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Abstract: Coastal wetlands are among the most productive and fluctuating ecosystems of the world. These ecosystems, however, are affected by human activities that may change their nutrient dynamics and water regime, causing the degradation of water quality, the disappearance of lagoons and wetlands, or the establishment of invasive species. In this context, the La Pletera salt marsh is composed of several coastal lagoons and wetlands that were affected by the incomplete construction of an urban development in 1987. This area has been the focus of two LIFE restoration projects aimed at recovering its ecological functionality, and protecting a threatened endemic fish species (Aphanius iberus). Thanks to these projects, a new lagoon was created in 2002 simply by excavating below sea level, which ensured water permanency all year round. Between 2014 and 2017, samples were regularly taken to measure temperature, salinity and water levels in the lagoons of the La Pletera salt marsh. In this study we focus on two natural lagoons (Life A and Life B), and the one created in 2002 (Life C). Using the one-dimensional General Lake Model (GLM), we evaluated water inflows and outflows and evaporation fluxes, since water circulation determines the resultant salinity in these lagoons. This model is an open source model that, to our knowledge, is being used for the first time in such small lagoons. The study focuses mainly on dry periods, when the lagoon inflows decrease and evaporation increases. Results show that Life A and Life B are more affected by evaporation and that lagoon water circulation was higher in Life-C. From a management point of view, the maintenance of salinity conditions is fundamental for the protection of Aphanius iberus, a species adapted to high salinity fluctuations but strongly affected by competition from the invasive gambusia (Gambusia holbrooki) when water salinity is not high enough or variable. During 2014 and 2018 additional lagoons were created in the La Pletera salt marsh as part of a new LIFE project. Knowledge of the hydrology and the resultant water salinity in the new lagoons are

essential to ensure the continued survival of Aphanius iberus in the area.

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Dear Associate Editor,

Thank you very much for reviewing our manuscript. We also greatly appreciate the reviewers for their comments and suggestions. Please, find attached a point-by-point response to reviewer's concerns for the manuscript **HYDROL29614**. We hope that you find our responses satisfactory and that the manuscript is now acceptable for publication.

Xavier Casamitjana

COMMENTS FROM EDITORS AND REVIEWERS

Associate Editor :

after going through the comments and manuscript, I found that the manuscript needs a lot of improvement in documentation and technical contents. The authors have mentioned the model name and its citation. for more readable, at least fundamental equations used in the model are required. The discussion should highlight major findings and scientific contribution clearly.

The fundamental equations of the model have been added and the whole methods section have been changed to include a larger description of the model. One new table and two new figures have been added to clarify the main findings. The Highlights have been completely changed and the discussion modified to highlight the main findings of the paper. We typed in red all the added or modified sections to better help the revision.

Reviewer #1:

General comments
A potentially interesting study, but the paper has a number of flaws, including the discussion of the results. The authors need to address the issues below, and then see if this impacts on their conclusions (I haven't reviewed these due to the issues in the paper). As such, the paper will need further review after revision.

Specific comments
1. Highlights: need to consider revising these. All dot points are too long (maximum allow is 85 characters including spaces - closest is the second dot point, and this has just over 100 characters). First highlight is too general, and not informative. 3rd highlight: reason for the lower salinity in the third lagoon is not the age, but rather an issue with the construction (not engineered to ensure a higher salinity at the end of the summer. 4th point doesn't capture everything (misses the salinity of the inputs) but suggests that it does cover all the key drivers. 5th point is not a highlight of the paper as this is not the focus of the research discussed here. This is a highlight of earlier work on this issue.

All the highlights have been changed

2. Line 18: "La Pletera salt marsh is composed …"

3. Line 31: "… 2014 and 2018, additional lagoons …"
4. Line 37: 2nd highlight: "3 year" rather than "3 years"
5. Line 67: "coastal enclosed lagoons" uses different terminology (enclosed) from that introduced earlier (open and closed). Is this different (if so define what enclosed means), if not, use "closed"
6. Line 73: "is composed" rather than "are composed". Would be "are" if using "The La Pletera salt marshes …"

2-6 corrected

7. Line 79: given only 11 years have been used to estimate the mean, how representative is this period in terms of longer-term variability?

Is the period during what ACA (Water Catalan agency have data). 10 years is normally considered a representative time series for meteorological data.

8. Line 94: again, different terminology "confined" introduced.

This is the word used in the work of Trobajo et al 2002 and Quintana et al., 1998, however in our work we prefer the word enclosed.

We change to: Therefore, lagoons in the area were defined by Trobajo et al. (2002), as confined coastal lagoons

9. Line 135: Suggest something like "Vertical profiles of salinity and temperature were measured …"

ok

10. Line 151: if adjusting the inflows and outflows to match the known water volumes, then cannot use the water levels as a measure of the performance of the model? How do you decide which to adjust?

11. Line 152: again, need information on how this was done. Given what is said on the next page, may be better to say something like "the temperature and salinity profiles were used to set parameters defining the water circulation characteristics (e.g. outlet water level).

10 and 11- We changed the whole section of methods to avoid confusion. See the first two paragraphs in the section 2.2 Application of the model

12. Line 174: manually calibrated and set? Calibrated against what? What is the calibrated value a typical one? Is this a validation, or was 1.7 tested because it is a typical value?

Now it is written:

As the GLM uses a constant light attenuation factor, this parameter was set to 1.7 m^{-1}, a typical value for eutrophic waters (Armengol et al., 2003).

13. Line 180: "as this gave the best fit for temperature and salinity."

ok

14. Line 182: So the salinity variations were used to determine the outlet level? Try not to leave the reader guessing what you did.

Now it is written:

Therefore, the temperature and salinity profiles can be used to determine the outlet level. The fact that the outlet level was not at the deepest point of the lagoon can be explained by taking into account that the lagoon bottoms are covered by fine sediments, making any exchange of water with the aquifer at this point less feasible

15. Line 189: hence the model is not sensitive to this parameter in this case, so little information is available on where the inflow is coming from?

As the lagoons depth are so small and mixing very active, there is not much difference if the water enters the surface or the bottom.

16. Line 194: Suggest "estimated" would be better here than "determined" as the fit to the bathymetry has been used, and therefore there is some uncertainty?

Ok. As there are not measurements of the inflows and ouflows, they have to be estimated from the water level of the lagoons

17. Line 196: some additional information must have been used, otherwise there would be in infinite number of possible values as you are setting two quantities based on 1 piece of information (you could increase inflow, and offset by an increase in outflow). Presumably, the outflow is determined from the water level in the lagoon? If so, you are not determining the outflow, rather the relationship between outflow and lagoon water level.

The rev. is right. The calculation of how to estimate the inflows and outflows was a little confusing. Now we changed the whole section. See 2.2 Application of the model, to explain how it was done.

18. Line 201: can these be determined uniquely given the available information?

19. Line 204: This cannot be correct. Shouldn't the 1/O_i be 1/mean O?

the formula was incorrectly typed and has been modified

20. Line 206: The term inside the summation in the numerator and denominator should be squared

the formula was incorrectly typed and has been modified

21. Line 209: is this for lagoons, or generally (e.g. rainfall runoff models). A very subjective statement, and of little use in this case.

Is for hydrological models, can be found in the references

22. Line 213: "kg" rather than "Kg"

ok

23. Line 216: "average time for its calculation increases" is wrong. This suggests time taken for doing the calculation influences the accuracy of the calculation.

Ok, now it is written:

The accuracy of E would decrease as the measurement interval of q increases.

24. Line 217: what is the error for daily time steps? What is the impact of this uncertainty on the model?

Taking into account that water levels were determined on a daily basis, and salinity and temperature were determined bimonthly, it has been considered sufficient to use a daily time scale for the model.

25. Line 226: How temporally variable were these allowed to be? Not done on a daily basis I assume?

The GLM model uses daily data for the inflows (volume, temperature and salinity). The last step consisted of setting up the temperature and salinity of the inflow at a value that made the modeled and field profiles of these magnitudes similar. As there are not experimental measures of these magnitudes variations were allowed at a bimonthly scale

26. Line 230: Probably self evident, but maybe use ppt by mass to distinguish from ppt by volume?

It has been added: parts per thousand in mass fraction

27. Line 240: could be determined *from the data rather than then model?*

The results would be very similar for both cases

28. Line 250: do you have any data on the horizontal variability? If so, then presumably you are comparing the model to the horizontally averaged values, which means you can make use of the standard error in the mean. If you don't have any information on the horizontal variability (i.e. you have 1 measurement point), then you don't know whether this represents the mean value?

Data of temperature and salinity for the time series used in the model has been taken at the centre of the lagoons. At certain periods data at the borders also exist showing small variations.

29. Line 264: "inputs to Life C are higher than those to Life B"

ok

30. Line 280: Presumably 0.0005 cubic metres per day?

ok

31. Line 284: somewhat repetitive (c.f. last sentence of previous paragraph.

Results commented here are ones of Table 6, and in the last paragraph the ones of Figure 6, showing, of course similarities.

32. Line 291: again, a little repetitive

0k

33. Line 297: what drives the spatial variability in groundwater salinity?

ok

34. Line 299: Need to rephrase - incorrect grammar

Changed to:

These results match those obtained by Sadat-Noori et al. (2016), who observed inputs of the shallow brackish hypersaline pore water into the lagoons, during the winter months, when groundwater levels rise.

35. Line 309: but higher than sea salinity inputs for A and B, so is evaporation or inputs the main driver?

The groundwater inflows into these lagoons, mostly occurring during autumn cyclonic storm events, have characteristics similar to summer water outflows from these lagoons to the aquifer That's to say: Summer evaporated water circulates in the aquifer and go back to the lagoon

36. Line 501: I assume this should be Life C rather than Life B?

OK

37. Figure 4: There is obviously a problem with modelling the variation in salinity between days 600 and 800 for Life C. Authors should comment on the cause of this, and how this can be corrected.

It has been added the following comment:

Also, in Life-C, around day 700, the mixing estimated by the model is stronger and the variation of the predicted salinity was abrupter than the real one. Different reasons may account for this: the use of a constant light attenuation and mixing parameters (Table 3) and the lack of accuracy of one-dimensional models in situations of strong mixing (Imberger and Patterson, 1981)

38. Figure 7: surface area decreases with increasing water level makes no sense. Better to use a functional form that prevents this rather than a simple polynomial fit. Obviously, fit was done with the axes swapped. Need to ensure monotonicity.

Arranged

Reviewer #2:

Dear Authors and Editor,

Thanks for your kind invitation to review the manuscript entitled "Modeling the salinity fluctuations in the lagoons of the La Pletera salt marsh" by Xavier Casamitjana, Anna Mencio, Xavier D. Quintana, David Soler, Jordi Compte, Monica Martinoy and Josep Pascual.

This document investigates the hydrological cycle of a marsh called La Pletera, which is located next to the Mediterranean Sea in Spain. The study is carried out in three lagoons where there is a threatened fish species, Aphanius Iberus, whose conservation depends to a large extent on the fluctuations of water salinity and temperature, so the study can be useful for stakeholders in the conservation of the lagoon's ecosystem. The origin and magnitude of fresh and salt water that feeds the lagoons and evaporation to estimate the water balance is investigated.

