

# Estimation of Water Circulation in a Mediterranean Salt Marsh and its Relationship with Flooding Causes

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## ABSTRACT

Variations in water volume in small depressions in Mediterranean salt marshes in Girona (Spain) are described and the potential causes for these variations analysed. Although the basins appear to be endorheic, groundwater circulation is intense, as estimated from the difference between water volume observed and that expected from the balance precipitation / evaporation. The rate of variation in volume ( $V_R = \Delta V / \Delta t$ ) may be used to estimate groundwater supply ("circulation"), since direct measurements of this parameter are impossible. Volume-conductivity figures can also be used to estimate the quantity of circulation, and to investigate the origin of water supplied to the system. The relationships between variations in the volume of water in the basins and the main causes of flooding are also analysed. Sea storms, rainfall levels and strong, dry northerly winds are suggested as the main causes of the variations in the volumes of basins. The relative importance assigned to these factors has changed, following the recent regulation of freshwater flows entering the system.

Keywords: rate of variation of volume, turnover rate, salt marshes, water circulation, fluctuations, disturbances, conductivity, Emporda wetlands

## RESUMEN

*Se describen las variaciones en el volumen del agua de pequeñas depresiones de la marisma mediterránea de Aiguamolls de l'Empordà y se analizan las causas responsables de estas variaciones. A pesar de que estas depresiones muestran aparentemente un comportamiento endorreico, la circulación subterránea ha de ser muy intensa, tal como muestran las diferencias entre el volumen real de las depresiones y el volumen que sería esperable a partir del balance precipitación-evaporación. La tasa de variación de volumen ( $V_R = \Delta V / \Delta t$ ) puede usarse para estimar la circulación de agua a través de estas cubetas, puesto que la cuantificación del flujo de entrada de agua no es posible porque no hay una entrada continua de agua superficial. El uso del producto volumen · conductividad también permite la estimación de la circulación del agua a través de las depresiones y su origen marino o continental. Se analiza también la relación entre la variación del volumen de agua en las depresiones y las principales causas de inundación. Los temporales de mar, las precipitaciones y los vientos fuertes y secos del norte se muestran como las principales causas de variación del volumen de las cubetas. Su importancia relativa ha variado en los últimos años como consecuencia de la alteración y la regulación del flujo de agua dulce que entra al sistema.*

*Palabras clave: Tasa de variación del volumen, tasa de renovación, marismas salobres, circulación del agua, fluctuaciones, perturbaciones, conductividad, Marismas de l'Empordà.*

## INTRODUCTION

Mediterranean salt marsh depressions usually appear to be endorheic. Sudden flooding caused by heavy rains or storms coming in from the sea is usually followed by long droughts and periods

of concentration of salts. However, there may be more groundwater circulation than meets the eye. Changes in piezometric level, generally close to the topographical level lead to significant vertical circulation of water. This movement of water can be more important than the horizontal circulation,

caused by surface contributions of continental or marine origin, which is a common situation in coastal marshes (Valiela *et al.*, 1978).

Vertical flow influences hydric regime and water composition, which are turnover-dependent (Peterson *et al.*, 1985; Comín *et al.*, 1991; Comín & Valiela, 1993; Herrera-Silveira, 1993; Quintana *et al.*, 1998a). It is difficult, however, to quantify inflow and outflow volumes unless there are surface channels. Even where they exist, ignoring vertical flow to and from the aquifer may lead to underestimation of real flows.

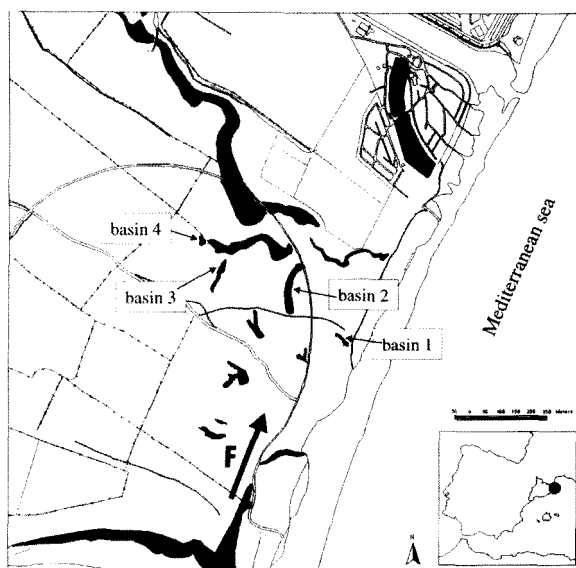
This paper gives estimates of volume and circulation rates in isolated salt-marsh basins of the Emporda wetlands (Girona, Spain), which have no surface inputs of water. The causes of floods and associated changes in water volumes are analysed. Two independent criteria were used for estimation, i.e. the ratio rainfall:evaporation, and the product volume·conductivity. The difference between predicted and observed volumes was attributed to groundwater circulation.

