ENSO and salinity changes in the Ciénaga Grande de Santa Marta coastal lagoon system, Colombian Caribbean

J.A. Blanco*, E.A. Viloria, J.C. Narváez B.

Instituto de Investigaciones Marinas y Costeras (INVEMAR), P.O. Box 1016 Santa Marta, Colombia

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Abstract

Salinity changes in the Ciénaga Grande de Santa Marta and Pajarales Complex coastal lagoon system in northern Colombia, and their relation with local rainfall, tributaries’ streamflow and ENSO, are analyzed. Being markedly low (< 1321 mm yr⁻¹), local rainfall is assumed to be insignificant for mean salinity changes. The non-linear model proposed explains the variations in salinity and tributaries’ streamflow with ENSO intensity, measured as Southern Oscillation Index (SOI) anomaly. Streamflows are directly and salinity inversely correlated with SOI. Model analysis allowed to discriminate between natural and hydraulic management situations and also how the occurrence of different environmental scenarios reflected on salinity changes. The link between global climate variability and local conditions becomes clearer and worthy to be brought into account in management and decision making processes dealing with continental as well as other marine and coastal aquatic environments in the Caribbean region.

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1. Introduction

When El Niño phenomenon is mentioned, it is usually associated with its oceanographic manifestation in the Pacific Ocean, and there are obvious reasons for this outlook. Nevertheless, the linkage of this large scale climatic phenomenon with atmospheric changes taking place in regions far from the Pacific Ocean, is being documented. Atmospheric circulation in the Caribbean basin is also influenced by El Niño-Southern oscillation (ENSO) events (Giannini et al., 2000, 2001). Large scale atmospheric perturbations on regional climate are not likely to be refrained by a low continental physiography, like the Panama isthmus. Poveda and Mesa (1997) have shown how ENSO atmospheric manifestations reach not just western Colombia, but northeastern South America as well. Their broad effects on the North Atlantic are documented by Giannini et al. (2000). Drought in Australia and northern South America, and floods in central Europe (Epstein, 1998) seem to have a common origin in El Niño.

The Ciénaga Grande de Santa Marta (CGSM)—Pajarales lagoon Complex (PC) is Colombia’s largest coastal lagoon system (nearly 800 km²). It is located at the center of the Colombian Caribbean coast, between the Sierra Nevada de Santa Marta (SNSM) and the Magdalena River. Complete descriptions are found in Wiedemann (1973), González and Hernández (1992), PROCIENAGA (1995) and Botero and Mancera (1996). Kaufmann and Hevert (1973) showed the dependence of the CGSM hydrology on the streamflow of the Magdalena River, connected through three channels to the PC. Other tributaries inflowing only CGSM, but not the PC, are the Sevilla, Fundación and Aracataca rivers, proceeding from the western slope of the SNSM to the east (Fig. 1). The system has been intervened since the middle of the last century by road works, which caused hydrological perturbations in the lagoon and neighboring coastline (Von Erffa,
(1973). Restrepo and Kjerfve (2000) showed a clear direct correlation between Southern Oscillation Index (SOI) anomalies and streamflow changes in the Magdalena River. Purca et al. (2001) supplied evidence about a teleconnection between anomalous conditions in the Peruvian Pacific and changes in the Magdalena River discharges to the Caribbean Sea. A clear link between air–sea anomalies in the equatorial Pacific and those in north tropical Atlantic has been described, functioning like an atmospheric bridge (Alexander et al., 2002).

Salinity is perhaps the variable that better describes hydrological changes in an estuarine system as this one. Its increase or diminution depends on the amount of freshwater entering and leaving the system. Hence, the available freshwater sources and their variability have to be brought into account to get a real picture of change. In 1990–1995, a prolonged increase of water salinity in the system had a noticeable impact on living communities, leading even to mass fish kills in the mid 1990s (Mancera and Vidal, 1994; Epstein et al., 1995). This caused a societal–economic effect on the inhabitants of the nearby villages, mostly artisanal fishers, whose income dropped and their livelihood was at stake. In addition, many hectares of mangrove died off (Botero and Mancera, 1996). Salt deposits in soil, desiccated by exposure to wind and sun, are other factors influencing the salinity balance in the system, mostly in the PC.

