A dynamic model to simulate water level and salinity in a Mediterranean coastal lagoon

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ABSTRACT

In this study, a dynamic model for a Mediterranean coastal lagoon (Albufera des Grau, Menorca, Western Mediterranean) is presented. A simple model with limited data requirements was constructed to simulate the daily variations in water level (WL) and water salinity (S) in the lagoon. Both parameters constitute the main descriptors of the lagoon hydrology and have substantial ecological significance. The model consisted of three coupled submodels: a submodel for the water balance in the watershed, a submodel for the water balance in the lagoon and a submodel for the salt mass balance in the lagoon. The results of the study revealed that the model simulated the temporal dynamics of both WL and S with reasonable accuracy (mean error of 7.6 cm and 2.8 g L^{-1} for WL and S, respectively). The model made it possible to determine the annual water and salt budgets, which were characterised by intense inter-annual variability. A simulation carried out for the last 30 years accurately predicted the long-term range of variation of salinity, and even severe hyperhaline periods were correctly simulated. The model is believed to be a useful tool in predicting the occurrence of ecologically degraded situations and could contribute to future biogeochemical studies.

1. Introduction

Mediterranean shallow lakes and lagoons are characterised by complex limnological dynamics, which result from the vast temporal variability in hydrogeochemical and meteorological forcings (de Vicente et al. 2006; Beklioglu et al. 2007; Moreno-Ostos et al. 2007). Salinity variations, nutrient dynamics and water level fluctuations are important factors in the functioning of these water bodies, and influence the alternations between macrophytic and phytoplanktonic regimes (Beklioglu et al. 2007).

The Albufera des Grau (island of Menorca, Balearic archipelago, western Mediterranean) is an enclosed coastal lagoon without tidal influence and is one of the most well-preserved lagoons in the Balearic Islands. The ecological status of the lagoon is highly dependent on the hydrology, mainly described by water level (*WL*) and salinity (*S*). Unusual variations in these hydrological parameters can lead the system to critical situations with important ecological consequences. These include haline stratification and consequent bottom anoxia due to the massive entrance of seawater (Pretus and Obrador 2004), mid-term salinisation, which can result in hypersalinity (Pretus 1989; Cardona 2001; Pretus 2003), and littoral desiccation, which is caused by low water levels and can lead to large-scale mortality of the dense and extensive macrophyte meadows that are found throughout the lagoon (Obrador et al. 2007).

To prevent such undesirable situations, the water exchange between the lagoon and the sea is regulated by two sluices. The management of this system mainly focuses on the maintenance of *WL* and *S* within the optimal range for the conservation of the macrophyte meadows and the consequent effect on waterbird species (Noordhuis et al. 2002; Moreno-Ostos et al. 2008). The hydrological management is subject to a trade-off between *WL* and *S* because the entrance of seawater (to minimise summer littoral desiccation) can lead to quick salinity shifts and increase the risk of vertical density stratification and consequent bottom anoxia (Pretus and Obrador 2004). Since there are no gauging stations in the streams or in the outlet channel, the management practices are not fed by direct data of the water flows in the lagoon. The hydrological information currently available consists of a time series of water level and salinity, from which rough estimates of monthly water and salt flows are calculated (Pretus and Obrador 2004). These estimates are inaccurate and cannot be used for evaluating small flows or assessing the lagoon hydrology on a daily basis.

Given the limited possibilities for hydrological management on the lagoon (only the outflow or the seawater inflow can be modified) and the lack of information, a simple dynamic model to simulate *WL* and *S* with few data requirements would be a useful tool in the management of the lagoon. The quantification of the water fluxes could also serve as a basis to calculate nutrient loads into the lagoon. The model could also help identify effective management schemes under changing climate scenarios. Besides this, a hydrological model run on a daily basis would also improve the understanding of the hydrological regime and serve as a basis for further nutrient budget calculations in the Albufera des Grau.

The objective of the present study was to model the hydrological regime of the Albufera des Grau using daily water and total salt mass balances. Water level and water salinity were the desired output variables. The quantification of water and salt flows and the determination of the mean annual water and salt budgets in the lagoon were also objectives of the present study.

2. Study site

The Albufera des Grau (surface area 78 ha, volume 1 hm^3) is a brackish coastal lagoon located in the northeast coast of the island of Menorca (Balearic Islands; Fig. 1). The average depth is 1.37 m with a maximum of 3 m (Pretus 1989). The climate is typically Mediterranean; mean air temperature is 17 ºC and annual precipitation is 549 mm. The lagoon is located on Palaeozoic siliciclastic turbidites and receives only surface water inputs from inland. The system is connected to the sea by a narrow channel, which is 500 m long; here, a small floodgate (c.a. 2 m^2) regulates the lagoon-sea connection when the sand barrier at the end of the channel is opened. The water exchange with the sea is irregular and does not represent an important renewal of water in the system (Pretus and Obrador 2004). The freshwater inputs are frequently torrential and are supplied by two streams that drain an area of 56 km^2. These water inputs are nowadays strongly intermittent and typically occur during the autumn and winter; but the permanent flow of freshwater to the lagoon has been documented until the 1960s, when the springs that supplied water to the streams were dry, probably due to aquifer overexploitation.

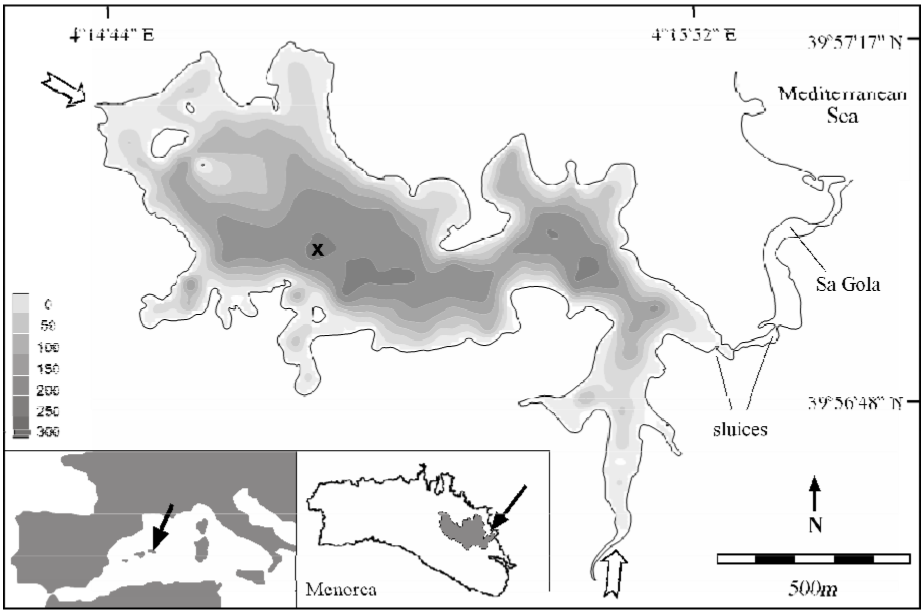

Figure 1. Location and bathymetric map (50 cm isobaths) of the Albufera des Grau coastal lagoon. The freshwater inputs (arrows) and the fixed sampling site (cross) are shown. The dashed area in the inset corresponds to the catchment area.

The watershed is mainly composed of Palaeozoic siliciclastic sands and silts (26%) and Mesozoic dolomites (40%). The main land covers in the watershed comprises 47% woodlands, composed of Mediterranean Holm oak and Aleppo pine forests, 9% shrublands, and 41% extensive dry farming land (authors' unpublished data).

Currently, the lagoon is a macrophyte-dominated system with dense and extensive meadows of the euryhaline macrophyte *Ruppia cirrhosa*. In these meadows, the highest biomass ever reported for this species is found (up to 1760 gDW m^{-2}; Obrador et al. 2007). Intense phytoplankton peaks, which are the main drivers of turbidity dynamics in the lagoon (Obrador et al. 2008), are observed every year usually in relation to the entrance of nutrients from the watershed or from the decomposition of the macrophyte meadows (Obrador et al. 2007). In the past, the lagoon has been described as a macroalgae-dominated system (Margalef 1952; Pretus 1989); and hyperhaline events (up to 60 g L^{-1} in 1995, authors' unpublished data), haline vertical stratifications, and dystrophic crises have also been reported (Pretus 1989; Cardona 2001).