Understanding circulation and the causes of flooding is particularly relevant to the Emporda salt marshes. Here, a sluice gate has been installed to regulate drainage and increase the area remaining under water (Romero, 1996). Potential causes explaining uncontrolled floods before and after the sluice gate began operating are analysed. An understanding of these changes is important in light of the worsening in water quality apparently caused by the alteration of the natural hydrological regime (Quintana *et al.*, 1998b).

## METHODS

### Area of study and sampling

The study was carried out in a group of temporary ponds in the Emporda salt marshes, an area of coastal lagoons and Mediterranean salt marshes with typically Mediterranean hydrology (Fig. 1). These salt marshes show very sharp fluctuations in water level. Flash floods caused by sea storms moving inland, and relatively long dry periods are a common occurrence (Bach, 1989; Quintana,



**Figure 1.** Location of the study area. (F) Preferent freshwater flux derivated by the sluicegate. *Situación del área de estudio. (F) Flujo preferente de agua dulce desviado por la compuerta.*

1995). Most lagoons in the area and all basins studied are isolated most of the year and only link up when flooding is greatest. Continual fresh surface water input is limited to one single channel which flows out at the southern extreme of the area (see Fig. 1). On the same side of the park there is a drainage channel leading to the sea. A sluice gate was installed in this channel with the aim of increasing the flooded area of the salt marshes. This sluice gate has altered the hydric regime of the area, increasing the duration and frequency of flooding. This has reduced salinity and increased eutrophy in the area, as a result of the increase in fresh water supply and nutrients. More details about the area of study can be found in Quintana *et al.* (1998a and 1998b).

Four basins were chosen running in a line perpendicular to the coast (Fig. 1). They are small depressions in the salt marsh between the dunes, where flood water accumulates. The main morphometric characteristics of the basins are summarised in Table 1, following Hutchinson (1957). The topographical profile of each basin is given in Quintana, (1995). There is no continuous surface flow, in or out. Water levels change because

**Table 1.** Main morphometric characteristics of the basins under study when full.  $z$ , depth of the full basin;  $z_m$ , height above sea level of the deepest point;  $z_{mean}$ , average depth;  $l$ , length;  $b$ , average width;  $A$ , surface area;  $V$ , volume;  $D_v$ , development of the volume;  $z_r$ , relative depth;  $A_c$ , approximate area of the reception basin. Units in m,  $m^2$  and  $m^3$ . *Principales parámetros morfométricos de las cubetas estudiadas, medidas considerando las cubetas llenas.  $z$ , profundidad de la cubeta llena;  $z_m$ , altura sobre el nivel medio del mar del punto más profundo;  $z_{mean}$ , profundidad media;  $l$ , longitud;  $b$ , anchura media;  $A$ , superficie;  $V$ , volumen;  $D_v$ , desarrollo del volumen;  $z_r$ , profundidad relativa;  $A_c$ , superficie aproximada de la cuenca de recepción. Unidades en m,  $m^2$  y  $m^3$ .*

Basin	$z$	$z_m$	$z_{mean}$	$l$	$b$	$A$	$V$	$D_v$	$z_r$	$A_c$	$A_c/A$	$A_c/V$
1	0.80	0.00	0.26	84	11.70	983	252.30	0.975	2.26	18750	19.07	74.31
2	0.46	0.14	0.18	181	27.66	5007	882.40	1.174	0.58	36500	7.28	41.36
3	0.70	0.10	0.43	149	21.72	3236	1401.70	1.840	1.09	16000	4.94	11.41
4	0.71	0.09	0.32	64	25.77	1649	523.43	1.352	1.55	41500	25.16	79.28

of sudden flooding in the case of surface input, or by filtration up or down through the sediment in the case of groundwater.

In each basin, level, temperature and conductivity ( $C = EC_{\text{c}}$ ) were measured at a point near the centre between April 1989 and March 1991; the sluice gate was installed in January 1990. Sampling was weekly or monthly, with more sampling in periods of disturbance. Samples were also taken to analyse nutrients and chlorophyll, and to count and classify phyto- and zooplankton. These results are presented elsewhere (Quintana *et al.*, 1998a and 1998b).