This work seems interesting to me, but I think it has a weak part that needs to be reinforced, I think there is a lack of materials and methods, so I recommend Major Revision. Below are my suggestions I hope they are helpful:

1. As minor issues there are formal aspects to improve: please, number equations, number all sections (in particular conclusions) and review the format of the bibliographic citations, e.g., sometimes the name of three authors is used in a citation. In the title, the international reader does not know where La Pletera was located please add the name of the country.

OK. Arranged.

2. In Figure 1, I believe that two aspects should be improved, placing the study area with better precision and better describing geology and hydrogeology. I recommend separating into two figures:
* It is difficult to locate the area of study. I recommend a map at a country scale, like the current one, and another map with more detail (e.g. the size of the current geological map) with georeferencing (coordinates). Place the rain gauge station here. The satellite map of the lagoons is fine, but another one of great precision is needed with the three lagoons.
* The current geological map is quite clear, but one or two geological cross sections are needed to identify the geology of the subsoil, possible Mesozoic or Cenozoic aquifers that can act as underground recharge of the lagoons, etc

A new figure has been added. Now figure 1 presents the geographical and geological situation, and hydrogeological cross sections of the study area. And Figure 2 is an aerial view of the Pletera marsh lagoons. Explanations for the Figures have been added. See also 112-116 for a better description of the geology.

3. Regarding the freshwater recharge, a division between surface and groundwater is not clear. It would be necessary to delimit the surface water catchment area and the surface drainage network that reaches the lagoons. Also the groundwater recharge zones. Please, indicate if there is any direct outlet of surface water to the Mediterranean Sea and what is the exit level in relation to the water level of the lagoons.

As can be seen now from Fig 1 and 2 there are not freshwater recharge to the lagoons and direct outlets to the sea. The surface catchment area of the Pletera lagoons is really small, comprising a very flat area with a surface smaller than 4 km^2, and without permanent or temporal streams arriving to the lagoons. In addition, the studied lagoons only receive freshwater runoff (as overland flow) during cyclonic storm events. According to Menció et al. (2017), the most important water inputs in these lagoons occur suddenly during intense precipitations and cyclonic storm events (mainly in spring and autumn), when freshwater, as well as sea water, may enter these lagoons. In particular, during cyclonic storm events associated to stronger easterly winds (known as ‘‘Llevantades”), sea level may rise more than 1 m (Marquès et al., 2001). In these periods, sea waves may enter in some of the lagoons (LFB and LFC) as surface water inputs. This input, together with freshwater surface, sub-surface (which percolate laterally through the topsoil) and ground water inputs, may cause an increase of 0.3–0.9 m.

4. As the bathymetry of the lagoons is known, it is necessary to provide the storage curve (volume vs water level of the lagoon and area vs water level of the lagoon(for the evaporation model)) for each lagoon in absolute values, the polynomial adjustment mentioned in the text, with its corresponding equations, and the performance analysis of these fits.

Now a new table has been added (Table 4), where the volume vs water level is provided together with R^2

5. A temporary graph with the absolute values measured of the water level in the three lagoons would be necessary and observe similarities and differences. Indicate if there could be groundwater flow between lagoons in the case the lagoons have different absolute water level.

We added a new figure (Fig. 3) showing the variations of water levels.

6. In Figures 2, 3, etc., it is doubtful to identify to which lagoon each graph belongs. Please identify with better clarity the correspondence between lagoons with graphics.

The figure captions were changed to reinforce this.

7. In google earth urbanization roads are observed. Please, indicate if there has been influence for the lagoons due to the presence of urbanization. Indicate if there has been any other significant change in land uses and their influence. Please, provide quantifications.

One new paragraph have been and another one have been modified in the Introduction to respond to reviewer demand (see lines 92-101; 103-141)

8. Regarding the water balance in the lagoons, it is not clear. An average balance of three years of research would be needed, with storage, inflows of groundwater, surface water and salt water, and outflows of groundwater, surface water and evaporation.

Is difficult to establish the water balance in the lagoons because inflows are composed by a mixture of surface, subsurface and underground waters and there are not available measurements on the relative amount of each. In a previous study Menció et al. (2017) showed that during the dry season groundwater inputs dominate. Because of that, the conclusions of our study are addressed for the dry periods, when the water circulation is mainly due to groundwater. The water balances for inputs, outputs and evaporation fluxes in these periods are showed in Figure 8 and in Table 7.

Abstract

Coastal wetlands are among the most productive and fluctuating ecosystems of the world. These ecosystems, however, are affected by human activities that may change their nutrient dynamics and water regime, causing the degradation of water quality, the disappearance of lagoons and wetlands, or the establishment of invasive species. In this context, the *La Pletera* salt marsh is composed of several coastal lagoons and wetlands that were affected by the incomplete construction of an urban development in 1987. This area has been the focus of two LIFE restoration projects aimed at recovering its ecological functionality, and protecting a threatened endemic fish species (*Aphanius iberus*). Thanks to these projects, a new lagoon was created in 2002 simply by excavating below sea level, which ensured water permanency all year round. Between 2014 and 2017, samples were regularly taken to measure temperature, salinity and water levels in the lagoons of the *La Pletera* salt marsh. In this study we focus on two natural lagoons (Life A and Life B), and the one created in 2002 (Life C). Using the one-dimensional General Lake Model (GLM), we evaluated water inflows and outflows and evaporation fluxes, since water circulation determines the resultant salinity in these lagoons. This model is an open source model that, to our knowledge, is being used for the first time in such small lagoons. The study focuses mainly on dry periods, when the lagoon inflows decrease and evaporation increases. Results show that Life A and Life B are more affected by evaporation and that lagoon water circulation was higher in Life-C. From a management point of view, the maintenance of salinity conditions is fundamental for the protection of *Aphanius iberus*, a species adapted to high salinity fluctuations but strongly affected by competition from the invasive gambusia (*Gambusia holbrooki*) when water salinity is not high enough or variable. During 2014 and 2018 additional lagoons were created in the *La Pletera* salt marsh as part of a new LIFE project. Knowledge of the hydrology and the resultant water salinity in the new lagoons are essential to ensure the continued survival of *Aphanius iberus* in the area.

***Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights

- Good response of the Lagrangian layer models to small lagoons.
- A prediction of the water fluxes in the studied lagoons was obtained.
- Lagoons presented higher evaporation ratios with higher Surface/Volume ratios.
- Differences in water circulations caused different salinities in summer.
- Summer evaporated water returned to the lagoons during autumn cyclonic storm events.

MODELING THE SALINITY FLUCTUATIONS IN THE LAGOONS OF THE *LA PLETERA* SALT MARSH

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Abstract

Coastal wetlands are among the most productive and fluctuating ecosystems of the world. These ecosystems, however, are affected by human activities that may change their nutrient dynamics and water regime, causing the degradation of water quality, the disappearance of lagoons and wetlands, or the establishment of invasive species. In this context, the *La Pletera* salt marsh is composed of several coastal lagoons and wetlands that were affected by the incomplete construction of an urban development in 1987. This area has been the focus of two LIFE restoration projects aimed at recovering its ecological functionality, and protecting a threatened endemic fish species (*Aphanius iberus*). Thanks to these projects, a new lagoon was created in 2002 simply by excavating below sea level, which ensured water permanency all year round. Between 2014 and 2017, samples were regularly taken to measure temperature, salinity and water levels in the lagoons of the *La Pletera* salt marsh. In this study we focus on two natural lagoons (Life A and Life B), and the one created in

2002 (Life C). Using the one-dimensional General Lake Model (GLM), we evaluated water inflows and outflows and evaporation fluxes, since water circulation determines the resultant salinity in these lagoons. This model is an open source model that, to our knowledge, is being used for the first time in such small lagoons. The study focuses mainly on dry periods, when the lagoon inflows decrease and evaporation increases. Results show that Life A and Life B are more affected by evaporation and that lagoon water circulation was higher in Life-C. From a management point of view, the maintenance of salinity conditions is fundamental for the protection of *Aphanius iberus*, a species adapted to high salinity fluctuations but strongly affected by competition from the invasive gambusia (*Gambusia holbrooki*) when water salinity is not high enough or variable. During 2014 and 2018 additional lagoons were created in the *La Pletera* salt marsh as part of a new LIFE project. Knowledge of the hydrology and the resultant water salinity in the new lagoons are essential to ensure the continued survival of *Aphanius iberus* in the area.

Highlights

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Keywords:

Coastal lagoons, Salt marsh hydrology, General Lake Model, Salinity fluctuations, Hydrological regime, Lake Modelling

1. INTRODUCTION

Coastal wetlands have usually been described as the confluence of inland and marine water. These ecosystems are considered among the most fluctuating and productive in the world, performing a wide range of services, including shoreline stabilization, sediment and nutrient retention, and coastal water quality buffering (Mitsch and Gosselink, 2000; Costanza et al., 1997; Gedan et al., 2011; Beer and Joyce, 2013).

Depending on their connection to the sea, coastal lagoons are categorized as open or closed lagoons. This second group includes lagoons that have no sea connection or only a short period of connection (Kjerfve and Magill 1989, Félix et al., 2015). Intermittently closed and open lagoons are characterized by their shallowness (less than 5 m deep, approximately), which results in a high ratio of sediment surface area to water volume, thereby increasing the relative importance of sediment-water column interactions (Tyler et al., 2001). In these systems, salinity can vary significantly (from fresh to brackish or hypersaline), depending on the amount of freshwater input, the climate, and the frequency and duration of the opening (Ridden and Adams, 2008). These lagoons have often been perceived as a surface expression of shallow aquifers and are thought to be fed by groundwater inputs during most of the year. As a result, they are vulnerable to minor changes in catchment and groundwater hydrology (Chikita et al., 2015; Sadat-Noori et al., 2016; Menció et al., 2017; Rodellas, et al., 2018).

The settlement and structure of biological communities in coastal closed lagoons are driven by morphological characteristics and freshwater inputs, which may vary naturally or due to human pressures on their flow rates and biogeochemical characteristics (Britton and Crivelli 1993; Alvarez-Cobelas et al., 2005; Beklioglu et al., 2007). Moreover, changes in water regimes cause the degradation of water quality, the disappearance of lagoons and wetlands, or the establishment and expansion of invasive species (Crivelli, 1995; Pérez-Ruzafa et al., 2002; O'Connell, 2003; La Jeunesse and Elliott, 2004; Badosa et al., 2007).

The *La Pletera* salt marsh is composed of wetlands and some coastal lagoons that were affected by the incomplete construction of an urban development in 1987. This protected area is located to the north of the mouth of the River Ter (NE Spain, Catalonia; Fig. 1 and Fig. 2), in a region dominated by agriculture and tourism. It presents a sub-humid Mediterranean climate with a mean annual temperature of 16°C and an average rainfall of 590 mm/year (Estartit meteorological station, 1966–2016 period; Pascual, 2017; www.meteolesrtartit.cat; and Montaner , 2010). The River Ter is the main watercourse (Fig. 1) and presents a mean discharge of 8.74±0.29 m^3/s in Torroella de Montgrí

(2006–2016 period; ACA, 2016; www.gencat.net/aca). Flooding events caused by the River Ter in the studied area have been reduced due to the construction of several dams upstream during the 1960s, and river channeling in the 1970s. Besides, the construction of several levees in different points of the marsh area isolated some of the lagoons from surficial freshwater runoff, and any permanent or temporal stream reaches these lagoons (Fig. 2).