3. Methods

3.1 Model description

The model consisted of three coupled submodels and simulated water level and salinity on a daily basis (Fig. 2). The Runoff Model (RM) was a water balance in the watershed (in mm) and allowed the calculation of the stream runoff entering the lagoon. The Lagoon Water Model (LWM) dealt with the water flows in the lagoon to calculate a daily balance of the lagoon water volume (in m^3), from which the water level was calculated. The LWM was fed by climatic data and by the runoff calculated in the RM submodel (Table 1). Finally, the Lagoon Salt Mass Model (LSM) was a balance of the total salt mass contained in the lagoon (in kg) and was fed by climatic data and by the water flows of the LWM. The relationships between the submodels and the respective inputs and outputs are shown in Table 1. The model was built and run using STELLA software (High Performance Systems).

The Runoff submodel (RM)

The total runoff was calculated from a water balance between precipitation and evapotranspiration in the catchment using a simplified version of a global hydrological model for runoff (Döll et al. 2003). The data inputs required to run the RM were daily average, maximum and minimum temperature, wind speed, relative humidity and rainfall. The fraction of the rainfall converted into runoff was determined by daily water balances in the canopy and in the soil from the following equations:

$$\frac{dS_c}{dt} = P_r - E_c - TF \qquad \text{Eq. (1)}$$

$$\frac{dS_S}{dt} = TF - ET_S - R_T \qquad \text{Eq. (2)}$$

where S_c is the water stored in the canopy (mm), P_r is precipitation (mm d^{-1}), E_c is the evaporation in the canopy (mm d^{-1}), *TF* is the throughfall (mm d^{-1}), S_S is the water content in the soil (mm), ET_S is the evapotranspiration from the soil (mm d^{-1}), and R_T is the total runoff (mm d^{-1}).

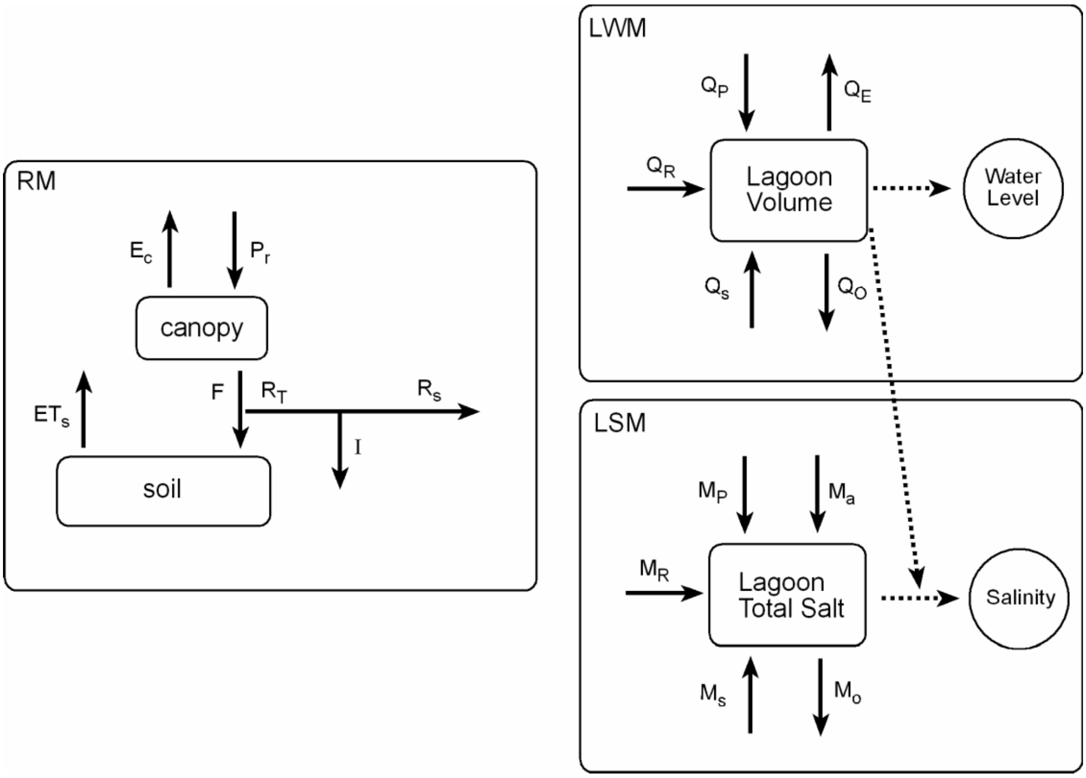

Figure 2. Schematic diagram of the Albufera des Grau h ydrological model. The watershed model (RM) generates runoff inputs to the lagoon water model (LWM), from which the water level is computed. The salt mass model in the lagoon (LSM) together with the LWM allows the calculation of lagoon water salinity. Symbols are as follow: P_r: precipitation; E_C: evaporation in the canopy; *TF*: throughfall; ET_S: evapotranspiration from the soil; R_T: total runoff; *I*: infiltration; R_S: surface runoff; Q_P: direct rainfall; Q_R: stream runoff; Q_E: evaporation; Q_S: seawater flow; Q_O: lagoon outflow; M_P: salt input from precipitation; M_R: salt input from stream runoff; M_a: atmospheric deposition of salt; M_S: salt input from seawater flow; M_O: salt output due to lagoon outflow.

The evaporation of the water stored in the canopy E_c (mm d^{-1}) was calculated as (Deardorff 1978 in Döll et al. 2003):

$$E_c = ET_o \left(\frac{S_c}{S_{C\max}} \right)^{2/3} \qquad \text{Eq. (3)}$$

where ET_o is potential evapotranspiration (mm d^{-1}), and $S_{c\max}$ is the maximum water stored in the canopy (mm). $S_{c\max}$ was calculated assuming that each leaf is covered by a 0.3 mm-thick water film

(Döll et al. 2003):

$$S_{c\max} = 0.3 \cdot LAI \qquad \text{Eq. (4)}$$

where *LAI* is the average Leaf Area Index. A constant value of 3 was taken for *LAI* from GIS data of land cover in the catchment (authors' unpublished data). Throughfall *TF* (mm d^{-1}) was calculated from the daily balance between precipitation and E_c .

Potential evapotranspiration ET_o (mm d^{-1}) was calculated from the Penman-Monteith equation (Penman 1948) for the energy and mass balance during evaporation of water following the FAO guidelines (Allen et al. 1998):

$$ET_o = \frac{0{,}408\Delta(R_n - G) + \gamma_c \frac{900}{T+273} u(e_s - e_a)}{\Delta + \gamma_c(1 + 0{,}34u)} \qquad \text{Eq. (5)}$$

where Δ is the slope of the saturation vapour pressure curve (kPa ºC^{-1}), R_n is net radiation on the soil surface (MJ m^{-2} d^{-1}), *G* is soil heat flux density (MJ m^{-2} d^{-1}), γ_c is the psychrometric constant (kPa ºC^{-1}), *T* is mean daily air temperature (ºC), *u* is wind speed (m s^{-1}), e_s is saturation vapour pressure (kPa) and e_a is actual vapour pressure (kPa). Net radiation R_n corresponds to the difference between the incoming net shortwave radiation R_{ns} and the outgoing net longwave radiation R_{nl} (Allen et al. 1998). Net shortwave radiation R_{ns} was calculated as (Allen et al. 1998):

$$R_{ns} = (1 - \alpha_c)R_{si} \qquad \text{Eq. (6)}$$

where R_{si} is the estimated incoming radiation and α_c is the albedo coefficient (set to 0.18; Linacre 1992). Details of the computation of R_{si}, R_{nl}, G, γ_c, Δ, e_s and e_a from air average, maximum and minimum temperature, relative humidity and wind speed can be found elsewhere (Allen et al. 1998; Xu and Singh 2001).

The water balance in the soil (Eq. (2)) was calculated using the throughfall, the water content of the soil, the total runoff, and the evapotranspiration from the soil ET_s (mm d^{-1}). Evapotranspiration from the soil was calculated as (modified from Döll et al. 2003):

$$ET_s = (ET_o - E_c)\frac{S_s}{S_{s\max}} \qquad \text{Eq. (7)}$$

where $S_{s\max}$ is the soil water capacity (mm). The value of $S_{s\max}$ for the soils of the watershed was taken from Estradé (2003).