#### Meteorological data and estimates of evaporation

Meteorological data were obtained from two weather stations near the coast, 2km and 20km from the basins. The component of the wind perpendicular to the NNE-SSW coastline (PCC) was calculated from wind velocity and direction. Thus:

$$PCC = u \cdot \sin(a - 22.5^\circ)$$

where  $u$  is intensity and  $a$  is wind direction ( $N = 0^\circ$ ;  $E = 90^\circ$ ;  $S = 180^\circ$ ;  $W = 270^\circ$ ), from which the approximate direction of the coast is subtracted ( $NNE = 22.5^\circ$ ). South-easterly winds will have a very positive component ( $PCC = u \sin 90^\circ = u$ ), pushing the sea towards the coast and tending to raise sea level there. North-westerlies ( $PCC =$

$u \sin 270^\circ = -u$ ) will have the opposite effect, so that their component is negative. For winds close to NNE-SSW the component will be near zero, independently of wind strength.

The volume of water lost by evaporation was calculated from differences in water and air vapour pressure and windspeed, following the methodology described elsewhere (Penman, 1948; Dingman *et al.*, 1968; TVA Report, 1972; Kuhn, 1978; Hsu, 1983; Livingstone & Imboden, 1989). Evaporation may have been overestimated, i.e. saltier water is both denser and has lower vapour pressure than fresher water. The water in the basins can be considered to be dilute seawater, since seawater has a density of  $1.028 \text{ g cm}^{-3}$  (Margalef, 1989), very close to that of freshwater. Thus, the maximum error in estimating the density of brackish waters will be less than 3 %. The effects of salinity on vapour pressure are greater than on density. These effects depend on both salt concentration and the ionic composition of salts. Concentrated seawater has a vapour pressure 0.87 times that of pure water (Salhotra *et al.*, 1985). Evapotranspiration has not been taken into account. Effects of evapotranspiration could have compensated for overestimation errors because we used equations applying to freshwater. Plant growth, however, was restricted to the banks of basins.

#### Estimations of volume and hydric balance

To quantify the amount of water entering and leaving the system, the expected volume of water was

estimated for each basin for each sampling day, and then compared to observed volumes. The volume expected was estimated assuming input was only from rainfall, and loss was only by evaporation. Any discrepancy between the estimated volume and that observed suggested an input or an output of water from the system. Expected volumes were obtained in two ways, both ways using the observed volume on day  $t-1$ , i.e.

1. From the rainfall - evaporation balance, and

2. From the conservation of the volume-conductivity product ( $V \cdot C$ )

1. In the first case, the volume expected on day  $t$  was calculated as

$$V_{ep} = V_{t-1} + V_p - V_e \quad (1)$$

where  $V_{ep}$  is the predicted volume on day  $t$ ,  $V_{t-1}$  the real volume on day  $t-1$  and  $V_p$  and  $V_e$  rainfall and evaporation between days  $t$  and  $t-1$ , respectively. The difference between real and predicted volumes ( $V_t$  and  $V_{ep}$ ) on day  $t$  will be equal to the net volume ( $V_x$ ) entering and leaving the basins at any level of rainfall and evaporation:

$$V_x = V_t - V_{ep} \quad (2)$$

$V_x$  also included surface runoff, because  $V_p$  was calculated for pond surface area, not catchment area.

2. The second way of estimating the volume of water expected in the system is based on the principle that the sum of the products  $V \cdot C$  (volume-conductivity) of all of the masses of water which are mixed together is equal to the same product for the resulting, mixed water mass

$$V_t \cdot C_t = V_{t-1} \cdot C_{t-1} + V_p \cdot C_p - V_e \cdot C_e + V_x \cdot C_x \quad (3)$$

The same notation used for volumes has been used for conductivities.

Junge & Gustafson (1957) estimated chloride concentration in rain water as 0.1-20 mg/l. Much higher concentrations, from 9 to 49 mg/l, have been found in urban, more polluted areas

(Custodio *et al.*, 1985). According to Reisman & Ovard (1974), the concentration of salts in the air is lower at a distance from the sea and larger at higher windspeeds. Along the coastline the air may contain 700 mg-salts/m<sup>3</sup> when wind speed is 50 km/h. In any case, where water is highly saline, the conductivity of rainfall ( $C_p$ ) and of evaporated water ( $C_e$ ) can be considered negligible. Furthermore, in the area studied, the greatest salt concentration coincided with sea storms (Bach, 1990). Thus,  $V_p \cdot C_p$  and  $V_e \cdot C_e$  can be equated to 0, and

$$V_t = (V_{t-1} \cdot C_{t-1} + V_x \cdot C_x) / C_t \quad (4)$$

The volume of water predicted for day  $t$  ( $V_{ec}$ ) if input and loss are solely from rain and evaporation will be:

$$V_{ec} = V_{t-1} \cdot C_{t-1} / C_t \quad (5)$$

The expected conductivity ( $C_{ec}$ ) can be calculated from  $V_{t-1}$  and  $C_{t-1}$ , adding or subtracting rainfall, evaporation and  $V_x$  ( $V_x$  is assumed to be a single water volume with conductivity equal to  $C_{t-1}$ ). The difference between  $C_{ec}$  and  $C_t$  allows the identification of the origin of water inputs.