The deterioration of the environmental conditions in the lagoon system motivated the interest of national and international agencies concerned with the environment, leading to a Monitoring Project. As a result, three old channels connecting the system with the Magdalena River were reopened. In 1996, the first channel, Clarín, was delivered and in 1998 the Renegado and Aguas Negras channels were also reopened. These two were furnished with sluice gates to control water flow. Monitoring of water conditions continued in order to assess the likely benefits brought by channeling works to the system. This work is aimed at offering an explanation for the observed salinity variations in waters of the CGSM–PC lagoon system, and also to provide a tool for management and decision making concerning this ecosystem.

2. Materials and methods

Rainfall data from the CGSM–PC area were recorded at four IDEAM (Colombian Institute for Environmental Studies) weather stations: Cocos (11°01’N–74°41’W), Tasajera (10°58’N–74°20’), Sevilla (10°56’N–74°16’W) and
Prado Sevilla (10°46′N–74°10′W). For consistency, only 1980–2001 precipitation data were used for calculations and time series analysis. Recent evaporation data for the same weather stations were not available. Nevertheless, annual precipitation and evaporation data (1967–1984) obtained by Universidad de los Andes (1993) were used here to compute the local hydrological deficit, by subtracting the mean evaporation rate from the corresponding annual precipitation average.

Monthly surface salinity data from 10 sampling stations allocated in the CGSM–PC system (Salazar, 1995) (Fig. 1), stored in the INVEMAR database from 1993 till 2002, were used to calculate annual mean salinity values in the CGSM–PC system for 1993–2002. Calculations did not include measurements at the inlet (Boca de La Barra) since marine influence affects the resulting average considerably. Salinity was measured using the Practical Salinity Scale. Values for individual years were assumed mutually independent.

The historical (1970–2002) monthly streamflow data for the Magdalena, Sevilla, Fundación and Aracataca rivers proceeded from the IDEAM’s flowmeter stations. Streamflow rate data used were in m$^3$ s$^{-1}$ and hereafter are referred to as streamflow data. Since there were no channel flow data available, the hydrological signal of the Magdalena River streamflow, measured at Calamar station by IDEAM, just before the channels, was used instead. Since this station is located roughly 100 km from the river mouth into the sea, and the total length of this river is 1612 km (Restrepo and Kjerfve, 2000), streamflow data are likely to reflect rainfall conditions in the inland watershed, rather than near the station. Though significant, the basins of the other three tributaries lie on the western slope of the Sierra Nevada at heights up to 4000 m, and their streamflows depend on a different precipitation–evaporation regime.

ENSO is conceived as a coupled ocean–atmosphere phenomenon, and Tropical Pacific SST data are currently used to follow the evolution of ENSO events; however, from the point of view of the associated atmospheric variability, linked with rainfall on the tributaries’ watersheds, as in our case on the Caribbean, the Southern Oscillation Index (SOI) might seem more appropriate, since it is based on atmospheric pressure differences at sea level (Ropelewski and Jones, 1987). Monthly averages of standardized SOI anomalies or deviations from neutral conditions (1970–2002) (http://www.cpc.ncep.noaa.gov) were used in our calculations. Being standardized anomalies, SOI data are dimensionless, despite the fact that original atmospheric pressures are recorded in hPa units.

Even though a linear model was appealing because of the relatively high correlation between SOI and dependent variables, to assume a linear model would infer that the relation between the variables could be described by a line with a single value for the slope (rate of change). This condition is not in agreement with the known intrinsic variability of the ENSO phenomenon. Considering the synergistic–antagonistic effects of anthropogenic actions (water management), the atmospheric-hydrological variation, and the fact that the impact of La Niña on streamflows is stronger than the impact of El Niño events (Poveda and Mesa, 1997; Restrepo and Kjerfve, 2000), the solution could hardly be straightforward. Thus, as deduced from the initial scatter plot analysis of row data (Fig. 2), the model would rather be non-linear, in order to include changing slope conditions. The basic exponential regression model (Draper and Smith, 1981) copes with these requirements; however, since the observed values for the dependent variables are different from 0, an additional parameter (P1) was used.

Repeated trials were performed before a satisfying expression was found, and then to estimate the corresponding parameters for each model. Selection criteria were $R^2$, 95% confidence intervals of parameter values, convergence in parameter estimations, and how close the model reproduced the observed values for the dependent variable (flows or salinity) in simulations.