Total runoff R_T (mm d^{-1}) was calculated as (Bergström 1995 in Döll et al. 2003):

$$R_T = (P_r - E_c)\left(\frac{S_s}{S_{s\max}}\right)^{\gamma} \qquad \text{Eq. (8)}$$

where P_r is rainfall (mm d^{-1}), and is a calibration parameter. The ratio $S_s/S_{s\max}$ determines the fraction of throughfall that is derived to runoff (Döll et al. 2003).

Total runoff was divided into surface runoff R_s (mm d^{-1}) and infiltration I (mm d^{-1}). Infiltration was considered as a fraction of the total runoff as $I = c_I R_T$, and c_I was used as a calibration parameter.

The lagoon water submodel (LWM)

A simple one-dimensional model was developed to simulate the water balance in the lagoon. For each time step, a balance between the inputs and the outputs in the lagoon was performed assuming an instantaneous (one-day) effect. All the fluxes in the LWM were calculated in m^3 d^{-1} and the volume of the lagoon V (m^3) was transformed to water level WL (cm a.s.l.) using the hypsographic curve of the lagoon (authors' unpublished data). The water balance equation is:

$$\frac{dV}{dt} = Q_P + Q_R + Q_s - Q_E - Q_o \qquad \text{Eq. (9)}$$

where Q_P is direct rainfall on the lagoon, Q_R is stream runoff, Q_s is seawater flow, Q_E is evaporation and Q_o is lagoon outflow.

Runoff inputs Q_R were calculated from R_s (the surface runoff of the WM) and the surface of the watershed (56 km^2). Direct precipitation on the lagoon Q_P was calculated from rainfall P (mm d^{-1}) and lagoon surface (ha) at each time step. Similarly, Q_E was calculated from the surface of the lagoon and the evaporation rate (E, in mm d^{-1}). The Penman equation (Eq. (5)) multiplied by a calibration parameter c_E, was used to calculate E assuming an albedo of 0.08 for water (Stumpf et al. 1999; Linacre 1992). The effect of salinity on evaporation was considered negligible for the range of salinity observed in the lagoon (Asmar and Ergenzinger 1999).

The fluxes between the lagoon and the sea (Q_S and Q_o) were computed with a simple hydraulic formula assuming a free-orifice flow (USBR 2001; Chauvelon et al. 2003):

$$Q = kA\sqrt{h} \qquad \text{Eq. (10)}$$

where Q is the discharge (m^3 s^{-1}), A is the area of the sluice opening (m^2), h is the height of the water column (m) and k is a calibration parameter that includes the gravity and the contraction and velocity coefficients of the free-orifice flow (USBR 2001). The model distinguished between two types of flow: a massive flow corresponding to the sluice opening (Q_{om} and Q_{sm}) and a flow resulting from filtration through the dam (Q_{of} and Q_{sf}). Massive lagoon outflow Q_{om} takes place when the water level is above a critical water level (WL_{om}) and the sluice is open. This flow results from the management of the sluice and reproduces the natural overflow of the lagoon at very high water levels. In this case, the height of the water column *h* in Eq. (10) was calculated from the difference between *WL* and WL_{om}, the sluice opening *A* was set to 2 m^2 and a calibration parameter K_{om} was used. On the other hand, the lagoon outflow resulting from filtration (Q_{of}) was computed when *WL* was above the critical level that results in filtration (WL_{of}); *h* was then computed from the difference between *WL* and WL_{of}. In this case, *A* was set to 0.025 m^2 and a specific calibration parameter (K_{of}) was used.

Seawater inflow (Q_s) only occurs when the lagoon is below sea level ($WL<0$). This flow was composed by a massive seawater flow (Q_{sm}) and a filtration flow (Q_{sf}). For the computation of Q_{sm}, a critical water level WL_{sm} was considered, below which, the sluice is opened. In this case *h* was calculated from the difference between *WL* and WL_{sm}, and a calibration parameter K_{sm} was used. Massive seawater inputs caused by extremely low water levels in the lagoon occur when the dam is opened to avoid littoral desiccation and large-scale mortality of macrophytes (Obrador et al. 2007). The natural equivalent of this flux occurs when the sand-bar naturally opens under pressure exerted by seawater in the channel. For Q_{sf}, *h* was calculated directly from *WL*, and K_{sf} was used as a calibration parameter. The values of *A* for the massive and the filtration flows were taken as in the lagoon outflow (2 m^2 and 0.025 m^2 respectively). The critical water levels of outflow and seawater flow, WL_{om} and WL_{sm}, were also used as calibration parameters.

The lagoon salt mass submodel (LSM)

The LWM was coupled with a submodel of the salt mass in the lagoon (LSM). The water salinity (*S*, in g L^{-1}) was calculated from the total salt mass and the lagoon water volume. The salt mass balance equation was expressed as:

$$\frac{dTS}{dt} = M_P + M_R + M_a + M_s - M_o \qquad \text{Eq. (11)}$$

where TS is the total salt content in the lagoon (kg), M_P is the salt input from direct precipitation, M_R is the salt input from stream runoff, M_a is atmospheric deposition, M_s is the salt input from seawater flow, and M_o is the salt output caused by lagoon outflow. The fluxes in the LSM were expressed as salt loads (kg d^{-1}) and those fluxes related to water fluxes were calculated from the corresponding water volume (m^3 d^{-1}) and salinity (g L^{-1}) of each flux. Thus, M_P was computed from Q_P taking the value of 0.11 g L^{-1} for the salinity of rainwater (Alcalá-García 2005); M_R was computed from Q_R and the average salinity of the streams entering the lagoon (authors' unpublished data); M_s was estimated from Q_s and the mean seawater salinity (38 g L^{-1}), and finally M_o was derived from Q_o and the lagoon water salinity at the previous time step. Both M_s and M_o were calculated in the same way, independently of the massive or filtration type of flow. Dry deposition of sea aerosol was computed as a function of wind speed following Gustafsson and Franzen (1996):

$$M_a = c_D(0.728 \cdot e^{0.478u}) \cdot D^{0.011} / D^{0.024u} \qquad \text{Eq. (12)}$$

where M_a is the salt deposition (mg m^{-2} h^{-1}), D is the distance from the sea (m), u is wind speed (m s^{-1}) and c_D is a calibration parameter that was used to fit the calculated deposition into the reported range of annual salt deposition in the island of Menorca (Jansà 1982).

Table 1. Summary of the characteristics and relationships between the submodels (see text for details)

	Watershed (RM)	Lagoon Water Volume (LWM)	Lagoon Salt Mass (LSM)
State variables	canopy water S_c (mm) soil water S_s (mm)	Water Volume V (m^3)	Total Salt TS (kg)
Output variables	surface runoff R_S (mm)	Water level WL (cm a.s.l.)	Salinity S (g L^{-1})
Inputs			
Climatic Data	P_r, T, T_M, T_m, u, RH	P_r, T, T_M, T_m, u, RH	u
Variables	-	R_S (from RM)	Q_P, Q_R, Q_S, Q_O, V (from LWM)
Calibration parameters	γ, c_I	c_E, WL_{om}, K_{om}, WL_{of}, K_{of}, WL_{sm}, K_{sm}, K_{sf}	c_D

3.2 Climatic and lagoon data

Daily values of rainfall (P_r), average temperature (T), maximum and minimum temperature (T_M and T_m), relative humidity (RH) and wind speed (u) were obtained from the nearest (7 Km) meteorological station (Spanish Meteorological Institute).

Daily values of WL (cm a.s.l.) in the lagoon were measured with a fixed scale near the outlet channel and provided by the Albufera des Grau Nature Park. The gaps in the data set were always lower than 10 days and were corrected by linear interpolation. A WTW-Cond315i conductivity probe was used to determine the water salinity at six depths (0, 50, 100, 150, 200 and 250 cm) on a monthly basis using a fixed sampling station located in the centre of the lagoon. The salinity values used here correspond to the average salinity of the entire water column. The Albufera des Grau is vertically homogeneous most of the time with vertical stratifications only observed occasionally (Pretus and Obrador 2004). A weighted salinity to correct the differences in the volume of each depth layer was not used because differences with the non-weighted average are minimal even during the stratification events (Obrador and Pretus, unpublished data).