La Pletera was affected by building works for a residential estate in the late 80s, and then discontinued in the 90s. Since then, it has been the focus of two LIFE Nature restoration projects (http://lifepletera.com/en/life-pletera/) aimed at recovering its ecological functionality. Through the first Life project (LIFE99NAT/E/006386), lagoons were first created in 2002 by simply excavating below the sea level, which ensured water permanency all year round. During the second LIFE project, in 2016 (LIFE13NAT/ES/001001), the remaining urban features (promenade, accesses, filling material, breakwaters, and debris) were dismantled and substituted by a set of new lagoons with different shapes and depths to have lagoons with distinct salinity and temporality characteristics (Quintana et al., 2018). However, in this study we focus on two old lagoons (Life A and Life B) and one created in 2002 (Life C).

The most important water inputs are produced during intense precipitations and cyclonic storm events, when freshwater, as well as sea water, may enter the lagoons. In particular, during cyclonic storm events associated with stronger easterly winds (known as *llevantades*), the sea level may rise more than 1 m (Marquès, Psuty and Rodríguez, 2001). In these periods, sea waves may enter in the saltmarshes, and together with surface, subsurface and groundwater runoff, may cause an increase of 0.3-0.9 m in the level of the marsh. Therefore, lagoons in the area were defined by Trobajo et al. (2002), as confined coastal lagoons, due to the absence of continuous surface water inputs. Rather, their hydrology is strongly dominated by the sea, with sudden flooding events during sea storms, followed by long periods of confinement, when salinity increases and water level decreases tending towards desiccation (Quintana et al., 1998, 2018; Badosa et al., 2006; López-Flores et al., 2006).

Hydrogeologically, the Pletera salt marsh area is linked to the shallowest level of the Quaternary sediments that constitutes the basin infilling (BTUA in Fig. 1; Menció et al., 2017). This unit acts as an unconfined aquifer, presents a total thickness of 10-30 m, and it is formed by the recent prograding alluvial deposits, which near the coast line are substituted by marsh and coastal deposits (Montaner, 2010; ICC, 2011a,b). Moreover, in a previous study, the origin of the lagoons' water was determined, and its dependence on groundwater resources was assessed (Menció et al., 2017). That study showed that during the dry season groundwater inputs may account for ~80% of the water in the *La Pletera* lagoons. Besides, water salinity depends on two main processes: 1) mixing of fresh and sea water within the lagoons or in the aquifer; and 2) evaporation.

These lagoons are the habitat of an endangered fish species, *Aphanius iberus*, which is endemic to the Iberian Peninsula (Doadrio et al. 2011) and has adapted to the fluctuating conditions of these waters by tolerating a high range of salinity (Planelles-Gomis, 1999). Besides habitat reduction, one of the main problems of *Aphanius iberus* conservation is the presence of *Gambusia holbrooki*, an invasive species introduced to the Iberian Peninsula at the beginning of the 20th century to control the mosquito population. At present, *Aphanius iberus* is relegated to habitats with high salinity fluctuations due to the presence of *Gambusia holbrooki*, which has spread thanks to increased eutrophication and reduced salinity (Alcaraz and Garcia-Berthou, 2007; Ruiz-Navarro et al., 2011). In La Pletera waters, *Aphanius iberus* and *Gambusia holbrooki* have coexisted with strong population oscillations which depend on seasonal and interannual salinity oscillations, with a greater abundance of *Gambusia holbrooki* in oligohaline waters and of *Aphanius iberus* in waters with high salinity fluctuations.

Thus, one of the aims of the restoration project is to promote the increase of the number of refuges for the *Aphanius iberus* population in the area by generating ponds with different salinity, connected during flooding events but remaining isolated during summer (Quintana et al., 2018). In spite of the proximity between one of the studied lagoons (Life C) to the urbanization roads removed by the restoration project, the new created lagoon beside Life C is close to 8 % higher in salinity during the warm period (April to October), indicating a relative isolation between these two nearby lagoons under low water level conditions. Moreover, zooplankton species composition has been described to be similar in existing lagoons and in newly created ones (Cabrera et al., in press), suggesting that the restoration actions did not modify significantly the ecological conditions of the salt marsh.

Given that the conservation of the threatened *Aphanius iberus* is one of the most important management objectives in the zone and that success is highly dependent on water salinity fluctuations, the aim of this study is to analyze the different water circulation patterns observed in the *La Pletera* lagoons, to depict the origin of these differences, and to establish the main guidelines for management policies. We use the one-dimensional General Lake Model (GLM) to assess the water balance and salinity dynamics in the two natural lagoons (Life A and Life B) and in a 12-year-old lagoon (Life C).

2. METHODS

The hydrological dynamics of the two natural lagoons (Life A and Life B) and the 12-year-old man-made lagoon (Life C) of the *La Pletera* salt marsh were modeled. The main characteristics of these lagoons are summarized in Tables 1 and 2. The largest lagoon, Life B, has a maximum volume of nearly 30,000 m^3 and a maximum depth of 3 m. The maximum volume of the smallest one, Life A, is 6 times less than Life B and its maximum depth is only 1.5 m. While the Life A and Life B lagoons originated when a river channel was abandoned, Life C was built in the first phase of the LIFE Restoration Project in 2002. Previous studies conducted in these lagoons have considered them as meso-euhaline water bodies (Badosa et al., 2007; López-Flores et al., 2006 and 2014).

In order to study the hydrological dynamics of the *La Pletera* salt marsh lagoons, water levels were determined on a daily basis, using Schlumberger water level data loggers (accuracy ±0.02m), from November 2014 to September 2017 (Fig. 3). It can be seen that water levels in the three lagoons follow a similar pattern, increasing in the recharge periods and decreasing in the driest ones. In Life A, the smaller lagoon this decrease is greater. Salinity and temperature were determined bimonthly using a CTD profiler (Sea & Sun Technology). While in the deepest lagoon, Life B, vertical profiles of temperature and salinity were measured every 10 cm through the entire water column, in the smallest lagoons, Life A and Life C, measurements were taken only at the surface and at the bottom.

Meteorological data needed to determine the evaporation and precipitation in these lagoons, such as daily maximum and minimum temperature, relative humidity, and precipitation, were obtained from the Estartit meteorological station 2 km from the lagoons (Pascual, 2017; www.meteoestartit.cat). Solar radiation data was obtained from the Sant Pere Pescador meteorological station (*Xarxa d'Estacions Meteorològiques Automàtiques de la Generalitat de Catalunya*) located 10 km north of the *La Pletera*.

2.1 The GLM model

The GLM, developed by Hipsey et al. (2014), computes vertical profiles of temperature, salinity, and density by accounting for the effect of inflows/outflows, mixing, and surface heating and cooling. The GLM incorporates a flexible Lagrangian layer structure similar to several 1-D lake model designs (Imberger and Patterson, 1981; Hamilton and Schladow, 1997). The Lagrangian design allows for layers to change thickness by contracting and expanding in response to inflows, outflows, mixing, and surface mass fluxes. The model accounts for the surface fluxes of momentum, sensible heat, and latent heat using the commonly adopted bulk aerodynamic formulae. GLM is an open-source model developed as an initiative of the Global Lake Ecological Observatory

Network (GLEON), which has been steadily improved after it was first introduced in 2012 and now several publications document simulations using the model (Bueche et al., 2017). However, to our knowledge the model has not been applied to small lagoons that, as in our case, do not exceed depths of 3 m.

The model uses measured, daily-average meteorological data and total daily inflow and outflow data. The surface momentum, sensible heat, and latent heat fluxes are computed from bulk aerodynamic formulae for the stress τ (Nm^{-2}), the sensible heat transfer H (Wm^{-2}), and the evaporative heat transfer E (Wm^{-2})

$$\tau = \rho_A C_D U^2 \quad (1)$$

$$H = -\rho_A C_P C_H U(T_A - T_S) \quad (2)$$

$$E = -\rho_A L_V C_W U(q_A - q_S) \quad (3)$$

where ρ_A= air density; U= wind speed; T= air temperature; q= specific humidity (all daily averaged); and subscripts A and S, air and water surface values, respectively. C_H, C_W and the drag coefficient C_D are bulk aerodynamic transfer coefficients, the values of which are determined by the height at which the data are taken. C_P and L_V are the specific heat of water at constant pressure and the latent heat of evaporation of water, respectively. The water mass evaporation of the lagoons in kg m^{-2} s^{-1}, can be calculated from E/Lv. The accuracy of E would decrease as the measurement interval of q increases. For example, Zhang, (1997) show that monthly mean data can be used to estimate monthly mean surface evaporation to within a relative error of about 10%.

The measured short wave radiant flux is distributed through the water column according to a Beer's law formulation

$$Q(z) = Q_o e^{-\eta z} \quad (4)$$

where Q_o= measured radiation at the surface; Q(z)= the intensity at depth z, and η= the light attenuation coefficient. As the GLM uses a constant light attenuation factor, this parameter was set to 1.7 m^{-1}, a typical value for eutrophic waters (Armengol et al., 2003). In the case of long wave radiation, LW_0, it is assumed to be totally absorbed and emitted by the uppermost layer according to the Stefan-Boltzmann equation:

$$LW_0 = \sigma T^4 \quad (5)$$

where T = absolute temperature; and σ= Stefan-Boltzmann constant, with adjustments made for surface emissivity, cloud cover, and atmospheric constituents.

Surface layer dynamics is based on an integral turbulent kinetic energy model (Imberger, 1998). The turbulent kinetic energy budget is divided into four discrete processes: wind stirring, convective overturn, interfacial shear production, and Kelvin-Helmholtz billowing. The energy available through each of these processes is calculated by the model, and is a function of the nature of the stratification and the strength of the forcing. This energy is compared with the potential energy required to combine the mixed layer with the layer immediately below. If sufficient energy is available, the layers are mixed by averaging their properties, and the available energy decremented by this potential energy gain. The process is repeated until insufficient energy remains within the present time step to continue the deepening process. This residual energy is then added to the available energy in the next time step. The parameterization for the available turbulent kinetic energy (KE$_A$) is

$$KE_A = \frac{C_K}{2}(w_*^3 + \eta_*^3 u_*^3)\Delta t + \frac{C_S}{2}\left(u_1^2 + \frac{u_1^2}{6}\frac{d\delta}{dh} + \frac{u_1\delta}{3}\frac{du_1}{dh}\right)\delta h \qquad (6)$$

while that for the required potential energy (PE$_R$) is

$$PE_R = \frac{C_T}{2}\left[(w_*^3 + \eta_*^3 u_*^3)^{\frac{2}{3}} + \frac{\Delta\rho g h}{\rho_o} + \frac{g\delta^2}{24\rho_o}\frac{d(\Delta\rho)}{dh} + \frac{g\Delta\rho\delta}{12\rho_o}\frac{d\delta}{dh}\right]\delta h \qquad (7)$$

where u_* and w_*= velocity scales for wind shear and penetrative convection, respectively; u_1 = shear velocity at the surface; $\Delta\rho$= density jump between the surface layer (with depth h) and the layer immediately below it (with depth dh); ρ_o is a reference density; δ is the Kelvin-Helmholtz billow thickness scale; Δt = the time step; and g= the acceleration due to gravity.

Hypolimnetic mixing is modeled by a turbulent diffusivity coefficient, D$_z$, the value of which depends directly on the dissipation of the turbulent kinetic energy and inversely on the stratification. The formulation used is based on Weinstock (1981), and is given by the expression

$$D_z = \frac{C_{HYP}\varepsilon}{N^2 + ut_*^2 k_o^2} \qquad (8)$$

Here k_O= wave number of the largest eddies; ut_* is the turbulent velocity scale; ε= dissipation; and C_{HYP} is a constant related to the mixing efficiency of the turbulence.