### Rates of variation of volume

To be able to calculate changes in volume between different-volume basins at different times of the year, the following rates were determined:

1. The rate of variation in volume of water in the basin per unit of time (Quintana *et al.*, 1998a), i.e.  $V_R = \Delta V / \Delta t$  (days<sup>-1</sup>).
2. Cumulative rate of variation in volume of water between two sampling days:  $V_A = \Delta V / V$  (dimensionless).
3. Predicted rate of variation in volume of water between two sampling days, estimated as the Rainfall / Evaporation balance, i.e.  $V_E = \Delta V_{ep} / V$  (dimensionless), where  $V$  is the mean basin volume maintained between  $t$  and  $t-1$ .

The rates will be positive or negative depending on whether the basins are filling up or emptying.

The use of  $V$ , has disadvantages (Quintana *et al.*, 1998a). First, filling is typically very fast, as occurs, for instance, after sea storms. Sampling frequency then only measures the average value of  $V_R$  during  $\Delta t$ , and underestimates the rate of filling. Second, sampling frequency was not constant. This must be allowed for when comparing rates in different periods.

$V$ , is not a true turnover rate, since it measures neither volume circulating nor its speed. Rather, it expresses net input or output. Thus, if volume circulating equals water lost during a given period,  $V_R$  will equal zero even when turnover is high. The cumulative rate of variation of volume ( $V_A$ ) was calculated between every two sampling dates to avoid dividing by  $\Delta t$ . The comparison of volume rates between dates can help interpret the dynamics at work, i.e. when the instantaneous rate of change in volume ( $dV / Vdt$ ) remains constant,  $V$ , will be the same for any  $\Delta t$ , irrespective of duration. As  $\Delta t$  increases, so will  $V_A$ . In contrast, a strong disturbance (i.e. very high  $dV / Vdt$ ) during a long period without changes (i.e.  $\Delta V / \Delta t = 0$ ), will make  $V$ , fall as  $\Delta t$  increases and  $V_A$  will remain constant.

## RESULTS AND DISCUSSION

### Causes of flash floods

Stepwise multiple regression is used to relate basins,  $V$ , to meteorological events (Table 2). Unfortunately, sea level data only exist from 1990 onwards, when the sluice gate was already working. Instead, sea level is substituted in the regression by the related variables, atmospheric pressure and wind variables (Vallespinós *et al.*, 1976; Rodríguez-Prieto, 1992), so that pre- and post-sluice gate periods can be compared. If sea level influenced changes in basin volume, we would expect these two variables to be correlated. PCC is used as a measure of the effect of wind on the volumes of basins. This variable includes the effect of wind intensity, and of direction, i.e. whether the wind tends to push the sea towards the coast or away from it. The regression between sea level and atmospheric pressure, and the PCC gave a correlation  $r$  of  $-0.740$  ( $p < 0.0001$ ). The partial correlations were  $r = -0.739$  ( $p < 0.0001$ ) for atmospheric pressure and  $r = 0.117$  ( $p < 0.05$ ) for the PCC.

Factors significantly correlated with  $V$ , were wind (i.e. PCC), sea storm occurrence

**Table 2.** Significant partial correlations ( $p < 0.01$ ) and multiple correlation coefficients  $r$  ( $p < 0.0001$ ) between the meteorological variables which may have had an influence over the level of the basins and their rate of volume variation  $V_R$  (dependent variable).  $P_{atm}$ , atmospheric pressure in mbars; PCC, perpendicular component to the coastline; "storm", number of days with sea storms (i.e. with waves more than 3-m high); pac, accumulated precipitation in mm; evap, evaporation in mm. "Total": all data have been included in analyses. "Before" and "After" are the days before and after the sluice gate began operating. (-) Non-significant correlations ( $p > 0.01$ ). *Correlaciones parciales significativas ( $p < 0.01$ ) y coeficiente de correlación múltiple  $r$  ( $p < 0.0001$ ) entre las diferentes variables meteorológicas que pueden tener influencia sobre el nivel del agua de las cubetas y la tasa de variación de volumen de las cubetas  $V_R$  (variable dependiente). Patm. presión atmosférica en mbars; PCC, componente perpendicular a la costa: "storm", número de días con temporal de mar (olas superiores a 3m); pac, precipitación acumulada en mm; evap. evaporación en mm. Total. todos los datos. Before y After, sólo los días antes y después respectivamente de la puesta en marcha de la compuerta. (-) Correlaciones no significativas ( $p > 0.01$ ).*

	$r$	$P_{atm}$	PCC	storm	pac	evap
Total	0.765		0.569	0.455	0.232	
Before	0.883		0.734	0.797		
After	0.691			0.394	0.632	
Basin 1	0.744		0.657	0.528		
Basin 2	0.588				0.588	
Basin 3	0.844		0.614	0.792		
Basin 4	0.807		0.729	0.591		

and rainfall levels. Neither atmospheric pressure nor evaporation were significant in the regression. Storms and PCC correlated with basin  $V_R$  before the sluice gate, whilst storms and precipitation were correlated with basin  $V_R$  after installation. All basins gave similar results to the data obtained before flux regulation, except basin 2 which only correlates partially with rainfall.