3.3 Calibration and validation

The model was calibrated from January 2002 to December 2005 by tuning the eleven parameters to get the best fit in *WL* and *S*. The model performance was evaluated with measures of “goodness of fit” and of the absolute error between the observed and predicted daily values of the model outputs (*WL* and *S*). Despite its limitations (Legates and McCabe 1999) the coefficient of determination R^2 between the observed and predicted values was used as a first measure of the goodness of fit for the model. The modified coefficient of efficiency E_1 (Nash and Sutcliffe 1970 in Legates and McCabe 1999) was also used:

$$E_1 = 1 - \frac{\sum \left| O_i - P_i \right|}{\sum \left| O_i - \overline{O} \right|} \qquad \text{Eq. (13)}$$

where O_i and P_i are the observed and predicted values of the variable (*WL* or *S*) at each time step *i*, and $\overline{O}$ is the mean of the observed values of the variable.

The root mean square error (RMSE) and the Mean Absolute Error (MAE) were used as estimates of the absolute error:

$$RMSE = \sqrt{\frac{1}{n} \sum \left(O_i - P_i \right)^2} \qquad \text{Eq. (14)}$$

$$MAE = \frac{1}{n} \sum \left| O_i - P_i \right| \qquad \text{Eq. (15)}$$

where *n* is the number of observations.

A sensitivity analysis of the lagoon state variables (*V* and *TS*) and of the output variables (*WL* and *S*) was performed by running the model with a +10% and -10% relative change in the parameters. A sensitivity index was calculated for *V* and *TS* (Haefner 2005):

$$SI_k = \frac{1}{n} \frac{\sum \left(\left| P_i - P_i' \right| / P_i \right)}{0.1} \qquad \text{Eq. (16)}$$

where SI_k is the standardised sensitivity index of the variable (*V* or *TS*) to a change of 10% in the parameter k, P_i is the value of the variable at the nominal value of the parameter, and $P_i^{'}$ is the value of the variable at the modified value of the parameter.

The sensitivity of the output variables *WL* and *S* was expressed as RMSE:

$$S_k = \sqrt{\frac{1}{n}\sum\left(P_i - P_i^{'}\right)^2} \quad \text{Eq. (17)}$$

where S_k is the sensitivity of the variable (*WL* or *S*) to a change of 10% in the parameter *k*. For both SI_k and S_k the average of the measure for 10%-increase and 10%-decrease runs was computed.

The model was validated for the years 2001 and 2006, and the model performance was assessed and compared to the results of the calibration.

3.4 Historical data

Data of water salinity for the period 1975-2000 were used to assess the capability of the model to predict long term changes in the salinity of the lagoon and to determine the mean annual water and salt budgets. The observed data set consisted of irregular records of water salinity obtained from several sources, including published literature (Pretus 1989; Pretus et al. 1992), technical reports (Moyà et al. 1988; Pretus 1996; Pretus and Obrador 2004) and authors' unpublished data. In some cases, the methodology or the exact sampling date for a given salinity value were missing or unclear, in which case, the salinity value was assigned to the central day of the reported period (month or season). The mean annual water and salt budgets in the Albufera des Grau were calculated from the model outputs for the period 1975-2006 and hydrological years (from September to August) were used.

4. Results

4.1 Model performance

The calibration of the model resulted in a general good agreement between the observed and predicted values of the output variables (Fig. 3). For water level, both the marked seasonal trend and the range of variable were correctly simulated. The upper limit of *WL* during the torrential events (e.g. February 2003 and October 2003) was slightly underestimated, but the timing of the events closely agreed with the observed data. A negative slope in the *WL* trend was correctly reproduced during the dry season due to evaporation in the lagoon. The R^2 coefficient for *WL* was 0.84, and the coefficient of efficiency E_1 was 0.62 (Table 2). For salinity, the seasonal trend was correctly simulated and a good agreement between the simulated and observed series was achieved (Fig. 3). The R^2 and E_1 coefficients computed for salinity were 0.87 and 0.62, respectively. In terms of the absolute error, the model outputs showed a RMSE of 11 cm (MAE of 8 cm) for *WL*, and 1.8 g L^{-1} (MAE of 1.5 g L^{-1}) for *S* (Table 2).

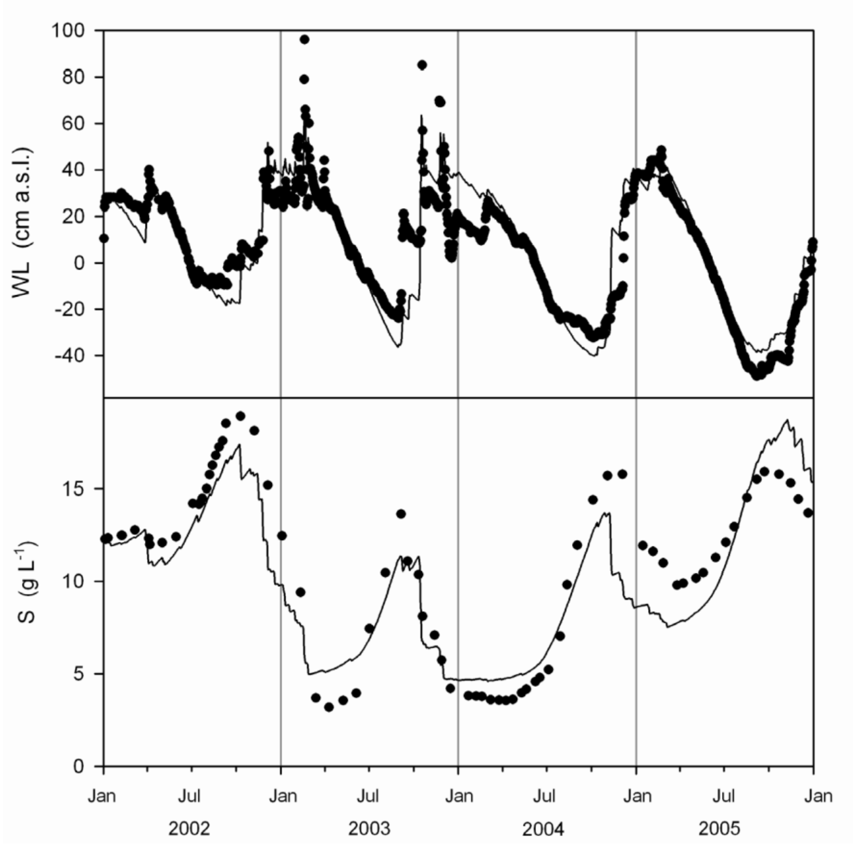

Figure 3. Temporal variation in the observed (dots) and predicted (line) values of water level and salinity for the calibration period.

Table 2. Measures of model performance based on the comparison between the observed and predicted values of WL and S. The R2 coefficient, the Efficiency coefficient (E1), the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) are shown for the calibration (2002-2005) and validation (2001 and 2006) periods.

		Calibration	Validation 2001	Validation 2006	Whole period
R^2	Water Level	0.84	0.86	0.98	0.89
	Salinity	0.87	0.82	0.94	0.69
RMSE	Water Level	11.0	13.5	5.7	10.4
	Salinity	1.8	3.1	5.3	3.6
MAE	Water Level	8.0	8.9	4.9	7.6
	Salinity	1.5	2.6	4.4	2.8
E_1	Water Level	0.62	0.66	0.83	0.55
	Salinity	0.62	0.12	-0.56	0.52

The results of the sensitivity analysis carried out on the parameters of the model are summarised in Table 3. The sensitivity of the state variables was always below 0.5 for *V* and below 3 for *TS*, which means that the response of the model to a 10% change in any parameter is below 5% for *V* and below 30% for *TS*. The equivalent sensitivity in terms of RMSE in the output variables was 5.5 cm for *WL* and 3.2 g L^{-1} for *S*. The *WL* was not sensitive to any parameter of the LSM submodel. The highest sensitivities were found on parameters of the RM and LWM submodels, being *WL* and *S* most sensitive to c_I . The model showed low sensitivity to changes in the initial values of the state variables.