One of the advantages of models developed from the Dynamic Reservoir Simulation Model (DYRESM), such as the GLM, is that the physical parameters C_K, η_*, C_T, C_S and C_{HYP} are related to the efficiency of the individual mixing processes and do not need calibration; their values are derived from theoretical considerations, laboratory experiments, and field observations (Imberger, 1998) and are set to the usual values (Table 3). However, the minimum volume and thickness of the Lagrangian layers are set to values smaller than usual because of the small volume and shallow depth of the lagoons.

Any number of inflows and outflows can be specified. Depending on the density of the inflow water entering the lake, the inflows will form a positively or negatively buoyant intrusion. As the inflow crosses layers, it will entrain water until it reaches neutral buoyancy. Outflows can be specified at any depth of the water column and are accounted for by removing water from the layer at the depth defined at the outlet point. The GLM also allows for inflow intrusion at a fixed depth and for the case of underground sources.

2.2 Application of the model

As there are not measurements of the inflows and outflows, they have to be estimated from the water level of the lagoons. From the known bathymetry (Table 2), a polynomial fit was used to determine the water volume at any single depth; values of R-squared (R^2) indicate a very good fit (Table 4). Then, by knowing the daily water depth in the simulated period, the real water volume of the lagoons was estimated on a daily basis, followed by the net daily inflow or outflow.

Furthermore, the model was run by setting the inflows and outflows to the net obtained estimated values, and the volumes predicted by the model were compared with the real water volumes. As the model incorporated evaporation and rain fluxes separated from the inflows and outflows, these volumes diverged and inflows and outflows were modified through an iterative process until the modeled and real volumes showed the smallest possible differences. As the inflows and outflows have been estimated from the water level of the lagoons, there were many inflows and outflows compatible with one water level. However, we hypothesize that for a certain day there is only inflow or outflow but not both at the same time. Of course in some situations the real inflow at the lagoon can be higher than the estimated one. This can happen in the periods of heavy rains when the water renewal estimated times were very small (less than 10 days); this normally occurred in Autumn. However, the conclusions of our study are addressed for the dry periods, when the water circulation is mainly due to groundwater.

In the dry periods, variations of the water table are mainly controlled by sea level, since groundwater exploitation in the alluvial aquifer, especially for agricultural purposes is low (Mencio et al., 2017). In most of the monitored wells, where water table is measured at a seasonal basis, the highest differences between campaigns are lower than 1.5 m (in the furthest wells), and lower than 0.75 m (or even 0.5 m) in those wells located closer to the Pletera salt marsh area (considering more than 15 potentiometric campaigns). Therefore, the mean gradient in this area ranges from $5x10^{-4}$ to $1.5x10^{-3}$ approx. In addition, the aquifer in this area is mainly constituted of silts and fine sands, thus having medium hydraulic conductivities (10^{-2} to 10^{0} m/d according to ICC (2011a)), and a mean groundwater flux in this area ranging $5x10^{-6}$-$1.5x10^{-3}$ m/d. This small circulation, is consistent with the previous assumption for the inflows and outflows.

As GLM needs to incorporate the depth of the outlet point, it was chosen at a height between 0 and 0.3 m ASL (see Table 2), as this gave the best fit for temperature and salinity. When the outlet was placed at a deeper point, the salinity layer remaining at the bottom of the lagoons disappeared and the simulated and predicted profiles of salinity diverged sharply. Therefore, the temperature and salinity profiles can be used to determine the outlet level. The fact that the outlet level was not at the deepest point of the lagoon can be explained by taking into account that the lagoon bottoms are covered by fine sediments, making any exchange of water with the aquifer at this point less feasible. Furthermore, some tests have been carried out to determine the height of inflow intrusion. During rainy and stormy periods (mostly in spring and autumn) the inflow is estimated to be a mixture of groundwater and surface water; however, during the rest of the year, when precipitation is lower, the inflow is mostly from underground sources (Menció et al., 2017). However, no remarkable differences were obtained when all the entrances were set as surface. The lagoons' shallow depths also support these findings (Table 2). The last step consisted of setting up the temperature and salinity of the inflow at a value that made the modeled and field profiles of these magnitudes similar. As there are not experimental measures of these magnitudes variations were allowed at a bimonthly scale Table 5 shows results for 2015; similar values were obtained for the rest of the simulated period.

Simulation performance was assessed using the commonly applied root-mean-square relative error (RMSRE)

$$RMSRE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{P_i - O_i}{O_i}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

and Nash-Sutcliffe efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (10)$$

with O observed, $\bar{O}$ observed mean and P predicted values. The NSE ranges between –∞ and 1.0 (perfect fit), and a value of zero indicates that the modeled mean is identical to the observed mean. Threshold values between 0.5 and 0.65 have been suggested to indicate a model of sufficient quality (Krause et al. 2005).

3. RESULTS AND DISCUSSION

3.1 Water volume, temperature and salinity evolution

In Figures 4a, 5a, and 6a the values of the real volumes estimated from the water levels of the Life A, B and C lagoons are compared to the GLM volume values. According to these figures, the model fits better when the volume of the lagoon is higher and is more difficult to adjust when volumes are small, i.e. during summer, or when volumes suddenly change. The RMSRE values are ~10% and the NSE is ~0.9 on average for the three-year period, which can be considered a fairly good adjustment given the sudden changes in volume (Table 6). In Life A and Life B during the summer, inflow salinities were set to a value sometimes higher than the seawater value (Table 5), while in Life C the salinity is close to the sea water value, which is expected to be around 30 ppt (parts per thousand in mass fraction). In the other seasons the contribution of groundwater increases and the salinity decreases to around 18 ppt in the coldest months. Temperature values in the dry season are set to 17ºC, a value close to the expected aquifer temperature (Menció et al., 2017). During the rest of the year this value changes, except in Life C, which remains steady, indicating that the water inflow comes mostly from the aquifer.

Results of the model show good agreement between experimental and predicted surface salinity for the three lagoons (Figs. 4b, 5b, and 6b). Salinity in the three lagoons increases in summer, showing the maximum peaks in the summer of 2015 (around day 700). The model fails to simulate the exact salinity of these peaks, especially in Life A. Also, in Life-C, around day 700, the mixing estimated by the model is stronger and the variation of the predicted salinity was abrupter than the real one. Different reasons may account for this: the use of a constant light attenuation and mixing parameters (Table 3) and the lack of accuracy of one-dimensional models in situations of strong mixing (Imberger and Patterson, 1981).

The very small value of the total volume (~50 m^3 for Life A; see Table 1) and the high values of the salinity that may cause errors in the CTD readings are probable causes of this. It is also clear that, although surface temperature in the lagoons is very similar, the salinity of Life A and B in the dry seasons is higher than that of Life C by more than 10 ppt, a result that follows from the higher input salinity in Life A and B (Table 5), and a higher evaporation of these lagoons, as will be shown. The agreement between experimental and predicted surface temperatures for the three lagoons (Figs. 4c, 5c, and 6c) is better than surface salinity, which can also be seen looking at RMSRE and NSE indexes in Table 6. The RMSRE and NSE values for temperature are respectively smaller and closer to one. Statistical results for salinity at the lagoon bottom are similar to the surface results (Table 6).

The evolution of experimental and simulated salinity in Life B are plotted in Figures 7a and 7b. According to this Figure, the model reproduces fairly well the increase in salinity in dry periods and the decrease in salinity caused by the inflows that occur mainly in winter and autumn during important cyclonic events. However, it is important to remember that one dimensional models cannot reproduce any horizontal processes that may occur in the lagoons. Besides, during humid seasons (mainly from autumn to spring), stratification is observed in the Life B lagoon, showing salinity values between 20 and 38 ppt in the upper layer, and values ranging from 45 to 50 ppt at the bottom. This stratification has also been obtained with the GLM results, which also reproduce well the high salinities observed in Life B lagoon during the first cyclonic events, produced just after the main dry periods. Also, in Figure 7c the modeled evolution of the new lagoon, Life C, is compared with a natural lagoon, Life B. The smaller salinity values and a weaker stratification are the most prominent features.

3.2 Water fluxes temporal and spatial evolution

For more detailed analysis of the hydrological and salinity dynamics during a dry period, Fig. 8a presents the relative volume (calculated as the volume of the lagoon divided by its volume on the initial day) of the three lagoons for the period from June to September 2015. The relative volume of water in Life A decreased more than in the other lagoons. In contrast, after an initial decrease, slight increases in water levels and in relative volumes were detected in the Life B and Life C lagoons, probably due to the scarce rain episodes registered in this period, with values of < 30 mm/event (Pascual, 2017). Water inputs to Life C are higher than those to Life B during this period and during the rest of the year, leading to lower salinity values in Life C (see Fig. 7). Differences in water input amounts and water salinity may be attributable to the composition and permeability of the lagoons' sediment. A thin sediment layer with very low permeability situated at a depth of between 30 and 90 cm from the surface makes the input of groundwater in the lagoons more difficult (Solà et al., 2016). Substrate composition was not considered in the creation of lagoons, which was simply based on digging a hole below sea level to ensure water permanency. The impermeable layer was most probably removed during construction. Differences in water salinity in Life C have been critical for the survival of populations of the invasive *Gambusia holbrooki*, which are more abundant in this lagoon than in the others (Quintana et al., 2018). The conservation of this impermeable layer to ensure higher salinity, more suitable for *Aphanius iberus*, was taken into account when new lagoons were created within the framework of the second LIFE project between 2014 and 2018 (LIFE13NAT/ES/001001).

Figures 8b, 8c, and 8d present the estimated inflows, outflows and evaporation fluxes, in cubic meters per day and unit of lagoon volume. According to this figure, water inflows in Life C are higher than in the other lagoons, demonstrating that this lagoon presents a different behavior in summer than the other lagoons. In addition, from July to September, i.e. from day 30 onward in Figure 8b, Life A only loses water by evaporation, while Life B and Life C have water outflows of ~0.0005 m^3 day^{-1}.

Finally, in Table 7 we computed the main fluxes per unit of volume of the water lagoons, determined from June to September 2015 (left) and from June to September 2016 (right). These fluxes are calculated in cubic meters per day per lagoon volume. Compared to the other lagoons, Life A behaved very differently, showing a higher evaporation flux and lower water circulation (i.e., In-Out/Volume). Although the differences between Life B and Life C are not so pronounced, the water circulation in Life C is higher than in Life B. Differences in evaporation between lagoons can be explained by differences in surface area to volume ratio (S/V). A higher S/V ratio means higher evaporation, which can be seen as the S/V ratio increases with the evaporation flux.

The bathymetric normalized profiles of lagoons Life A, B, and C are compared in Fig. 9. McJannet et al. (2008) show significant differences in evaporation depending on the surface area to volume ratio. In the dry periods of 2016-2017, the evaporation flux was higher when the S/V ratio increased; therefore, it is highest in Life A followed by Life B and Life C, as also seen in Fig. 9.