#### *Sea storms*

Sea storms were the main cause of flooding, and can be considered true disturbances. They are sudden, and change the physical and chemical composition of the water substantially. Flow is fast initially, and levels drop fast as the sea recedes. The sandy sediment favours this. North and NNW winds commonly follow storms, and may further accelerate the drop. Flows then slow down, allowing for some organisation and structuring in the basin (Quintana *et al.*, 19986).

#### *Sea level*

No clear correlation was observed between sea-level and basin level. Sea level data go back to 1990, when basin level was mainly influenced by flow control and freshwater input; hence the lack of correlation with sea level. In the first year, when freshwater input was less, one might have expected a link between basin and sea level. Thus, basin  $V_R$  would correlate well with the substitute-variables atmospheric pressure and wind. However, no clear link was apparent. The only possible correlation, therefore, was with wind, which may have affected the basins in other ways. No basin was directly connected to the sea. The seawater entering basins must have done so from underground *via* the aquifer, except during storms. This may have meant a lag in the production of changes in water level. Minor short-term oscillations caused by tides, waves, and other non-periodic oscillations did not affect the water level. The influence of the sea only appeared when its level stayed high enough for long enough.

#### *Wind (component perpendicular to the coastline, PCC)*

The influence of wind on basin levels was not confined to storms. Wind speed and direction may have affected levels directly. Winds with high PCC (i.e. blowing from sea to land) had a tendency to raise coastal sea levels. These humid winds often cause small local storms and storms over the sea, which may not get past the dunes, but which may last long enough to affect water levels in the basins. Negative PCC winds (i.e. blowing from land to sea) are the opposite, and tend to reduce water levels in the basins. These winds are from the North, NNW and NW, are very dry, and normally coincide with situations of high atmospheric pressure. They are also the strongest winds in this geographical area and are thought to cause the dessication of the salt marsh. In addition, this wind tends to push the sea back and lower the piezometric level.

#### *Precipitation, surface runoff and evaporation*

Although rainy periods coincided with increased basin levels, neither rainfall nor evaporation accounted for changes during the first period (Table 2). The hydric regime differed greatly from the precipitation-evaporation pattern. Precipitation alone had comparatively little effect on basin volumes, since flood events caused by storms, a rising aquifer and ensuing large freshwater inputs from the channel, commonly coincided with high rainfall. Evaporation levels may be considered mainly driven by wind action, rather than by the small differences in vapour pressure between air and water.

Since the watershed is small and flat (Table i), and the subsoil sandier at higher levels, surface runoff is considered negligible, i.e. most rainwater was retained close to where it fell. However, it is probable that surface runoff did transport abundant salts.

#### *Sediment and aquifer typologies*

The sediment of the area is mainly composed of silts and clays arranged in sand bars (Bach,