Table 3. Sensitivity of the state variables to a 10% change in the parameters. The sensitivity of *WL* and *S* is expressed as the average RMSE of the 10%-increase and 10%-decrease runs of the model. (^{c}: calibration parameter)

	Parameter	Value	Sensitivity Index		Sensitivity (RMSE)	
			V	*TS*	*WL* (cm)	*S* (g L^{-1})
RM						
	c_I ^{c}	0.799	0.26	2.96	5.5	3.2
	S_{smax}	100 mm	0.05	0.29	1.2	0.3
	γ ^{c}	3.093	0.05	0.26	1.0	0.3
	albedo watershed	0.18	0.02	0.17	0.4	0.2
	initial S_s	60 mm	0.01	0.05	0.4	0.1
LWM						
	c_E ^{c}	0.796	0.22	0.95	3.7	1.5
	initial *WL*	24 cm	0.08	0.39	3.0	0.7
	WL_{om} ^{c}	40	0.13	0.13	2.4	0.2
	A (filtration)	0.025 m^2	0.05	0.31	0.9	0.4
	K_{of} ^{c}	1.467	0.05	0.07	0.8	0.1
	K_{sf} ^{c}	0.895	0.03	0.24	0.7	0.3
	albedo water	0.08	0.02	0.07	0.3	0.1
	K_{om} ^{c}	1.224	0.01	0.01	0.2	0.0
	WL_{of} ^{c}	7.4 cm	0.01	0.03	0.2	0.0
	A (massive flow)	2 m^2	0.00	0.42	0.2	0.0
	K_{sm} ^{c}	0.689	0.00	0.00	0.0	0.0
	initial *S*	12.4 g L^{-1}	0.00	0.42	0.0	0.6
	WL_{sm} ^{c}	-62 cm	0.00	0.00	0.0	0.0
LSM						
	Seawater salinity	38 g L^{-1}	0.00	0.35	0.0	0.5
	Stream salinity	1.9 g L^{-1}	0.00	0.22	0.0	0.2
	Rainfall salinity	0.11 g L^{-1}	0.00	0.00	0.0	0.0
	c_D ^{c}	12.3	0.00	0.00	0.0	0.0

The validation of the model for 2001 and 2006 resulted in an overall good agreement between the observed and the predicted values (Fig. 4). The R^2 for *WL* and *S* were similar to, and at times higher than, those obtained with the calibration data set (Table 2). The RMSE for *WL* was 13.5 cm and 5.7 cm for 2001 and 2006, respectively. Nevertheless, results for salinity did not match the observed data very precisely, and despite the high R^2 coefficients, the RMSE was twice that found in the period 2002 to 2005 (3.1 g L^{-1} and 5.3 g L^{-1} for 2001 and 2006, respectively; Table 2). The poor match between observed and predicted salinity was especially apparent during 2006, when a negative efficiency coefficient was found. This indicates that the simulated salinity is not as good a predictor as the mean of the observed data (Legates and McCabe 1999). It is likely that the differences found for *S* in 2006 are related to an overestimation of the variable at the end of the year (Fig. 4).

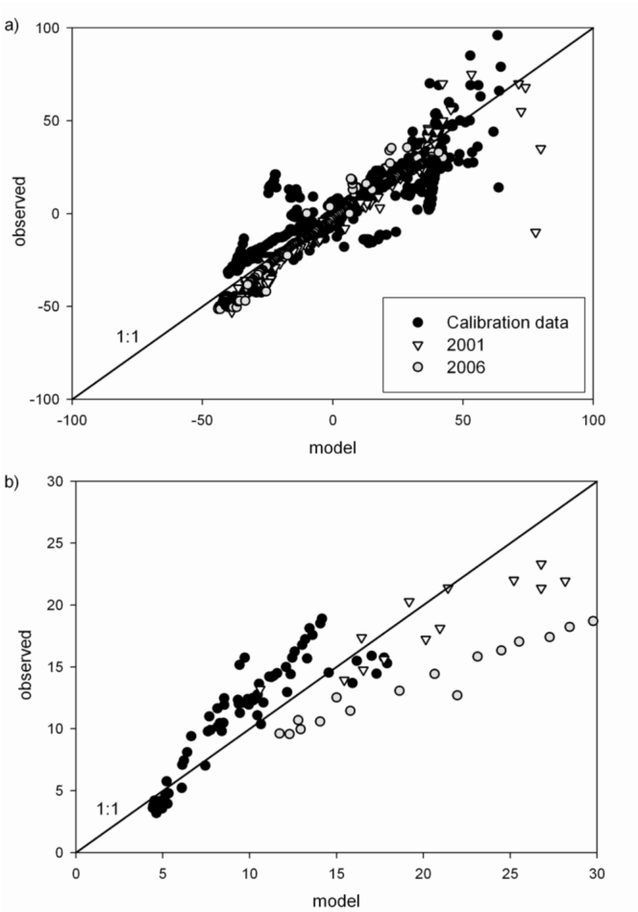

Figure 4. Scatterplot of the predicted water level (a) and salinity (b) for the calibration and validation periods.

4.2 <u>Historical period</u>

The salinity predicted by the model for the period 1975-2000 showed a clear seasonal trend but an important inter-annual variability was observed (Fig. 5). The range of the modelled salinity corresponded with the available observed data. The model correctly simulated the hyperhaline period (S>40 g L^{-1}) observed in the lagoon during 1994 and 1995, and it also successfully predicted the recovery of the polyhaline range (18-30 g L^{-1}) observed in the following years.

The water balance in the watershed was dominated by evapotranspiration, which accounted for 82% of the total water outputs in the catchment (Table 4). Surface runoff only accounted for 4% of the total annual precipitation on average. However, the daily runoff ratio (i.e. ratio between runoff and precipitation) was between 0.1% and 16% (mean 3%), which indicates that a higher proportion of precipitation turned into runoff during certain precipitation events.

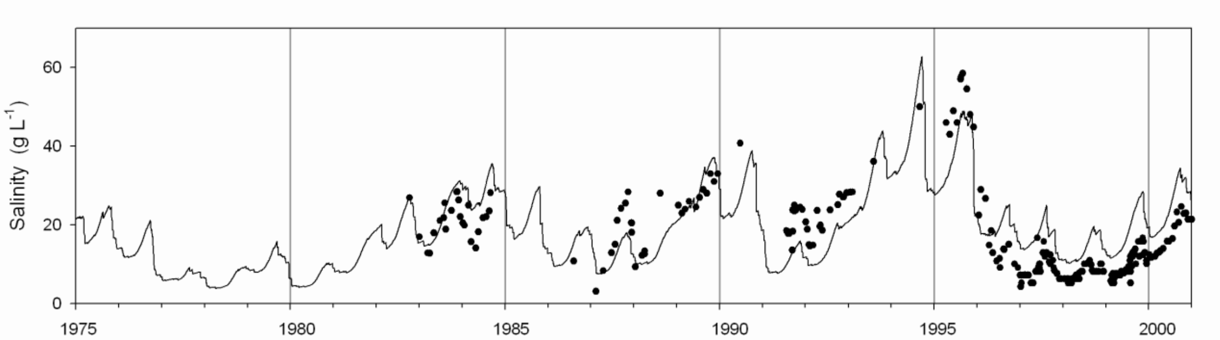

Figure 5. Temporal variation of the predicted (line) and observed (dots) water salinity for the period 1975-2000.

Table 4. Average annual water budgets (mean ± s.d.) in the watershed for the period 1975-2006. The mean of the percent contribution of each flux to total annual outputs is shown in brackets.

Component	Water budget (mm)	
Rainfall	549 ± 136	(100%)
Evapotranspiration	437 ± 76	(82%)
Infiltration	88 ± 56	(14%)
Runoff	22 ± 14	(4%)

Table 5. Average annual water and salt budgets (mean ± s.d.) in the Albufera des Grau during the period 1975-2006. The mean of the percent contribution of each flux to total annual inputs or outputs is shown in brackets.