SYSTAT 9.0 (SPSS, 1999) includes three parameter estimation methods for non-linear models: the Gauss–Newton method that computes exact derivatives and is based on a Taylor series (Draper and Smith, 1981); the Quasi-Newton that uses numeric estimates of the first and second derivatives; and the Simplex that uses a direct search procedure. If after a number of iterations the largest relative improvement of parameters is less than the value selected, then a convergence is assumed for the estimates. Each parameter estimate must satisfy this criterion. The Gauss–Newton method was more efficient to estimate parameters with the dimensioned anomalies, reaching convergence with less than 30 iterations, while the Quasi-Newton performed better when dealing with normalized data. Both methods were used accordingly.

Streamflow and salinity data were processed by subtracting the long term annual mean from the annual value and dividing by the standard deviation. The data were normalized to include a larger number of years (1970–2002) in order to represent the long term variation and validate the models. However, to provide estimates of flows or salinity to be used for management actions, models are based on 1993–2002 untransformed data. Short periods, epochs or regimes are characterized by a significant persistence in conditions over a period of several years (Dzerdzeevskii, 1962). As a consequence, short term based models seem to be more suitable for management tasks and perform better than long term models. In addition, dimensioned estimations can be readily used for management decision making without further processing.

Assuming SOI as the independent variable, positive and negative anomalies from the long term streamflow means describe the deviations of these dependent variables as related to SOI anomaly conditions in the model. Negative values of SOI are indicative of prevalent El Niño conditions, and positive ones indicate La Niña events. The model describes the effects on salinity and tributaries’ streamflows explained by ENSO intensity variation, rather than the frequency of the events.

3. Results

Two seasons or climatic periods are distinguishable in the multiannual mean monthly rainfall distribution in the CGSM–PC area (Fig. 3): a dry season running from December to March, and a rainy one from April to November with
two distinct peaks, one in May or June and another, more intense, in October. A brief reduction in rainfall takes place in July. The highest precipitation rate is observed in October both in Prado and Sevillano weather stations to the southeast of the lagoon system and lower than 250 mm a month. On the other hand, annual rainfall in Prado station is around 1321 mm and in Sevillano just 968 mm, while in the arid northernmost sites, like Los Cocos and Tasajera it is 736.9 mm and 401 mm, respectively. The precipitation average (1967–1984) for the northern area of the CGSM–PC system was 807 mm yr\(^{-1}\), the corresponding mean evaporation 1953.8 mm yr\(^{-1}\); the resulting mean deficit for the same period was \(-211.6\) mm yr\(^{-1}\).

Since it was expected that the tributaries’ inflow affected system’s salinity rather than local rainfall, a correlation analysis was performed using annual averages of monthly streamflow and salinity data (1993–2002). When 1997 salinity data were included, correlations were low and not significant. The Hadi multivariate outlier detection algorithm included in SYSTAT 9.0 (SPSS, 1999) was used to identify 1997 data pair as an outlier. When excluding 1997 data, correlation improved markedly as shown in Table 1. Correlations were inverse in all cases, but higher with Magdalena and Fundación.
streamflow data. The former with 49% and the latter with 40% of variance explained the salinity variation. Both are significant at the 90% level of confidence. Sevilla and Aracataca showed lower correlation values.

The exponential regression model used was \( Y = p_1 + \exp(p_2 + p_3 X_1 + p_4 X_2) \), where \( Y \) stands for annual mean streamflow or salinity anomalies and \( X \) for SOI anomaly. Standardized anomalies were preferred to original long term streamflow data (1970–2002) for easiness in graphical representation and to reduce convergence problems when using iterative procedures to compute regression parameters. The model analysis indicates (Fig. 4) that, historically, the streamflow of tributaries varies directly with SOI, while salinity varies inversely. Magdalena, Sevilla and Fundación streamflows seem to be more affected by positive SOI anomalies, increasing at faster rate under La Niña conditions. On the contrary, the Aracataca streamflow does increase, but at a slower pace.

The estimated parameters for modeling the multiannual variation trend in SOI, salinity and streamflow values are presented in Table 2. Resulting correlation coefficients were higher with Magdalena and Sevilla models (\( R = 0.69 \)) with a flow variance explained by SOI anomalies of 48% in both cases. The correlation results of SOI and salinity anomalies were inverse, as expected, and the highest (\( R = -0.95 \)) when excluding 1997 data. The variance explained by the model accounted for 90% of mean salinity variation in the CGSM–PC system.