Furthermore, to fit the GML results to the experimental data measured in the lagoons, the inflow salinity values in the Life A and Life B lagoons are set to values higher than the sea salinity (Table 5). These salinity values are similar to those at the bottom of the lagoon (see Fig. 7 for the case of Life B) and also coincide with the salinities of the water outflows. Therefore, these results indicate that the groundwater inflows into these lagoons, mostly occurring during autumn cyclonic storm events, have characteristics similar to summer water outflows from these lagoons to the aquifer. These results match those obtained by Sadat-Noori et al. (2016), who observed inputs of the shallow brackish hypersaline pore water into the lagoons, during the winter months, when groundwater levels rise. Santos et al. (2012) also described this process in estuarine environments, considering all the distinct driving mechanisms of pore water advection, and Rodellas et al. (2018) determined that water recirculating through permeable sediments in a coastal lagoon could account for more than 60% of the total inputs. In our case, this kind of circulation may explain a significant amount of the water flow that occurs at the beginning of the autumn (Fig. 7).

The dynamic behavior of the lagoons can be summarized as follows. At the end of the dry periods, the water level of the lagoons reaches the lowest values and salinity the highest ones, a situation caused by evaporation and outflows. Life A, with a higher S/V ratio shows the highest salinity, followed by Life B and Life C. Therefore, the water flowing out of the lagoons has a higher salinity than the sea water. During autumn cyclonic storm events, some of this water returns to the lagoons and the inflowing water has a salinity higher than the sea water (see Fig. 10). Also, 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.

All in all, the results presented here agree with those observed by Menció et al. (2017), who used hydrochemical and isotopic models to establish that the salinity of the *La Pletera* lagoons depended on two distinct processes: the mixing of freshwater and sea water within the lagoons or in the aquifer, and evaporation. However, this new study goes a step further, demonstrating that lagoon inflows after the main dry periods show higher salinities than sea water, and similar to those observed at the bottom of the lagoons during dry periods.

CONCLUSIONS

Results obtained with the GLM provide a comprehensive understanding of the hydrological dynamics in the lagoons of the *La Pletera* salt marsh. We studied two natural lagoons (Life A and Life B) and a 12-year-old lagoon (Life C). The depths of the lagoons range from 0.3 m (Life A) to about 3 m (Life B). Therefore, the use of the Lagrangian layer models and their good response to such small ponds has been assessed. The model has been used to estimate water inflows and outflows, as well as the evaporation and the salinity variation in the water column of the lagoons, giving us an understanding of their hydrological dynamics, especially in the dry periods when the groundwater recharge prevails.

The differences in the salinity dynamics of the *L*a Pletera lagoons could be explained not only by a distinct S/V ratio, but also by differences in water circulation. The old lagoons (Life A and Live B) have higher evaporation rates and, at the end of summer, present higher salinities than the new lagoon (Life C) and the sea. During the summer, the lagoons also lose water as groundwater outflows, but at the beginning of autumn, some of this water returns to the lagoon with the first cyclonic periods. This explains the refilling of Life A and Life B with water saltier than the sea and the refilling of Life C with water of a similar salinity to the sea. Furthermore, a thin sediment layer with very low permeability in Life A and Life B lagoons makes the input of groundwater more difficult than in Life C, and the results of the model showed a higher water circulation in this lagoon.

Given that salinity fluctuations are determinant for the competition between the endangered *Aphanius iberus* population and the invasive *Gambusia holbrooki*, understanding factors causing salinity changes becomes decisive from a management point of view. This knowledge also poses new research challenges, such as understanding nutrient dynamics in this aquifer-lagoon system, or how climate change will modify the water budget and salinity dynamics in the *La Pletera* lagoons.

Table 1: The main characteristics of the lagoons studied during the period from November 2014 to September 2017.

Lagoon	Life A	Life B	Life C
Lagoon name	Bassa Pi	Fra Ramon	G02
Origin	Natural	Natural	Created in 2002
Max depth (m)	1.5	3.0	2.2
Min depth (m)	0.3	0.9	0.9
Max volume (m^3)	1295	22956	2999
Min volume (m^3)	45	1506	584
Max surface(m^2)	5387	17290	2991
Min surface (m^2)	178	2160	1341

Table 2: Bathymetric characteristics of the Life A, Life B, and Life C lagoons. Height above sea level and accumulated water volume at any height.

Height ASL (m)	Accum. Vol. (m^3)		
	Life A	Life B	Life C
1.5		22956.1	3790.4
1.25		18703.3	3077.9
1	1295.8	14450.4	2427.9
0.75	449.4	10549.0	1865.4
0.5	222.0	7038.6	1421.6
0.25	131.4	3818.8	1040.4
0	68.7	1983.3	666.5
-0.5	0.0	971.8	168.8
-0.75		650.3	68.8
-1		328.8	0.0
-1.5		0.0	

Table 3. Values of GLM physical parameters included in the model.

Mixing and thermodynamic parameters		
C_K	Mixing efficiency-convective overturn	0.2
η	Mixing efficiency-wind stirring vs convection	1.23
C_S	Mixing efficiency-shear production	0.23
C_T	Mixing efficiency-kinetic requirement	0.51
C_{HYP}	Mixing efficiency-hypolimnetic mixing	0.5
Model structure		
Maximum Lagrangian layers		200 m^3
Minimum layer volume		0.025 m^3
Minimum layer thickness		0.005 m
Maximum layer thickness		0.05 m

Table 4 Polynomial fit ($V(x)= Ax^5 +Bx^4+Cx^3+Dx^2 +Ex+F$) for the lagoons Life A, B and C, where V(x) is the volume in m^3 and x the height above sea level in m (see Table 1). R^2 is the coefficient of determination.

	A	B	C	D	E	F	R^2
Life A	1551.5	627.73	- 411.33	+77.365	284.6	99.208	1
Life B	-170.88	-577.28	1659.9	6279.7	6811.5	3270.4	0.9992
Life C	0	0	20.952	550.22	1205	+ 667.4	0.9998

Table 5. Temperature and salinity of the inflows averaged bimonthly during 2015.

	Life A		Life B		Life C	
	T	Sal	T	Sal	T	Sal
Jan-Feb	6.0	18.0	6.0	18.0	17.0	18.0
March-April	9.1	18.0	9.1	18.0	17.0	18.0
May-June	15.6	33.0	15.6	33.0	17.0	21.4
July-Aug	17.0	59.9	17.0	36.9	17.0	23.6
Sept-Oct	6.0	27.9	6.0	27.9	17.0	28.9
Nov-Dec	6.0	22.0	6.0	22.0	17.0	15.0
Average	9.9	29.8	9.9	26.0	17.0	19.1

Table 6. Root mean relative square error (RMSRE) and Nash-Sutcliffe efficiency (NSE) for the different magnitudes for Life A, B, and C.

	RMSRE	NSE
Volume	0.12 0.11 0.08	0.95 0.9 0.98
Sal Surface	0.14 0.11 0.16	0.67 0.73 0.69
Sal bottom	0.11 0.07 0.18	0.55 0.57 0.60
Temp Surface	0.09 0.09 0.11	0.77 0.75 0.87

Table 7. Lagoon characteristics and relative daily averaged results of the GLM water budget, for the period from June to September 2015 (left) and for the period from June to September 2016 (right).

Lagoon	**Life A**		**Life B**		**Life C**	
Lagoon Surface/Lagoon Volume (S/V; m^{-1})	3.88	3.39	2.57	2.42	1.77	1.89
(Inflow-Outflow)/Volume (10^{-3} day^{-1})	-0.17	-0.67	4.23	-1.06	5.00	3.98
Evaporation/Volume (10^{-3} day^{-1})	-12.43	-11.67	-7.27	-7.56	-6.59	-7.44
Rain/Volume (10^{-3} day^{-1})	2.41	0.65	1.42	0.42	1.01	0.32
Total Water Budget/Volume (10^{-3} day^{-1})	-10.19	-11.68	-1.61	-8.20	-0.58	-3.13

ACKNOWLEDGMEENTS

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FIGURE CAPTIONS

Figure 1. Geographical and geologic situation, and hydrogeological cross sections of the study area. Legend: BTUA, Baix Ter upper aquifer; BTLA, Baix Ter lower aquifer (modified from ICGC (2011a,b)).

Figure 2: Aerial view of the Pletera marsh lagoons (modified from www.icc.cat/vissir3/).

Figure 3 Water levels for the lagoons Life A Life B and Life C

Figure 4. GLM results compared to field data in Life A lagoon (from November 2014 to September 2017): a) Real volume vs. GLM volume (in m^3); b) Real salinity vs. modeled salinity (in ppt); and c) Real surface temperature vs. GLM surface temperature.

Figure 5. GLM results compared to field data in Life B lagoon (from November 2014 to September 2017): a) Real volume vs. GLM volume (in m^3); b) Real salinity vs. modeled salinity (in ppt); and c) Real surface temperature vs. GLM surface temperature.

Figure 6. GLM results compared to field data in Life C lagoon (from November 2014 to September 2017): a) Real volume vs. GLM volume (in m^3); b) Real salinity vs. modeled salinity (in ppt); and c) Real surface temperature vs. GLM surface temperature.

Figure 7. Evolution of salinity in Life B during the study period (November 2014 to September 2017): a) Experimental results; b) Results obtained with the GLM; and c) Evolution of modeled salinity in Life C during the same period.

Figure 8. a) Relative water volumes (normalized to the volume of water of 1 June 2015) in Life A, Life B, and Life C lagoons from June 2015 to September 2015; and b), c) and d) Inflows, outflows and evaporation volumes of water, per unit of lagoon volume (relative water volumes), from June 2015 to September 2015 for Life A, B, and C.

Figure 9. Normalized bathymetric profiles of Life A, B and C lagoons. S/S_{max} is the surface area of the lagoon divided by the maximum surface and H/H_{max} is the depth divided by the maximum depth.

Figure 10. Schematic behavior of the lagoon basins during the dry season (top) and at the end of the dry season (bottom).