Component	Annual Water Flux (x 1000 m^3)		Annual Salt Flux (x 1000 kg)	
Rainfall	387 ± 118	(27%)	43 ± 13	(0.7%)
Runoff	970 ± 602	(59%)	1844 ± 1178	(27%)
Seawater inflow	153 ± 75	(14%)	5808 ± 2582	(72%)
Aerosol deposition	-		16 ± 4	(0.3%)
Outflow	692 ± 637	(38%)	7798 ± 6616	(100%)
Evaporation	823 ± 39	(62%)	-	

The lagoon annual water and salt budgets for the period 1975-2006 are shown in Figure 6. High variability in the water budget was observed between years, especially in those fluxes directly or indirectly related to precipitation: rainfall and runoff, and lagoon outflow, respectively. Evaporation was the most constant water flux with values of $823 \cdot 10^3 \pm 39 \cdot 10^3$ m^3. Stream runoff and direct precipitation accounted for an average of 59% and 27%, respectively, of total water inputs (Table 5). Evaporation played an important role in the water balance and was the most important water output (an average of 62% of the total water outputs; Table 5). From the total annual water inputs (mean 1.51 hm^3) and the mean water volume in the lagoon (1.03 hm^3) the mean water residence time was calculated as 8 months.

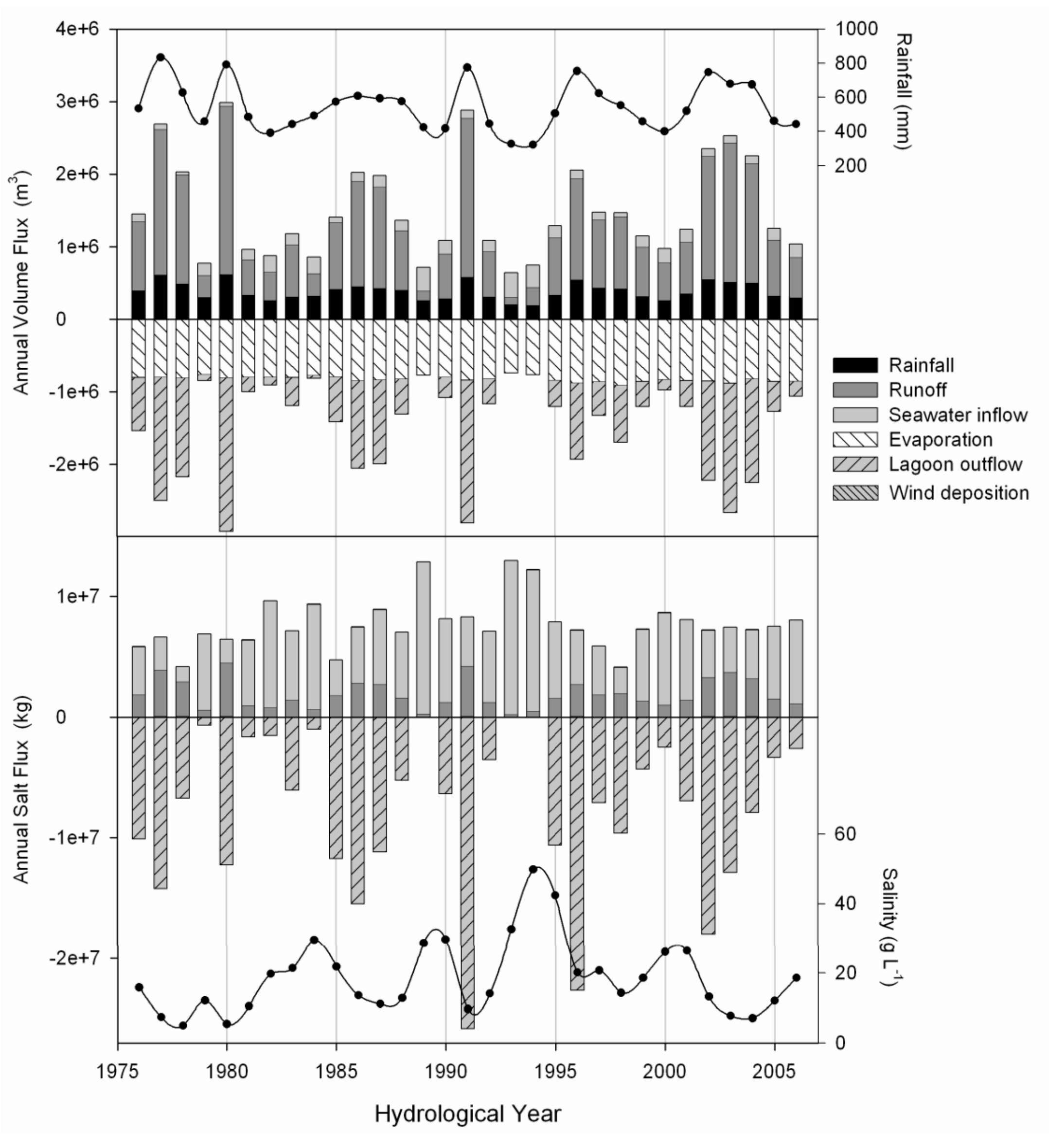

Figure 6. Annual water and salt budgets in the lagoon for the period 1975-2006. The annual precipitation and mean summer salinity are also shown for each hydrological year

The salt budget also reflected the high inter-annual variability observed in the water fluxes (Fig. 6). The salt inputs from direct rainfall and marine aerosol deposition had a negligible effect on the annual salt balance, and seawater inflow was responsible for an average of 72% of the annual salt inputs (Table 5). It is important to highlight that the contribution of the salt input from the watershed accounted for 27% of the total salt inputs on average (Table 5). The salt evacuation associated to the lagoon outflow was highly variable and was negligible in some years with very low water levels (1993 and 1994; Fig. 6).

During the historical period the mean annual salinity was related to the total precipitation of the previous hydrological year (Fig. 7a). From the relationship between the change in the mean annual salinity and the total annual precipitation (Fig. 7b), an “equilibrium” precipitation was calculated as 547 mm. This precipitation corresponded to the annual precipitation that would be necessary to maintain the lagoon without an inter-annual trend in salinity.

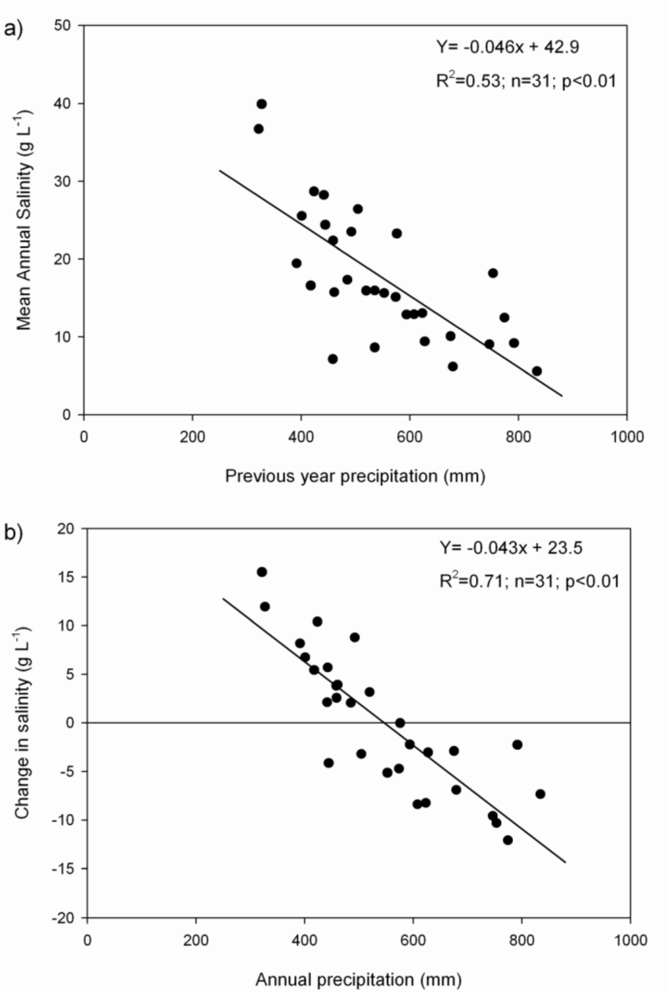

Figure 7. Relationships between mean annual salinity and total precipitation of the previous year (a), and between the change in the mean annual salinity and total annual precipitation (b). Each point corresponds to a hydrological year for the period 1975-2006.