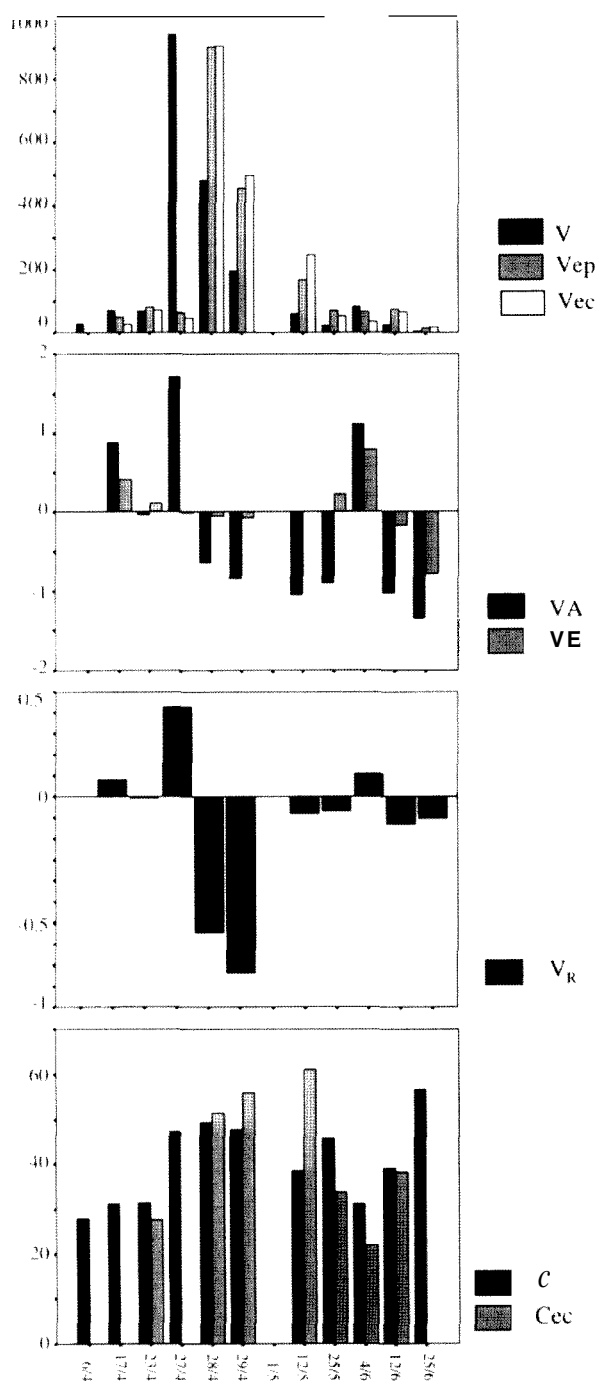
1990). This composition has major effects on the hydric regime. The sand bar pattern has sandier, more permeable subsoil at the upper levels, and less-permeable sediment which is rich in silt and clay at the lower levels of depressions (Bach, 1990). This means more permeability at high water levels, and more confinement at low water levels. These differences may have been decisive in causing variations in basin volume. Also, losses would be greatest at high levels and lowest near total dessication.

Sediment organization is also important. Bach (1990) described the surface aquifer as a 20-m deep layer of fine sand, usually overlain by a layer of clayey mud. The thickness and hydration of this top layer may allow water to rise through it, if there is sufficient force. Once there, it is harder for the water to filter back down, because of the shallow water column in the basin. Thus, basin level would be very sensitive to a rising level of the aquifer level, given its mass, but would be shielded from a drop in the water table by the relatively impermeable sediment. Permeability would also be influenced by the degree of hydration of the sediment and by the thickness of the clayey layer, if present.

*Flux regulation*

Data are unavailable for flow in the supply channel where the sluice gate was installed. Water from this channel is the main freshwater source to basins. Unfortunately, basin volume cannot be linked to changes in these supply flows. Flow regulation can be assessed indirectly, however, by examining volume-influencing factors before and after its introduction, using regressions in Table 2.

Potential causes of flooding after hydrological regulation of basins were separately analysed. After flux regulation, easterly storms caused less flooding and wind and sea level had negligible effects on water levels in the basins. Rainfall was an important cause of flooding because it increased channel inflows, rather than because of direct rainfall input to the basins. Thus, water levels in basins have become less dependent on weather events and more depend-



**Figure 2.** Variations of real (V) and expected (V<sub>ep</sub>, V<sub>ec</sub>) volumes; of real (C) and expected (C<sub>ec</sub>) conductivities and of the rates of volume variation (V<sub>R</sub>, V<sub>A</sub>, V<sub>E</sub>) in basin 1 during Spring 1989. *Variaciones de los volúmenes reales (V) y esperados (V<sub>ep</sub>, V<sub>ec</sub>), de las conductividades reales (C) y esperadas (C<sub>ec</sub>) y de las tasas de variación de volumen (V<sub>R</sub>, V<sub>A</sub>, V<sub>E</sub>) en la cubeta 1 durante la primavera de 1989.*

ent on both flows in the permanent supply channel, and on the level of the water retained at the sluice gate. Flow regulation destroyed the pattern of flash flooding and gradual emptying typical during and after storms. Instead, basin levels now depend on freshwater inputs and their chemical composition.

Spatial pattern was apparent in the way floods occurred. Partial correlations between rate of volume change and weather proxies, calculated individually for each basin, showed that basins 1, 3 and 4 behaved similarly, and were mainly influenced by storm and wind. These three basins behaved effectively as parts of one single salt marsh. The exception was basin 2, where correlations resembled those after flow control. The multiple correlation coefficient was smaller, and only precipitation gave a significant partial correlation coefficient. Basin 2 gained most water through the sluice gate, and was the most affected by regulation of flows (Fig. 1).