Figure 1

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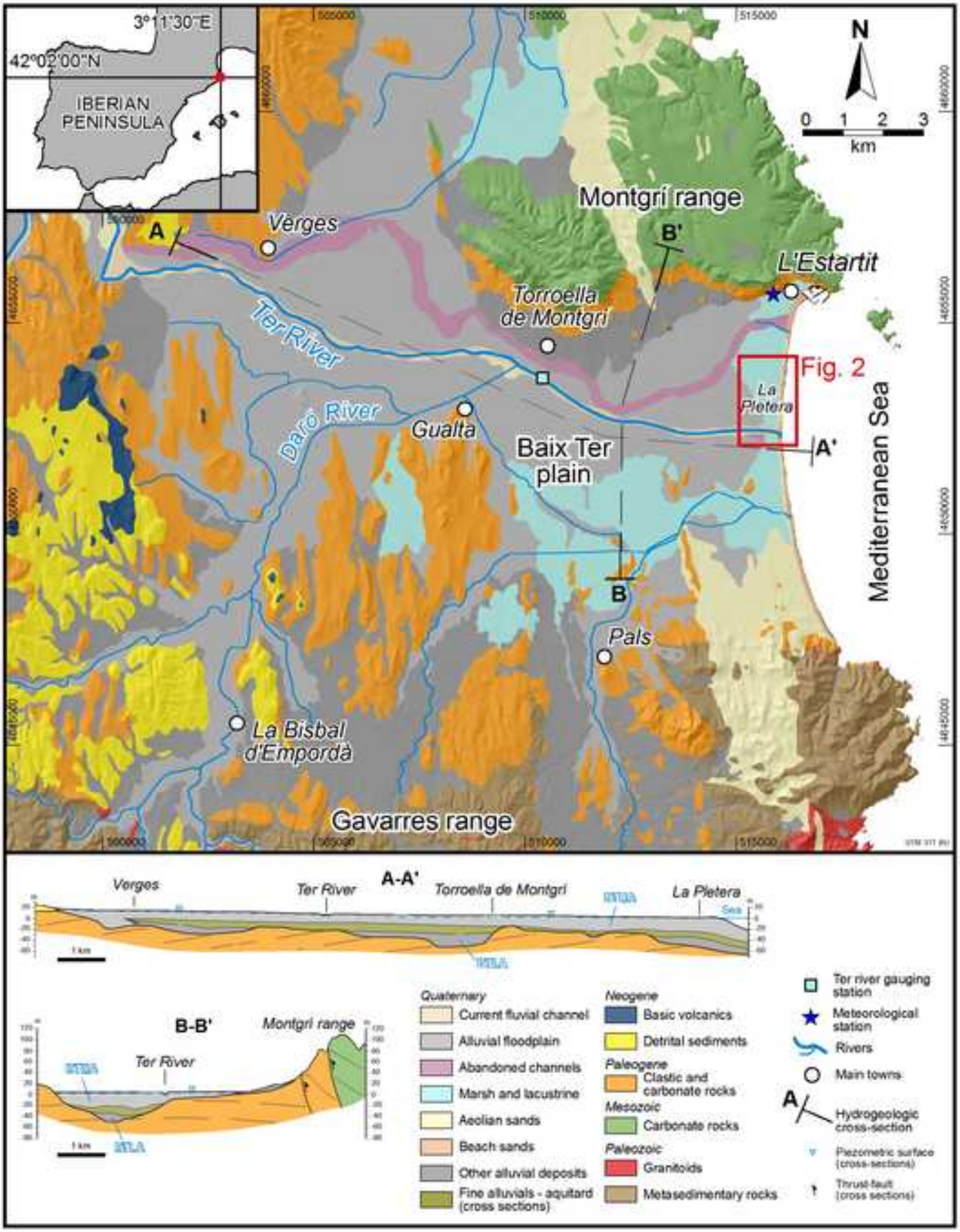


Figure 2


N
0
100
200
300
m
516000
4653500
515500
Alluvial floodplain
LIFE C
La Pletera marsh
Aeolian dunes
4653000
LIFE A
LIFE B
Sand beach
4652500
Ter River
515500
516000
UTM 31T (N)

Figure 3

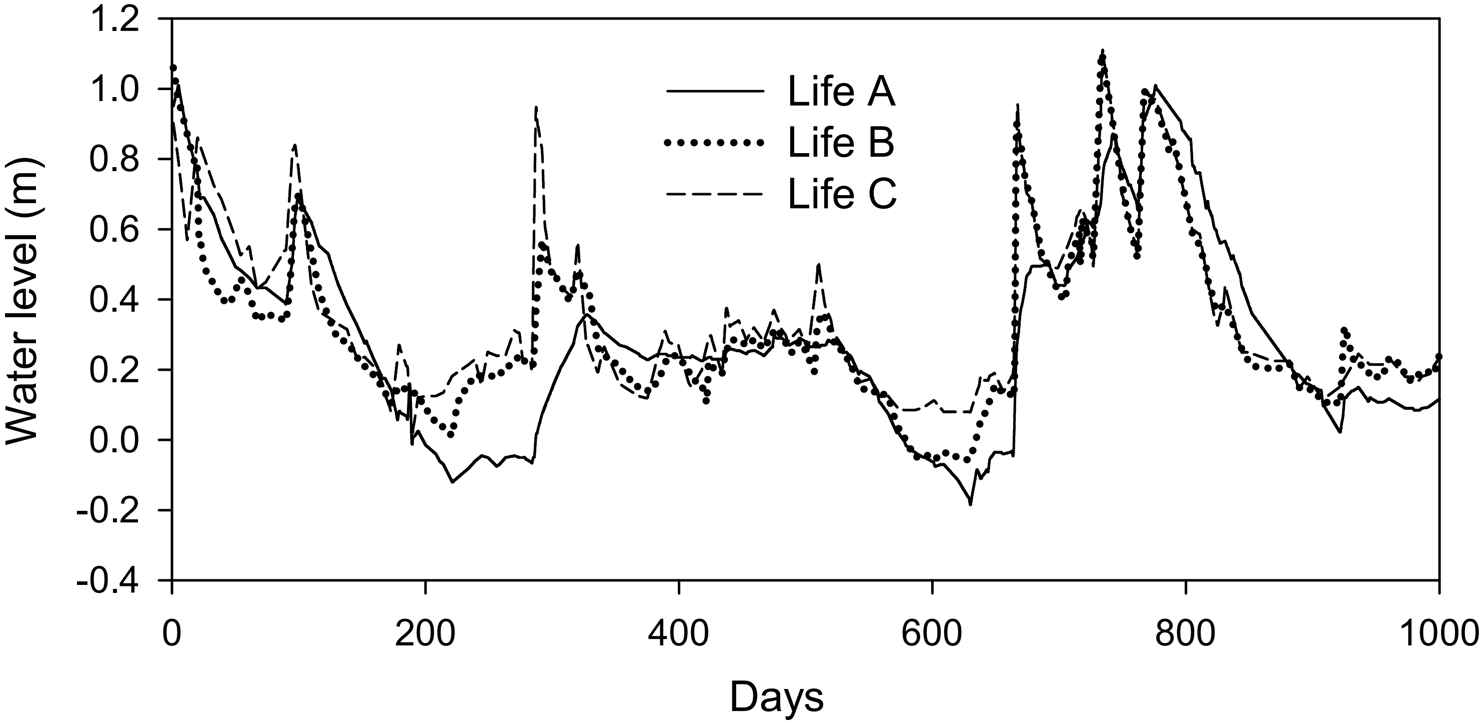

1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Water level (m)
0
200
400
600
800
1000
Days
Life A
Life B
Life C

Figure 4

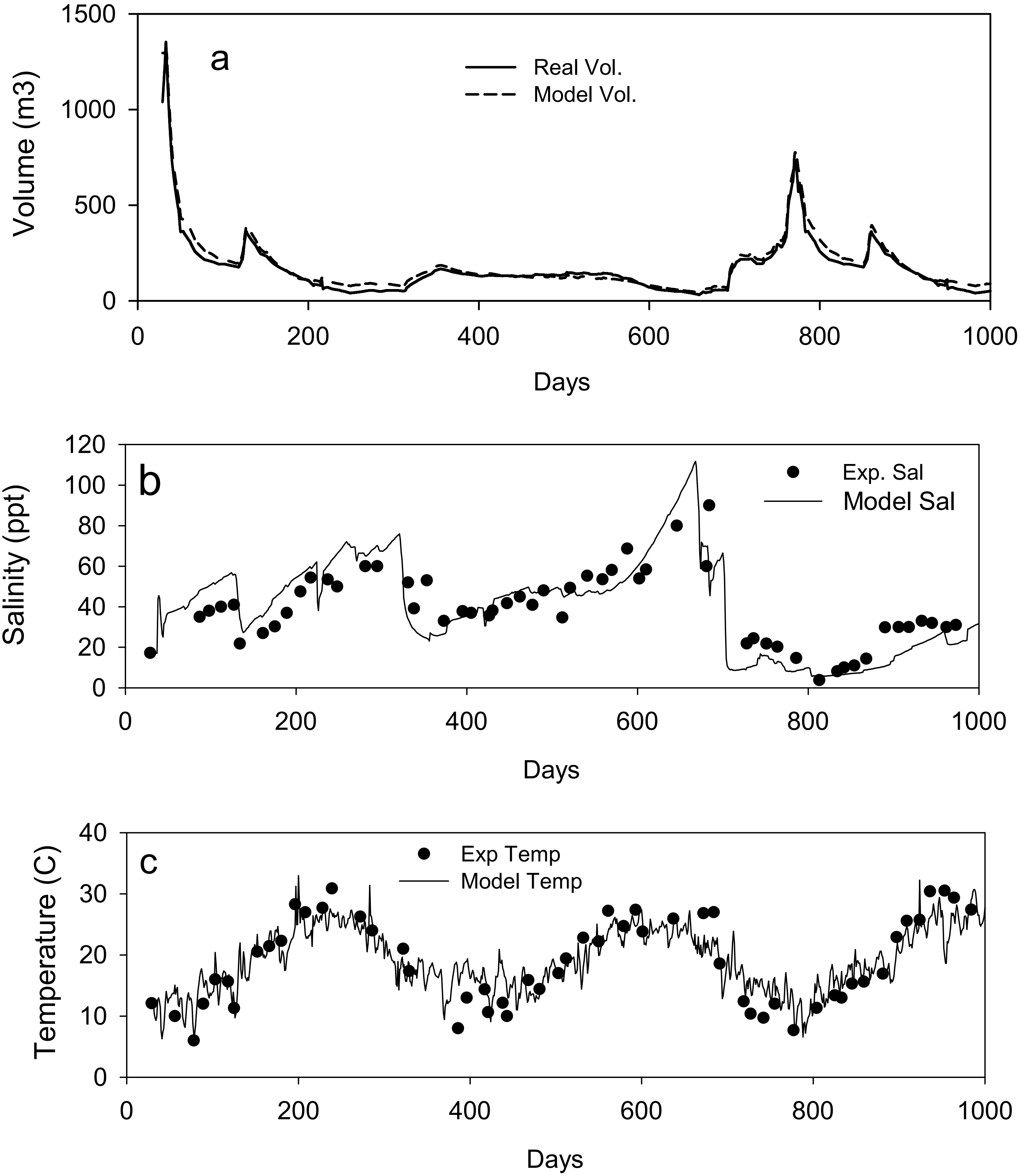

a
Real Vol.
Model Vol.
Volume (m3)
1500
1000
500
0
0
200
400
600
800
1000
Days
b
Exp. Sal
Model Sal
Salinity (ppt)
120
100
80
60
40
20
0
0
200
400
600
800
1000
Days
c
Exp Temp
Model Temp
Temperature (C)
40
30
20
10
0
0
200
400
600
800
1000
Days