5. Discussion

The model correctly simulated the basic hydrological processes of the lagoon. The seasonal trends were correctly simulated, and a reasonable adjustment between the observed and the predicted series of both *WL* and *S* was obtained. The model outputs showed low sensitivity to changes in most of the parameters or in the initial values of *WL* and *S*, and the highest sensitivities were observed in the parameters of the runoff submodel.

With regard to the lagoon model, the mean MAE for *WL* was 7.6 cm, which is an acceptable value given the range of variation of *WL* and the depth distribution of macrophytes (Obrador et al. 2007). On average, the RMSE was 30% higher than the MAE for *WL*, indicating the presence of outliers in the series. These outliers corresponded to the peaks in *WL* during the torrential events, which were slightly underestimated. Given the higher sensitivity of the model to the parameters of the runoff submodel, an inaccurate prediction of the torrential inputs is suggested. This could be due to spatial heterogeneity in the rainfall, which is described as being important in the island (Jansà 1979). More probably, the inaccurate prediction of the torrential events may be explained by the spatially averaged approach used to model the watershed. More detailed approaches based on a spatially explicit hydrology of the watershed would help to improve the accuracy of the model during such torrential events. This would be desirable if nutrient loads are to be calculated, since most of the nitrogen inputs enter the lagoon during these events (authors' unpublished data). However, despite the inaccuracies in the peaks, the model correctly predicted the dynamics of *WL*, properly adjusting the slope during the dry season and giving the appropriate response when the lagoon had low *WL* values. Moreover, the hydrology of the watershed was realistic in terms of the annual water budget. The mean annual water balance in the watershed for the historical period (considering hydrological years) was similar to the water budgets for the island of Menorca reported in the literature (Fayas 1999; Estradé 2003). Furthermore, the runoff ratio (below 16%) was within the reference values for similar Mediterranean areas (Martin-Vide et al. 1999; Rulli et al. 2006).

With regard to salinity, the model correctly simulated the temporal dynamics and the range of the variation of the variable. The mean MAE for the whole period was 2.8 g L^{-1}, which is acceptable for the management of the lagoon. Despite a good agreement was obtained in the calibration, a significant overestimation of salinity was observed in the validation of the year 2006 (Fig. 4). This could be due to a misdetermination of the water fluxes between the lagoon and the sea. It is important to highlight that the wood sluices were changed the previous winter, which could have changed the flow conditions for the year 2006 and the end of 2005 (M. Truyol, pers. comm., 2007). On the other hand, assuming a constant level of salinity for each water flux could also be criticised. Firstly, the salinity of the so-termed seawater inflow does not actually correspond to the salinity of seawater because intense evaporation and dilution can occur all along the outlet channel, which is intermittently connected to the sea. Similarly, it is unrealistic to assume constant stream salinity because it naturally decreases with discharge. A variable salinity was not used because robust data of the salinity-discharge relationship for the streams of the Albufera des Grau was not available; using it otherwise would have added another element of uncertainty to the model. The salinity of the lagoon outflow is also subject to a certain degree of variation because during very intense torrential events the output salinity can be slightly higher than the average salinity of the lagoon. This is explained by incomplete mixing and a forced hypolimnetic discharge (Pretus and Obrador 2004). Nonetheless, the very simple hydraulic equations used in the model resulted in a reasonable degree of accuracy in the determination of the seasonal dynamics and the range of variation of water salinity. Moreover, the simulation of the historical period 1975-2000 revealed that the model could predict long-term dynamics in the salinity of the lagoon. The low quality of the historical salinity data set prohibited a formal validation of the salinity simulation, and only the range of the variable was considered. High salinity ranges (30-40 g L^{-1}) and even a hyperhaline period in the lagoon (years 1994 and 1995) were correctly simulated despite the model being calibrated in a much lower range (between 2 and 20 g L^{-1}).

In conclusion, the model is believed to be a useful tool to simulate the dynamics of water level and salinity in the Albufera des Grau. Both variables have substantial ecological significance and are highly informative descriptors of the risk of critical situations such as the hypersalinisation of the lagoon and the littoral desiccation due to low water levels, both with severe adverse effects on the macrophyte meadows and the fish community (Cardona 2000; Pretus 2003). Numerous models have been developed to simulate the hydrology of Mediterranean costal lagoons; most of them are two- or three-dimensional models designed to describe circulation patterns resulting from wind, river or tidal forcing (Covelli et al. 2002; Chauvelon et al. 2003; Umgiesser et al. 2004; Ferrarin and Umgiesser 2005; Marinov et al. 2006; Niedda and Greppi 2007). In the Albufera des Grau, a detailed hydrodynamic model would be useful in describing the risk of haline stratification and bottom anoxia. It would also be useful to evaluate the suitability of different management strategies related to the height of the sluice opening (Pretus 2003). Nonetheless, in the case of the Albufera des Grau, an enclosed lagoon without tidal influence, the fluctuations in water level are driven mainly by the precipitation-evaporation regime. In this context, and given the existing difficulties in applying detailed two- or three-dimensional models for shallow waters (D'Alpaos and Defina 2007), a simple model referred not to hydrodynamics but to the water and salt balances would be the most appropriate approach. This is especially relevant in the absence of a robust dataset for the hydrology of the system, as in the case of the Albufera des Grau. In this sense, the advantage of the model comes from its simplicity and the fact that it does not require a large data set (Jørgensen and Bendoricchio 2001).

The results of the simulations during the historical period allowed us to determine the water and salt budgets in the lagoon on an annual basis. As expected, the salt fluxes were characterised by a dependence on the water fluxes, and the direct aerosol deposition on the lagoon was insignificant in the annual salt budget. Despite the high inter-annual variability observed in the water fluxes, total water input was dominated by the runoff input (59% of total water inputs) followed by direct rainfall (27%) and seawater inflow (14%). Evaporation accounted for 62% of the water outputs in the lagoon, however, its temporal dynamics combined with the seasonality of the precipitation, appeared to determine the temporal trend in water level and salinity.

In this study, a description of the annual water budget of the lagoon is given as a first application of the model outputs. A detailed exploration of the hydrological processes that control the dynamics in *WL* and *S* was not within the purpose of this paper. Nonetheless, a brief exploration into the inter-annual variability in salinity revealed a clear relationship with the total annual precipitation. The hypersalinisation of the years 1994 and 1995 occurred after two consecutive dry years characterised by annual precipitation below 400 mm. The low freshwater inputs were responsible for a null outflow over a two–year period (1993 and 1994), thus increasing the total salt in the lagoon and consequently water salinity.

By establishing the relationship between precipitation and water salinity (Fig. 7) the level of annual precipitation required to maintain a constant salinity in the lagoon could be calculated. The resulting "equilibrium" precipitation was 547 mm, which is very close to the mean annual precipitation during the historical period (549 ± 136 mm; Table 4). This suggests that the springs that supplied permanent freshwater inputs to the streams, which suffered drought in the 1960s, are not essential in maintaining the lagoon in an optimal state. These findings are in accordance with previous observations (Pretus 2003). The corresponding salinity at "equilibrium" precipitation is 17.7 g L^{-1}, which is an appropriate salinity target for the management of the lagoon and thus indicates the inappropriateness of any management targets significantly outside this value. However, this should be confirmed by a detailed evaluation of the seasonal timing of the fluxes and not just by conclusions based on annual averages. Historical records with information on the ecological status of the lagoon during the last decades, together with palaeolimnological studies designed to reconstruct the palaeosalinity of the system, may also improve the understanding of the hydrology of the lagoon before the anthropogenic alteration of the water cycle in the watershed.

6. Conclusions

The model simulated the dynamics of the hydrological descriptors of the Albufera des Grau coastal lagoon with reasonable accuracy. Both the timing, with a marked seasonal trend, and the range of water level and water salinity were accurately modelled with low sensitivity to parameter changes. The simulations carried out over a period of 30 years accurately predicted the long term range of variation of salinity in the lagoon, even at salinity levels above the usual range of variation. The simplicity of the model and the fact that it does not require a large data set makes it an attractive tool for lagoon management in assessing the risk of adverse ecological situations in the lagoon. However, the model cannot accurately predict torrential water inputs; this would probably require a more explicit approach in the modelling of the watershed hydrology. The model made it possible to describe the annual water and salt budgets, which were characterised by high inter-annual variability.