## VARIATIONS IN VOLUME

The variations in real and expected volumes during two representative periods in Basin 1 were taken as examples of the most opposing conditions during the period of study (Fig. 2 & 3). Figure 2 shows variations in real and expected volumes ( $V_{ep}$  and  $V_{ec}$ ) during a period with large changes in water level (Spring 1989), before the sluice gate was installed and when a strong sea storm was followed by a prolonged dry period. Rates of volume change are also given, along with real and expected conductivities ( $V_R$ ,  $V_A$  and  $V_E$ ,  $C$  and  $C_{ec}$ ). Figure 3 shows the same variables during a period with small changes in water level (Autumn / Winter 1990-1991), with the sluice gate in operation. During these periods, two minor sea storms occurred, and a constant freshwater supply was achieved thanks to flood control. The four basins followed similar patterns to those in Basin 1 during regulated periods. During the rest of the study, similar or intermediate situations were found. For more information on these changes, the Reader is referred to Quintana (1995).

A flood occurred on 25 April, 1989, coinciding with an intense sea storm, which had ended a long dry period (Fig. 2). The basin, thus, presented very low water levels. The other basins had been practically dry all winter because of the prolonged drought. The volume was much higher than  $V_{ep}$  and  $V_{ec}$  immediately after the storm, but  $V_{ep}$  and  $V_{ec}$  differed little because conductivity before and after the storm was similar (47.4 and 49.5 mS  $cm^{-1}$ , respectively). Thus, we conclude that salinity of the water input was similar to that of the basins.

After storms, the water level decreased rapidly in the basins (i.e.  $V_R$  and  $V_A$  much more negative than  $V_E$ ) although they did not desiccate completely. The differences between  $V_E$  and the other volumes suggest loss of water by filtration. Loss of water could have been aided by dehydration of the sediment caused by prolonged drought. Emptying coincided with rising freshwater inputs ( $V_{ec} > V_{ep}$ ;  $C_{ec} > C$ ), which reduced conductivity below expected levels. Freshwater input is common following sea storms (Quintana, 1995). This is probably because rain falling inland will eventually feed the aquifer.

Conductivity was higher than expected during the period with low rainfall levels, coinciding with positive  $V_E$ . This expected volume increase did not materialise until later, when rain raised levels. Despite freshwater input, emptying continued via filtration. During this period, the values of  $C_{ec}$  ( $C_{ec} < C$ ) and the differences between  $V_{ep}$  and  $V_{ec}$  ( $V_{ep} > V_{ec}$ ) suggest an entry of salts into the basin, probably through surface runoff after rains. The small volume of basins at the time may have magnified the importance of surface runoff. Subsequently, the basin dried out altogether. When levels were low, estimation carried significant error, so the differences observed during this period have not been included in analyses.

Autumn-winter 1990-91 differed from the previous period (Fig 3). Flow control had been operating for months, and the aquifer was presumably more hydrated. Also, sea storms and rain were mild. Therefore, basin volume oscillated little (i.e.  $V_R$  close to 0). Three different periods of hydrological change can be distinguished, i.e.



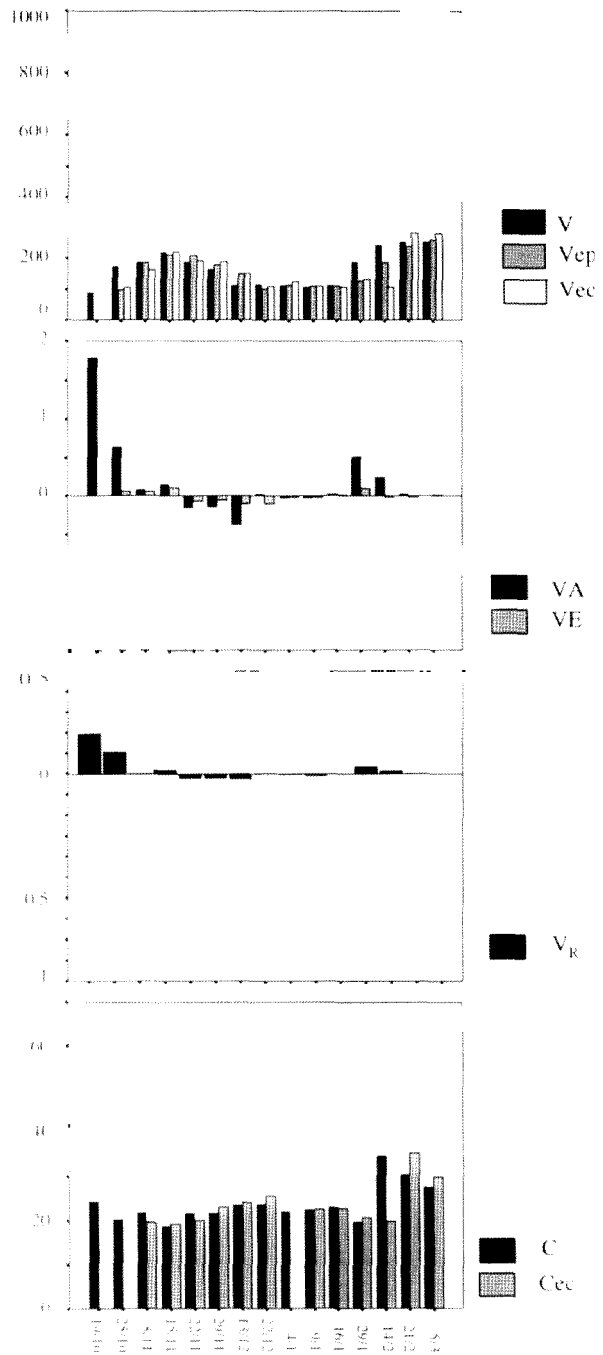
October-December was typified by small fluctuations of positive  $V_R$ ,  $V_A$  and  $V_E$  during the first days, which turned negative later. Although  $V_R$  values were near 0, circulation through the aquifer may be inferred both going in as well as out of the basins.  $C$  was alternatively higher and lower than  $C_{ec}$  suggesting that water input was salt or fresh. This may depend on the relative importance of factors driving inputs (e.g. minor oscillations in sea level, slight rain). Changes in conductivity, however, were apparently absorbed by "inertia" of the aquifer, and differences between  $C$  and  $C_{ec}$  were small.