Figure 5

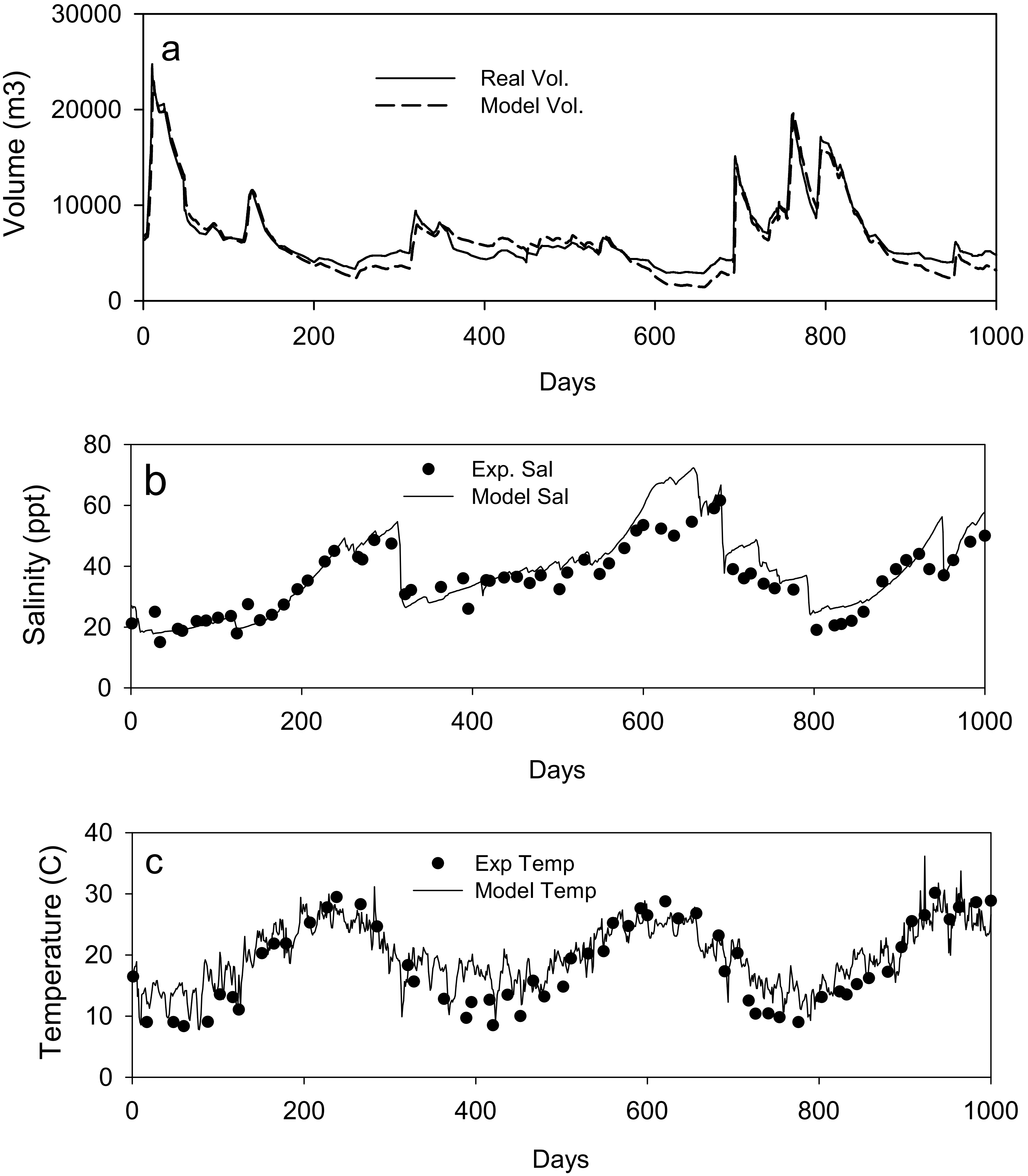

a
Real Vol.
Model Vol.
Volume (m3)
30000
20000
10000
0
0
200
400
600
800
1000
Days
b
Exp. Sal
Model Sal
Salinity (ppt)
80
60
40
20
0
0
200
400
600
800
1000
Days
c
Exp Temp
Model Temp
Temperature (C)
40
30
20
10
0
0
200
400
600
800
1000
Days

Figure 6

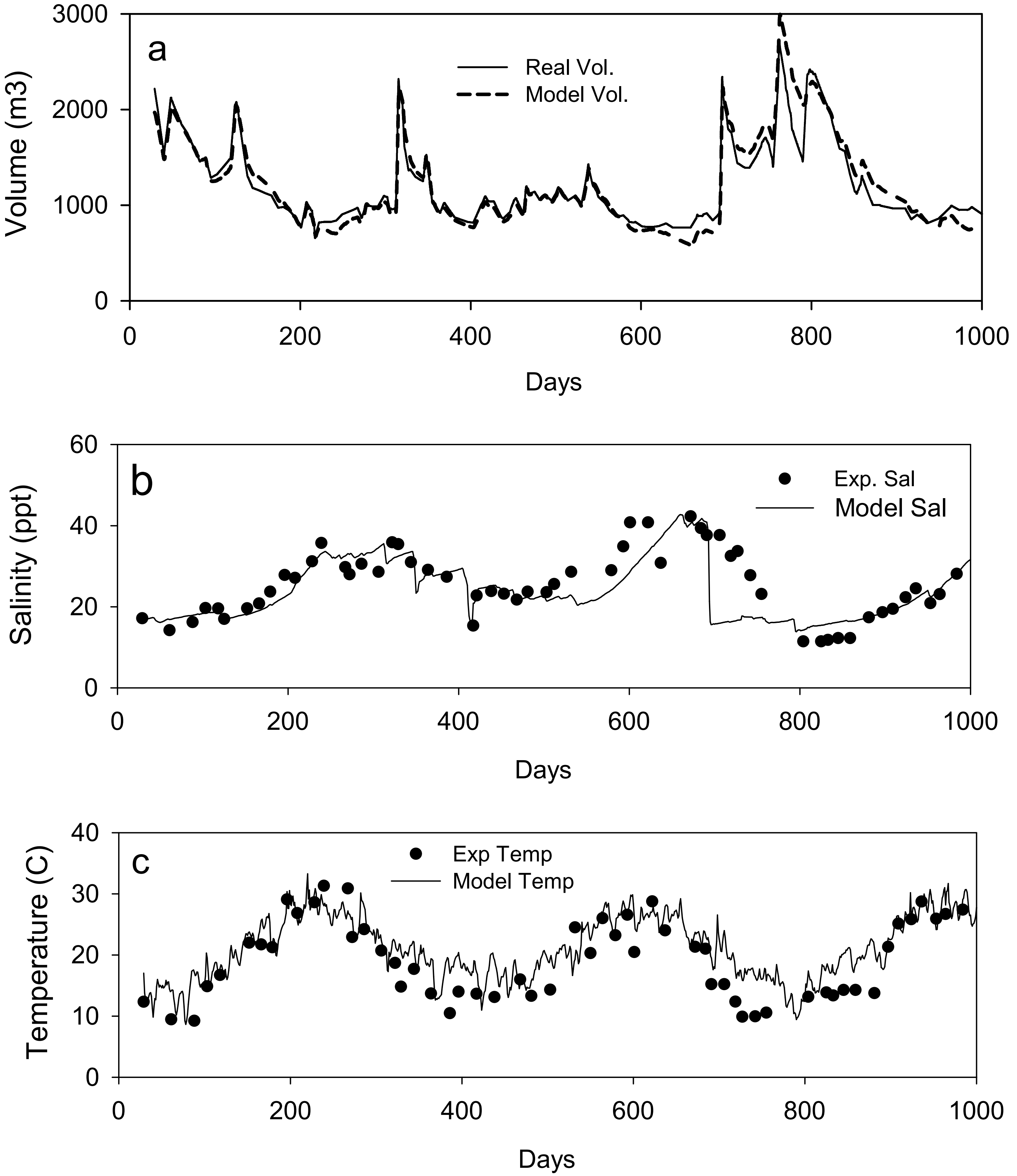

a
Real Vol.
Model Vol.
Volume (m3)
3000
2000
1000
0
0
200
400
600
800
1000
Days
b
Exp. Sal
Model Sal
Salinity (ppt)
60
40
20
0
0
200
400
600
800
1000
Days
c
Exp Temp
Model Temp
Temperature (C)
40
30
20
10
0
0
200
400
600
800
1000
Days

Figure 7

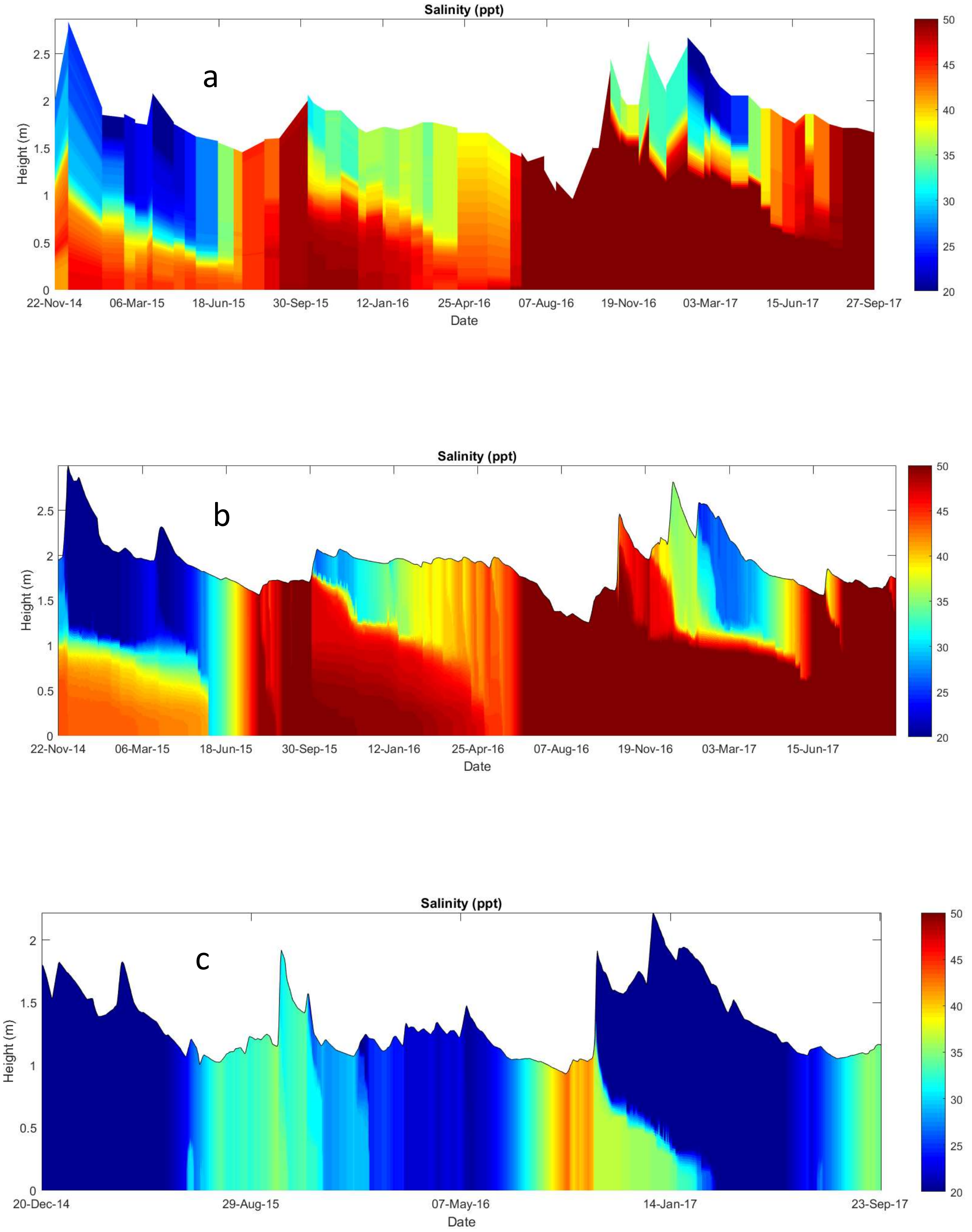
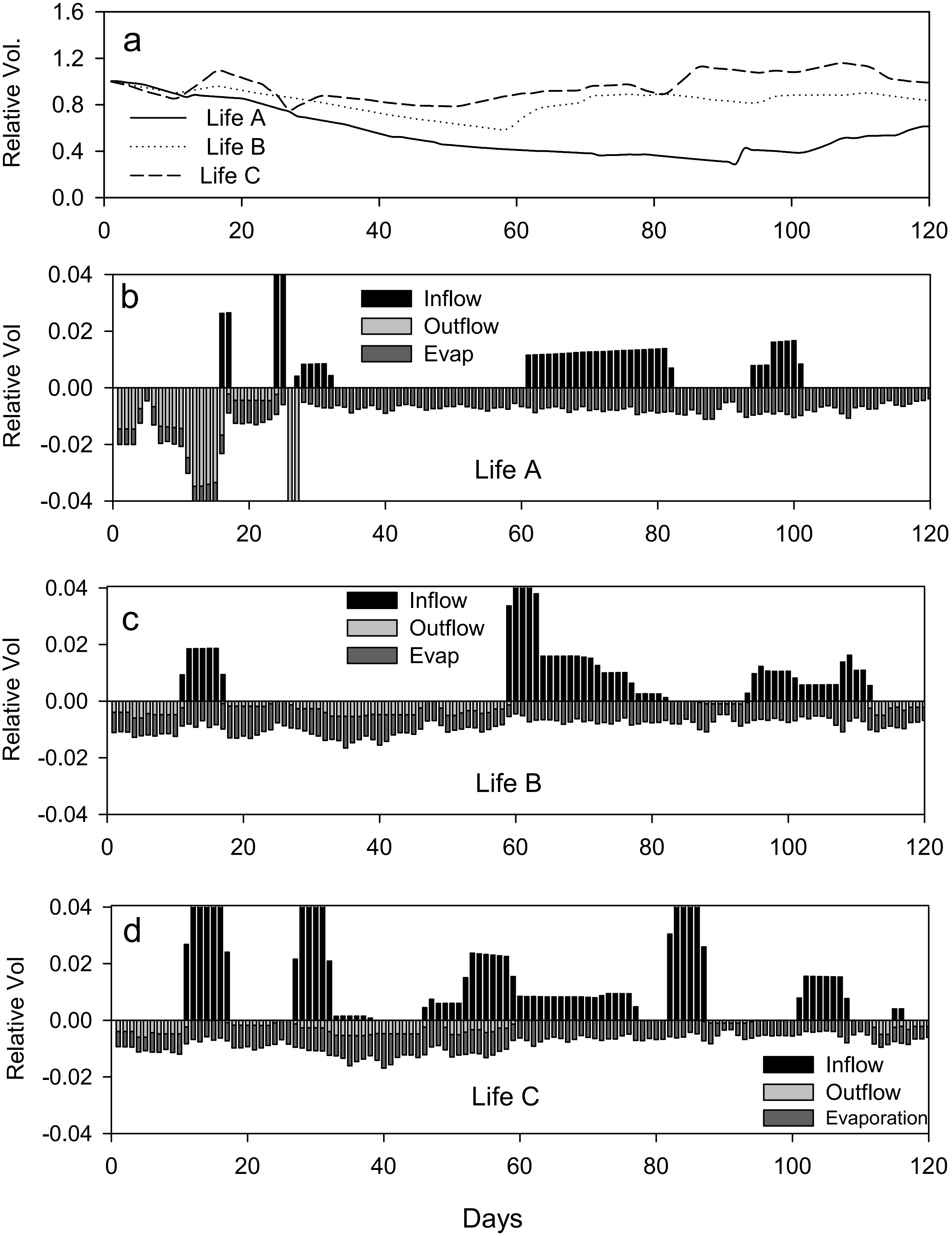