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References

Alcalá-García, F.J. 2005. Recarga a los acuíferos españoles mediante balance hidrogeoquímico. Ph D Thesis. Departament d'Enginyeria del Terreny, Cartogràfica i Geofísica. Universitat Politècnica de Catalunya

Allen, R., L. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration— guidelines for computing crop water requirements— FAO Irrigation and Drainage paper 56. Roma: FAO

Asmar, B., and P. Ergenzinger. 1999. Estimation of evaporation from the Dead Sea. Hydrological Processes 13: 2743–2750

Beklioglu, M., S. Romo, I. Kagalou, X. Quintana, and E. Bécares. 2007. State of the art in the functioning of shallow Mediterranean lakes, workshop conclusions. Hydrobiologia 584: 317–326

Bergström, S. 1995. The HBV model. In Computer models of watershed hydrology,Cardona, L. 2000. Effects of salinity on the habitat selection and growth performance of Mediterranean flathead grey mullet Mugil cephalus (Ostichthyes, Mugilidae). Estuarine, Coastal and Shelf Science 50: 727–737

Cardona, L. 2001. Non-competitive coexistence between Mediterranean grey mullet, evidence from seasonal changes in food availability, niche breadth and trophic overlap. Journal of Fish Biology 59: 729–744. doi:10.1111/j.1095-8649.2001.tb02376.x

Chauvelon, P., M. Tournoud, and A. Sandoz. 2003. Integrated hydrological modelling of a managed coastal Mediterranean wetland (Rhone delta, France): initial calibration. Hydrology and Earth System Sciences 71: 123–131

Covelli, P., S. Marsili-Libelli, and G. Pacini. 2002. SWAMP: A twodimensional hydrodynamic and quality modeling platform for shallow waters. Numerical Methods for Partial Differential Equations 18: 663–687. doi:10.1002/num.10014

D'Alpaos, L., and A. Defina. 2007. Mathematical modeling of tidal hydrodynamics in shallow lagoons: A review of open issues and applications to the Venice lagoon. Computers and Geosciences 33: 476–496. doi:10.1016/j.cageo.2006.07.009

De Vicente, A., E. Moreno-Ostos, V. Amores, F.J. Rueda, and L Cruz-Pizarro. 2006. Low predictability in the dynamics of shallow lakes, implications for their management and restoration Wetlands 26: 928–9382

Deardorff, J.W. 1978. Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation Journal of Geophysical Research 86C: 1889–1903. doi:10.1029/JC083iC04p01889

Döll, P., F. Kaspar, and B. Lehner. 2003. A global hydrological model for deriving water availability indicators, model tuning and validation. Journal of Hydrology 270: 105–134.

Estradé, S. 2003. Aportacions al coneixement del balanç hídric de l'aqüífer de Migjorn de Menorca. Working Paper 9/2003. Maó: Social and Environmental Observatory of Menorca-OBSAM

Fayas, A. 1999. El agua. In: Actes de les Jornades sobre la Reserva de la Biosfera de Menorca.. 89–108. Maó: Institut Menorquí d'Estudis

Ferrarin, C., and G. Umgiesser. 2005. Hydrodynamic modeling of a coastal lagoon: The Cabras lagoon in Sardinia, Italy. Ecological Modelling 188: 340–357. doi:10.1016/j.ecolmodel.2005.01.061

Gustafsson, M.E., and L.G. Franzen. 1996. Dry deposition and concentration of marine aerosols in a coastal area, SW Sweden. Atmospheric Environment 30: 977–989. doi:10.1016/1352-2310 (95)00355-X

Haefner, J. 2005. Modeling biological systems, principles and applications. 2New York: Springer

Jansà, A. 1979. Climatologia de Menorca. In: Enciclopèdia de Menorca. Tom 1. Geografia Física. 85–160. Maó: Obra Cultural de Menorca

Jansà, A. 1982. Vent i aerosòl marí a Menorca. Avaluació i efectes agraris i ecològics. Maó: Consell Insular de Menorca

Jørgensen, S.E., and G. Bendoricchio. 2001. Fundamentals of ecological modelling, 3rd edn. Amsterdam: Elsevier

Legates, D., and G. McCabe. 1999. Evaluating the use of "goodnessof- fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research 35: 233–241. doi:10.1029/ 1998WR900018

Linacre, E.T. 1992. Climate data and resources. London: Routledge

Margalef, R. 1952. Materiales para la hidrobiología de la isla de Menorca. Publicaciones del Instituto de Biología Aplicada 11: 5– 112

Marinov, D., A. Norro, and J.M. Zaldivar. 2006. Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). Ecological Modelling 193: 52–68. doi:10.1016/j.ecolmodel.2005.07.042

Martin-Vide, J.P., D. Ninerola, A. Bateman, A. Navarro, and E. Velasco. 1999. Runoff and sediment transport in a torrential ephemeral stream of the Mediterranean coast. Journal of Hydrology 225: 118–129. doi:10.1016/S0022-1694(99)00134-1

Moreno-Ostos, E., S.L. Rodrigues da Silva, I. de Vicente, and L. Cruz-Pizarro. 2007. Interanual and between-site variability in the occurrence of clear water phases in two shallow Mediterranean lakes. Aquatic Ecology 41: 285–297. doi:10.1007/s10452-006- 9072-0

Moreno-Ostos E., M. Paracuellos, I. de Vicente, J.C. Nevado, and L. Cruz-Pizarro. 2008. Response of waterbirds to alternating clear and turbid water phases in two shallow Mediterranean lakes. Aquatic Ecology. doi:10.1007/s10452-007-9141-z Moyà, G., A. Martínez, and J.L. Pretus. 1988. Estudi limnològic de s'Albufera des Grau. Palma de Mallorca: Universitat de les Illes Balears

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models, Part 1—a discussion of principles. Journal of Hydrology 10: 282–290

Niedda, M., and M. Greppi. 2007. Tidal, seiche and wind dynamics in a small lagoon in the Mediterranean Sea. Estuarine, Coastal and Shelf Science 74: 21–30. doi:10.1016/j.ecss.2007.03.022

Noordhuis, R., D.T. van der Molen, and M.S. van den Berg. 2002. Response of herbivorous water-birds to the return of Chara in Lake Veluwemeer, The Netherlands. Aquatic Botany 72: 349– 367. doi:10.1016/S0304-3770(01)00210-8

Obrador, B., and J.L. Pretus. 2008. Light regime and components of turbidity in a Mediterranean coastal lagoon. Estuarine, Coastal and Shelf Science 77: 123–133

Obrador, B., J.L. Pretus, and M. Menéndez. 2007. Spatial distribution and biomass of aquatic rooted macrophytes and their relevance in the metabolism of a Mediterranean coastal lagoon. Scientia Marina 71: 57–64

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society London A193: 120– 146

Pretus, J.L. 1989. Limnología de la Albufera de Menorca (Menorca, España). Limnetica 5: 69–81

Pretus, J.L. 1996. Ecologia de s'Albufera. Informes tècnics 1 a 5. Barcelona: Universitat de Barcelona

Pretus, J.L. 2003. Ecologia i gestió sostenible de s'Albufera des Grau. Butlletí Científic dels Espais Naturals Protegits de les Illes Balears 1: 51–67

Pretus, J.L., and B. Obrador. 2004. Informe anual del seguiment de s'Albufera des Grau. Barcelona: Universitat de Barcelona

Pretus, J.L., J. de Manuel, and L. Cardona. 1992. Temporal heterogeneity, zooplankton composition and fish food supply in the Albufera of Minorca, a highly fluctuant environment. Bulletin de l'Institute Océanografique Monaco 11: 179–188

Rulli, M.C., S. Bozzi, M. Spada, D. Bocchiola, and R. Rosso. 2006. Rainfall simulations on a fire disturbed Mediterranean area. Journal of Hydrology 327: 323–338

Stumpf, R.P., M.L. Frayer, M.J. Durako, and J.C. Brock. 1999. Variations in water clarity and bottom albedo in Florida Bay from 1985 to 1997. Estuaries 22: 431–444

Umgiesser, G., D. Canu, A. Cucco, and C. Solidoro. 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. Journal of Marine Systems 51: 123–145

USBR. 2001. Water measurement manual. 3Washington, DC: US Bureau of Reclamation

Xu, C., and V. Singh. 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. Hydrological Processes 15: 305–319