January was characterized by the dominance of a high-pressure system and low sea levels. Basin volume and conductivity were as expected and  $V_R$ ,  $V_A$  and  $V_E$  were close to 0. These variables were the same as in the other three basins studied (Quintana, 1995). This was the only time during the two years when the hydrological regime could be explained by the balance precipitation - evaporation. The lack of either sea or atmospheric input, along with highly hydrated sediment caused by the regulation of flows, impeded the circulation of water through the basin.

Rainfall on 29 January and a small storm on 14 February ended the period of hydrological stability associated with the high-pressure system. Initial saltwater input was followed by freshwater inputs, similarly to what occurred after the Spring 1989 storm, albeit changes were not as pronounced.

**Water circulation and flooding patterns**

Volume and conductivity varied greatly in the basins under study. Factors other than evaporation and precipitation were responsible for these changes. Although the basins were isolated and received little surface input, circulation was evident. Differences between real and expected volume and conductivity were substantial (Figs. 2 & 3). The only explanation for these differences is active groundwater circulation. Fresh and saltwater move freely though the aquifer in opposite directions (Bach 1990). The force exerted by the



**Figure 3.** Variations of real ( $V$ ) and expected ( $V_{ep}$ ,  $V_{ec}$ ) volumes, of real ( $C$ ) and expected ( $C_{ec}$ ) conductivities, and of the rates of volume variation ( $V_R$ ,  $V_A$ ,  $V_E$ ) in basin 1 during Autumn-Winter 1990-1991. *Variaciones de los volúmenes reales ( $V$ ) y esperados ( $V_{ep}$ ,  $V_{ec}$ ), de las conductividades reales ( $C$ ) y esperadas ( $C_{ec}$ ) y de las tasas de variación de volumen ( $V_R$ ,  $V_A$ ,  $V_E$ ) en la cubeta 1 durante otoño-Invierno de 1990/91*

two masses of water is responsible for the oscillations in basin level. Thus, filling and emptying of the basins was more dependent on these vertical movements than on possible horizontal surface flooding. Likewise, basin conductivity depended largely on the freshwater/ saltwater balance in the aquifer. The balance could have moved rapidly. Basin fluctuations of conductivity would have been damped when fresh and saltwater masses were active together. On the other hand, when one mass predominated over the other, the range of variation of conductivity would have increased.

The regulation of flows slowed down changes in basin volume, by supplying enough water to compensate for filtration losses. The water supplied continuously *via* the permanent channel and through the sluice gate to the saltmarsh, hydrated the surface aquifer, and reached the basins through underground, or through basin 2. With the sediment thus hydrated, rainwater loss could be reduced compared to before regulation.

Initially, the regulation of water flows only had superficial effects. Eventually, excess water hydrated the aquifer and the effects of regulation were multiplied. Greater differences appeared in the water chemistry of basins when input was from the surface, depending on the origin of the inputs. When input was from groundwater, differences between basins were less (Quintana *et al.*, 1998a). This homogenising effect was slower to appear, though and continued even when channel flow was considerably reduced. There was no input under these conditions. However, there were no filtration losses, either, because the well-hydrated aquifer prevented it. The hydrological regime, then, approached a precipitation-evaporation balance.

The predominance of groundwater flow had a major effect on the circulation and accumulation of substances carried in solution, especially of nutrients. Nitrate, for example, circulated freely and was easily washed out, while phosphates did not, and had a tendency to accumulate. This phenomenon of 'differential confinement' (Quintana *et al.*, 1998a) plays an important role in explaining the tendency to eutrophicate of these coastal environments.

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