Salinity (ppt)
a
Height (m)
0
0.5
1
1.5
2
2.5
22-Nov-14
06-Mar-15
18-Jun-15
30-Sep-15
12-Jan-16
25-Apr-16
07-Aug-16
19-Nov-16
03-Mar-17
15-Jun-17
27-Sep-17
Date
20
25
30
35
40
45
50
Salinity (ppt)
b
Height (m)
0
0.5
1
1.5
2
2.5
22-Nov-14
06-Mar-15
18-Jun-15
30-Sep-15
12-Jan-16
25-Apr-16
07-Aug-16
19-Nov-16
03-Mar-17
15-Jun-17
Date
20
25
30
35
40
45
50
Salinity (ppt)
c
Height (m)
0
0.5
1
1.5
2
20-Dec-14
29-Aug-15
07-May-16
14-Jan-17
23-Sep-17
Date
20
25
30
35
40
45
50

Figure 8



a
Relative Vol.
1.6
1.2
0.8
0.4
0.0
Life A
Life B
Life C
0
20
40
60
80
100
120
b
Relative Vol
0.04
0.02
0.00
-0.02
-0.04
Inflow
Outflow
Evap
Life A
c
Life B
d
Life C
Evaporation
Days

Figure 9

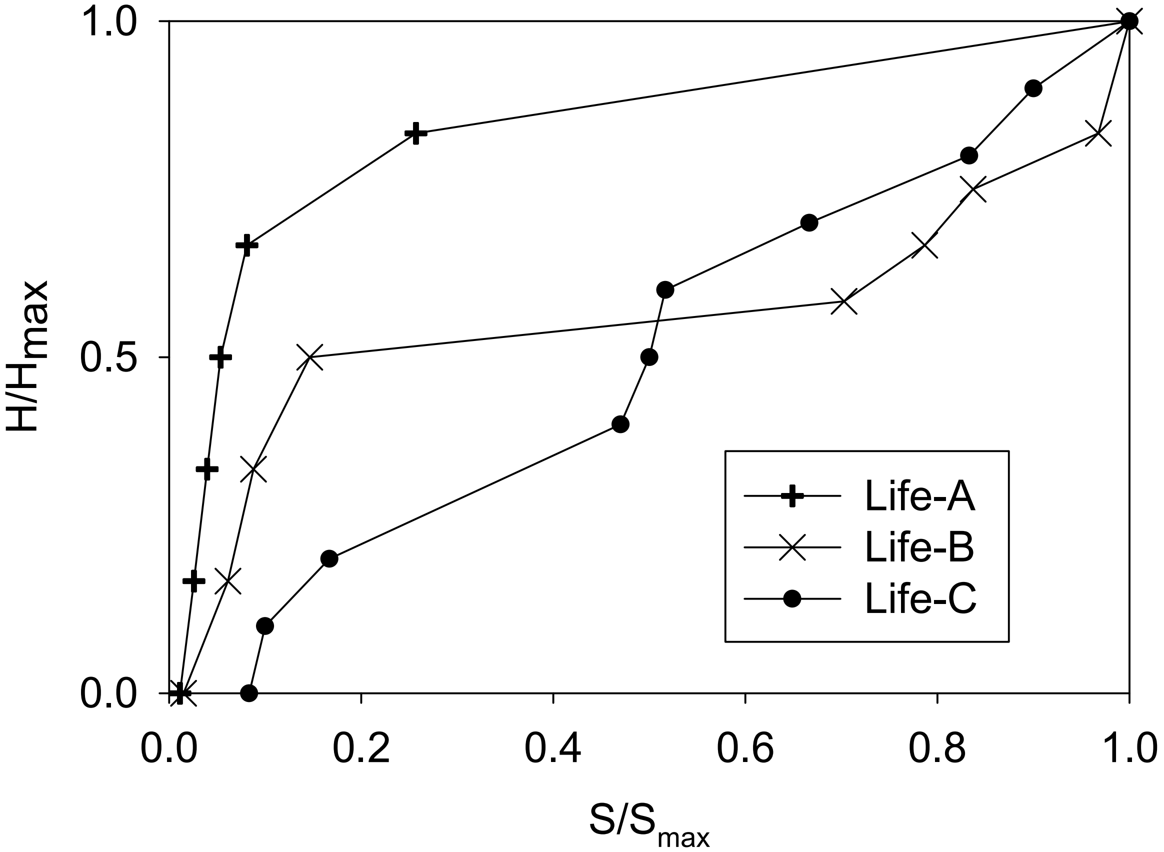
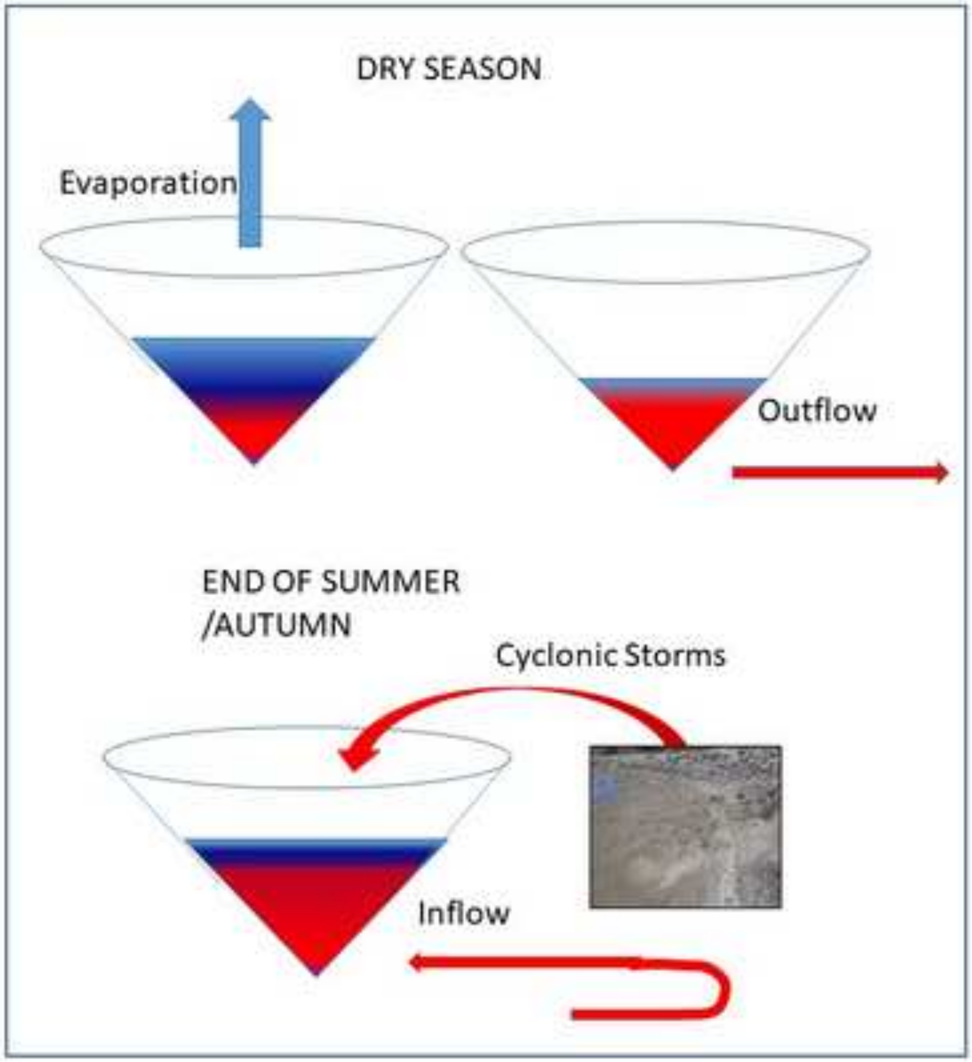


Figure 10


DRY SEASON
Evaporation
Outflow
END OF SUMMER /AUTUMN
Cyclonic Storms
Inflow

***Declaration of Interest Statement**

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: