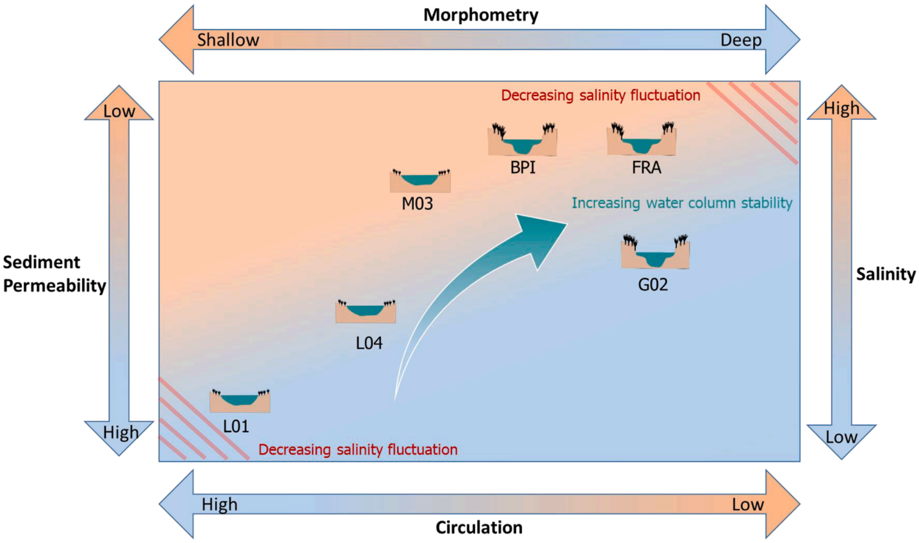

Fig. 6. A conceptual model describing the hydrological stability and salinity fluctuation in a highly variable system. Individual lagoons are distributed according to their sediment permeability, morphometry, circulation and salinity level. Relationships reveal more hydrological stability with lower circulation and water level fluctuations, while salinity fluctuations are reduced to either consistently high or low according to the depth of their morphometric features and connection with the aquifer.

were probably removed during construction. At the time, the intention was to increase refuges for the *Aphanius iberus*. However, in the years that followed, G02 showed higher circulations and consistently lower salinity levels than the desired fluctuations, with evidence of a higher connection with the aquifer (Casamitjana et al., 2019). This has resulted in higher populations of *Gambusia holbrooki* (Fig. 7). Knowledge of this inspired the preservation of low permeability layers during the construction of the new lagoons in 2016, in the hope of reducing an efficient connection with the aquifer and increase salinity fluctuations. As the results of this study suggests, there has been an element of influence from low-permeability layers, and early indications suggest that the *Aphanius iberus* is benefitting from these measures (Fig. 7).

5.3. A tentative conceptual model

Our observations offer some conceptual insight into the La Pletera salt marsh hydrology as summarized in Fig. 6. In a coastal lagoon system that is highly variable, finding an annual pattern related to hydrological, biogeochemical, and ecological functioning can be challenging. With the exception of surface temperature, variation among the lagoons of the La Pletera salt marsh is high, with a range of 30% to 127 % for all variables (Table 6), illustrating the diversity in lagoon structure and hydrological behavior. Variation within the individual lagoons is also very high, indicating the different ways individual lagoons behave to external climatic and hydrogeological influences. This results in a hydrologically dynamic system with correlating parameters often overlapping when analyzing relationships, which can be seen in the correlation matrix in Table 7. This has been noted in other studies, where the overall hydrology is strongly conditioned by the Mediterranean climate, which is irregular and unpredictable and cause wide fluctuations in lagoon physical, chemical, and biological composition (Álvarez-Cobelas et al., 2005; Beklioglu et al., 2003; Fernández-Aláez, et al., 1999; Quintana et al., 2006; Romo et al., 2004).

Despite this unpredictability and variability, our results suggest an emergence of annual patterns of salinity levels and more hydrological stability (less water circulation). These are seemingly determined by morphometric features and distributions of underlying low-permeability layers, despite all having the same climatic limitations. This interaction is better summarized in the conceptual model in Fig. 6, where all 6 lagooń s hydrological patterns of circulation and salinity levels are plotted according to their morphologies and the presence or absence of low-permeability layers. Lagoons that are efficiently connected with the aquifer and are shallow in terms of their morphometric features (higher surface area to volume ratios), tend to exhibit higher circulation and less variation in salinity (in our case low salinity as freshening was occurring from groundwater inputs in L01). Conversely, lagoons that are deeper with less surface area to volume ratios and have low permeable underlying layers, tend to exhibit more hydrological and salinity stability, with lower circulation and higher salinity levels (FRA). This illustrates that hydrological variability within the lagoons can be proportional to their physical and geomorphologic variability. When comparing the restoration of the new lagoons to the natural lagoons, we can see that the topographical distribution, morphology, and underlying lithology preservation resulted in distinct hydrological behaviors. The new lagoons' inflows and outflows that occur during high precipitation and sea storm events override the annual patterns of confinement seen in the natural lagoons, and are more susceptible to climatic influence in their annual hydrological pattern. Studies have noted that confined coastal lagoons in arid or semi-arid regions with little freshwater inflow, limited water exchange with the sea and high evaporation rates may result in longer turnover times, more stable water columns and become highly saline (Copeland, 1967; Moore and Slinn, 1984; Saccà, 2016). While small in scale, our study has shown the extent of variation among and within the lagoon systems and highlights the importance of morphology and groundwater contributions in a system highly driven by climatic changes. From a restoration perspective, understanding hydrological behavior and parameters that drive them can help to achieve specific ecological functioning objectives outlined in a project.

5.4. *Aphanius iberus* conservation and ecological functioning.

In terms of conservation efforts of the *Aphanius iberus* versus the *Gambusia holbrooki*, an important aspect that often influences their population dynamics is varying climate, i.e. the wet years (which usually results in less salinity in the lagoons) favor the *Gambusia holbrooki*, while the dry years favor the *Aphanius iberus* (with more salinity). Nevertheless, two aspects arise from the conceptual model drawn in Fig. 6. First, lagoons with less permeable sediments with resulting higher water salinity, and/or less deep water columns with higher salinity fluctuations appear to be the more suitable conditions for *Aphanius iberus* (brown parts of Fig. 6). Second, there is a trade-off in these *Aphanius iberus* favorable conditions: shallow lagoons facilitate salinity variability (depending on the connection with the aquifer), but with more risk of desiccation during dry years, while deep lagoons prevent desiccation, but exhibit less salinity variability in wet years. The actual populations and distributions of the two species from 2018 to 2019 can be seen in Fig. 7, where BPI, FRA and M03 held better numbers of *Aphanius iberus* versus *Gambusia holbrooki*, despite the significant rainfall and sea storm events (Fig. 4 C, D). Therefore, a combination of several different water bodies, with different morphologies and water depths, seems to be the best solution to ensure the conservation of *Aphanius iberus* in restored Mediterranean salt marshes.

In terms of ecological functioning, the La Pletera salt marshes have seen plant succession towards more mature habitats over the years following the construction of the lagoons and restoration of the area. The intention was to create rich and diverse mosaic of habitats and some halophyte populations have already been established in areas of high salinity, while the perennial and globally distributed *Rupia cirrhosa* has already started to colonize the new lagoons (Bou et al., 2018). This species is of great importance in the La Pletera, as it not only usually grows in deeper waters and tolerates more saline conditions, but it also creates favorable habitats for the *Aphanius iberus* (Bou et al., 2018). Therefore, the management and conservation of both these species could fall within the same favorable conditions, depending on lagoon morphology and the presence and absence of low-permeability layers. Also, investigation into ecosystem metabolism dynamics of the old and new lagoons, from 2016 to 2018, found that although the Gross Primary Productivity to Ecosystem Respiration values (GPP:ER) were close to 1, G02 and FRA were slightly heterotrophy and the potential productivity occurred in winter, when nutrient loading occurs from water inputs (Bas-Silvestre et al., 2020). Another study by Carrasco-Barea et al. (2018) found that carbon storage in sediments were 3-fold higher in BPI, FRA and G02 than in L01, L04 and M03. Although G02 had not reached the same levels as the natural lagoons, it was concluded that lagoon age is an important factor determining carbon storage. A similar idea was hypothesized by Boadella et al. (2021) that investigated microbial heterotrophic functioning. This study suggested that after 15 years of restoration, G02 could achieve functional recovery through organic matter and nutrient cycling, while it was difficult to conclude completed restoration of the new lagoons 1 year after construction (2017). From a hydrological perspective, the magnitude of water inputs and circulation facilitating nutrient loading could be influenced by an efficient connection with the aquifer and/or susceptibility to climate events and surface inputs due to shallower lagoon morphology. This could ultimately influence GPP and ER, as well as the entrance and cycling of organic matter.

Overall, the construction and restoration of the La Pletera salt marshes have been largely successful in terms of restoration criteria established in Quintana et al. (2018). These include the preservation of the flooding-confinement model, increasing existing colonies of the Iberian toothcarp by increasing salinity fluctuations and conserving the ecological functioning of the ecosystem. The different lagoon morphologies and varying permeability layers have not only influenced salinity levels, but also the heterogeneity of water circulations and levels of confinement, which is typical of these ecosystems and to which all the species present are adapted. As the hydrological behavior of the lagoons has already been established by the GLM, further study into water quality by means of aquatic ecology modeling is a logical next step in providing deeper insight into not only the effects of hydrology and hydrogeology on the nutrient cycle, but also the response of the lagoon communities to different scenarios driven by increased or decreased anthropological activities and climate change.

6. Conclusions

Increasing anthropogenic activity threatens to degrade Mediterranean coastal lagoons and reduce their numbers. With an ever-increasing need to protect and restore coastal lagoons, comes also the need to increase our mechanistic understanding of coastal wetland hydrology and ecohydrological processes. One of the main restoration objectives of the La Pletera saltmarshes is the conservation of the endangered Iberian toothcarp, which requires higher salinity fluctuations. The construction of the new lagoons in the La Pletera saltmarsh preserved the underlying low-permeability layers, to create more of a confined pattern during the summer months and increase salinity levels. Our results indicate that while the presence and absence of low-permeability layers can influence salinity fluctuations, lagoon morphometry can also promote hydrological and salinity stability. The interplay of these two parameters, however, can also have overriding effects on annual hydrological and salinity patterns. This could prove important when constructing and restoring lagoons according to predetermined morphology and underlying sediment patterns, as it could ultimately limit or enhance the success of set objectives and overall ecological functioning in a flooding – confinement driven lagoon ecosystem conditioned by irregular and unpredictable climatic events.

CRediT authorship contribution statement

Warren Meredith: Conceptualization, Formal analysis, Visualization, Writing – original draft. **Xavier Casamitjana:** Methodology, Conceptualization, Writing – review & editing. **Xavier D. Quintana:** Conceptualization, Writing – review & editing. **Anna Menció:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is provided in the supplementary material, as well as in the online repository

Acknowledgements

The authors would like to thank Mònica Martinoy and Josep Pascual, who provided the water level, salinity measurements, and meteorological data for the La Pletera lagoons. WM benefited from a Ph.D. grant (IFUdG 2019) from the University of Girona. Financial support was provided by the Life + Program from the European Commission (Life Pletera; LIFE13NAT/ES/001001), the *Ministerio de Economía y Competitividad* (CGL 2016-76024-R AEI/FEDER/UE) and the *Ministerio de Ciencia e Innovacion* (PID2021-123860OB-100) and the European Commission-Horizon 2020 (H2020-LCCLA-2019-2). Open Access funding provided thanks to the CRUE-CSIC agreement with Elsevier.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128259.

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