When the same exponential models were fitted to annual SOI anomalies, but using actual averaged streamflow (in m³ s⁻¹) and salinity data (1993–2002) instead of standardized annual anomaly values, correlation improved, being higher than 0.90 in all cases (Table 3), except for salinity (\( R = -0.95 \)). The corrected \( R^2 \) values with tributaries’ flows showed that the selected model performs better for Magdalena and Sevilla cases than for the other tributaries. The corrected \( R^2 \) value (0.81) with salinity was the highest, with better predicting capabilities. Apparent discrepancies shown in Tables 2 and 3 could be explained by data from different years (\( n \)) included in model fitting and the recent likely changes in the streamflows of tributaries. The variance explained (\( R^2 \)) in Table 2 and \( R^2 \) corrected in Table 3 do not differ much for each case, with the exception of Magdalena River, though.

A graphic representation of the exponential model fitting to annual monthly mean streamflow, salinity data and corresponding SOI anomalies in 1993–2002, excluding 1997 data, is shown in Fig. 5. As when dealing with anomalies above, streamflows appear to be more affected by positive SOI anomalies (La Niña conditions) than by negative values, except for Sevilla flow, which decreases markedly with negative SOI anomalies (El Niño conditions). At its turn, system’s salinity increases steadily with negative SOI anomaly values, resembling a linear relationship.

Given that the exclusion of 1997 data pair improved correlation with SOI, these data behaved as an outlier point, also detected by Hadi algorithm, a situation that deserved a closer analysis. Initial scatter plot (Fig. 2) and correlation analysis of mean annual salinity data (1993–2002) with SOI, resulted in an inverse and a quite high correlation. As above, a non-linear regression analysis was considered appropriate. When the exponential model used before was fitted to all resulting data

![Fig. 3. Mean (± standard error) monthly rainfall distribution in the CGSM–PC area (1980–2001).](image)

![Fig. 4. Non-linear modeling of anomalies in CGSM–PC mean salinity (1993–2002), mean tributaries’ streamflow annual variation (1970–2002) and corresponding SOI values.](image)

<table>
<thead>
<tr>
<th>Tributaries</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
<th>( R )</th>
<th>( R^2 )</th>
<th>( n ) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magdalena</td>
<td>-1.150</td>
<td>0.076</td>
<td>0.487</td>
<td>0.69</td>
<td>0.48</td>
<td>32</td>
</tr>
<tr>
<td>Aracatca</td>
<td>-9.029</td>
<td>2.206</td>
<td>0.041</td>
<td>0.44</td>
<td>0.19</td>
<td>31</td>
</tr>
<tr>
<td>Fundación</td>
<td>-0.483</td>
<td>-0.814</td>
<td>1.176</td>
<td>0.61</td>
<td>0.38</td>
<td>31</td>
</tr>
<tr>
<td>Sevilla</td>
<td>-0.980</td>
<td>0.144</td>
<td>0.667</td>
<td>0.69</td>
<td>0.48</td>
<td>31</td>
</tr>
<tr>
<td>Mean salinity</td>
<td>-32.828</td>
<td>3.487</td>
<td>-0.024</td>
<td>-0.95</td>
<td>0.90</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 1 Correlation of annual system mean salinity and tributaries’ streamflow variation (1993–2002) excluding 1997 data

Table 2 Parameters for the exponential models fitted to anomalies, variance explained and number of cases used for estimation. Streamflow data: 1970–2002; salinity data: 1993–2002.
pairs \( (n = 10) \), the model became: (a) salinity = \(-285.915 + \exp (5.6991 \times (-0.0154) \text{SOI}) \), with \( R = -0.69 \) and 48\% of the variance explained (Table 4). These outcomes show an inverse relation between mean salinity and SOI; nevertheless, they are undoubtedly influenced by the 1997 data pair with SOI = 1.8 and annual salinity average 6.9, which may be assumed as a trend anomaly (Fig. 6).

After removing this anomalous value (outlier) from the original data set, the fitting improved strikingly and the model became: (b) salinity = \(-352.950 + \exp (5.9041 \times (0.018) \text{SOI}) \). Hence, \( R = 0.95 \) and 90\% of the variance explained by the model. The resulting curves (Fig. 6) show a better fit of b model with mean salinity values calculated using field data, than that of model a, including all 10 data pairs. Model b prediction for 1997 (SOI = 1.8) mean salinity in CGSM–PC was 25.4 and the average salinity value calculated from field data was 6.9 for the same year, thus indicating a clear incongruity in the multiannual trend described by the model and the verification of the outlier.

The inverse variation found between SOI and annual mean salinity is portrayed as time series in Fig. 7. The agreement of predicted salinity by b model with calculated average values is manifest, but for the 1997 value. Even though correlation is significant for both a and b models \( (p < 0.05) \), with b model (without the outlier) it is very significant (Table 4), underlining the importance of ENSO variability for mean salinity changes in the system. The outlier detected indicates the occurrence of unusual environmental conditions resulting in an anomalous low mean salinity value. The latter should have been higher, according to the trend depicted by b model, since May 1997 through April 1998 El Niño was one of the strongest events ever recorded in the decade (Wolter and Timlin, 1998).

4. Discussion

4.1. ENSO and local rainfall

Rather than temperature, rainfall and trade winds’ circulation determine seasons in this dry marine area on the northeastern Caribbean coast of Colombia (Portig, 1976; Snow, 1976). Even though neither Wiedemann (1973) nor Kaufmann and Hevert (1973) indicated but two climatic periods a year, several authors claimed the existence of four climatic seasons in the area (Espinosa et al., 1995; PROCIENAGA, 1995; Salazar, 1995; Botero and Salzwedel, 1999), and some even three (Santos-Marínez and Acero, 1991). Existing data on rainfall support the yearly occurrence of only one dry and one rainy period (or season). The former runs from December to mid April, coincident with the strengthening of the trade winds in the Caribbean region (Blanco, 1988; Giannini et al., 2000). The rainy season goes from April to November, as in most of the Caribbean basin. Long term data analysis (1980–2001) indicates that two distinct rainfall peaks occur within the single rainy season, a light one in May–June, and a heavier one in October–November, with a brief local

Table 3

<table>
<thead>
<tr>
<th>Tributaries</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
<th>( R^2 )</th>
<th>( R^2 ) (corr.)</th>
<th>( n ) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magdalena</td>
<td>5964.430</td>
<td>6.535</td>
<td>1.372</td>
<td>0.98</td>
<td>0.60</td>
<td>10</td>
</tr>
<tr>
<td>Aracataca</td>
<td>14.015</td>
<td>-0.897</td>
<td>1.599</td>
<td>0.98</td>
<td>0.27</td>
<td>9</td>
</tr>
<tr>
<td>Fundación</td>
<td>15.812</td>
<td>2.381</td>
<td>0.348</td>
<td>0.96</td>
<td>0.36</td>
<td>9</td>
</tr>
<tr>
<td>Sevilla</td>
<td>-1.089</td>
<td>2.867</td>
<td>0.289</td>
<td>0.90</td>
<td>0.49</td>
<td>9</td>
</tr>
<tr>
<td>Mean salinity</td>
<td>-352.950</td>
<td>5.904</td>
<td>-0.018</td>
<td>0.90</td>
<td>0.81</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Model</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
<th>( R^2 )</th>
<th>( R^2 ) (corr.)</th>
<th>Probability</th>
<th>( n ) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model a</td>
<td>-285.915</td>
<td>5.699</td>
<td>-0.015</td>
<td>0.48</td>
<td>0.60</td>
<td>0.027</td>
<td>10</td>
</tr>
<tr>
<td>Model b</td>
<td>-352.950</td>
<td>5.904</td>
<td>-0.018</td>
<td>0.90</td>
<td>0.81</td>
<td>0.000</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig. 5. Non-linear modeling of mean CGSM–PC system salinity, tributaries’ streamflow and SOI variation in 1993–2002.
minimum in July (Fig. 3), too short and rainy enough as to be considered a “dry intermediate season”. Those peaks mentioned above, are also noted concurrently with the bimodal distribution of tropical cyclogenesis in the Caribbean (Inoue et al., 2002) both within the rainy season.

Local precipitation is not very abundant in this dry marine area, with total rainfall multiannual means of 1321.3 mm and 968 mm in southeastern stations like Prado and Sevillano, respectively. Northernmost stations like Cocos and Tasajera have mean values of 646.9 mm and 401 mm, respectively; that is, annual rainfall values increase southwards of the system (Snow, 1976) (Fig. 1).

Nevertheless, our calculations show a local hydrological imbalance ranging from −211.6 mm yr⁻¹ in the south to −1146.8 mm yr⁻¹ in the north of the system. Other results on local rainfall shortage are reported by Simon (1981) as −1500 mm yr⁻¹, PROCENIAGA (1995) as −1800 mm yr⁻¹, and Botero and Salzwedel (1999) as −1031 mm yr⁻¹. All of these outcomes point out that the amount of freshwater actually added by local rainfall, does not seem to play a decisive role on salinity reduction in the whole lagoon system. Because of its lower density, rain water remains as a surface thin layer on the brackish waters, and no quick mixing takes place; it needs some hours, even days and wind action to mix these water masses. Under tropical sun though, it is not unlikely that this surface freshwater film evaporates even before enough mixing occurs.

Since the flowmeter station on the Magdalena River at Calamar is located roughly 100 km from the river mouth into the sea, and the total length of this river is 1612 km (Restrepo and Kjerfve, 2000), streamflow data are likely to reflect rainfall conditions in the inland watershed, rather than near the station. Though smaller, the basins of the other three tributaries lie on the western slope of the Sierra Nevada at heights up to 4000 m, and their streamflows depend on a different precipitation—evaporation regime.

In a broader scope, the annual distribution of rainfall in Colombia is primarily influenced by the position of the intertropical convergence zone (ITCZ). Poveda (2004) provides an updated account on Colombia’s hydro-climatology and its relation with ENSO. Recent developments in the variability in the tropical Atlantic (TAV) (Giannini et al., 2000) also identify ENSO as one of the leading factors in the interannual climatic variability in the Caribbean basin. An ENSO event causes broad tropical anomalies in atmospheric circulation with a direct effect on rainfall variability, and an indirect one by means of sea surface temperature (SST) generated in remote basins (Alexander et al., 2002).

The trend is toward drier than average conditions when divergent atmospheric circulation prevails, during the rainy season prior to a mature El Niño event. The inter-basin mode, manifested as a zonal fluctuation in the sea level pressure (SLP) between the tropical Atlantic and the equatorial eastern Pacific, is correlated with ENSO (Giannini et al., 2000).

High variability in local rainfall, is also an indication that other factors different from ENSO (i.e. NAO) might also influence precipitations (Waliser et al., 1999), and the coincidence in time of the mature phase of an event and the onset of the seasons could have either synergic or antagonistic effects on rainfall (Poveda and Mesa, 1997).
4.2. ENSO and flow variation in tributaries

Tributaries’ flows seem to be more affected by extreme La Niña events, meaning high streamflow values and floods, while severe El Niño events would cause smaller flow (negative) anomalies in tributaries, meaning droughts. Individually, Fundación flow appears to be less affected by El Niño conditions than the flows of other rivers, but flow values increase rapidly with La Niña conditions. Sevilla, a smaller river, shows a stepped up increment and decrease in streamflow with SOI, while the Aracataca decreases as the former, but its flow increments in La Niña years are not as marked. The Magdalena flow does not seem to be much disturbed by light El Niño conditions, but it is markedly affected by extreme ENSO events, although not as much as the flows of Sevilla or Fundación, because these were smaller streams.

These variations in pattern differences might be due to the fact that tributary rivers from the SNSM, Fundación, Sevilla and Aracataca have their watersheds geographically near the CGSM—PC system, thus precipitations on them are quickly manifested on streamflow levels reaching the lagoon complex. Nevertheless, the nearly straight trend shown by Aracataca river’s curve could be explained because streamflow data are being recorded after the sluice gates of ditches conveying water for irrigation purposes, and not before as in the other two rivers’ streamflow gauges. This implies that freshwater being measured is actually reaching the lagoon system, but the amount of water entering depends on the irrigation demands, the latter being higher in years of drought (El Niño).

The tributaries from the SNSM have reduced flooding areas and the annual average streamflow for Fundación river is 25.2 m$^3$s$^{-1}$, for Sevilla 12.6 m$^3$s$^{-1}$ and for Aracataca river 17.4 m$^3$s$^{-1}$. At its turn, the Magdalena River basin runs through most of Colombia’s inland (Restrepo and Kjerfve, 2000); it has a broad flood plain area and provides freshwater to the system through the three channels mentioned earlier. Its peak mean annual streamflow, for the decade was 10,106 m$^3$s$^{-1}$, in 1999. The Magdalena’s multiannual mean streamflow is 7394 m$^3$s$^{-1}$, though just a fraction of that flow could actually enter the lagoon system, since nominal flow rate for all three channels operating together is barely 160 m$^3$s$^{-1}$ (PROCIENAGA, 1995).

In October 1970 a La Niña event started and prolonged till October 1971 with a consistent positive anomaly. Kaufmann and Hevert (1973) stated that the unusual floods they observed then were caused by the enhanced inflow of the SNSM tributaries and the Magdalena River acting together. When Wiedemann (1973) discussed about the “catastrophic” 1970–1971 flood in the CGSM–PC area, he mentioned that local people recalled another great flood event in 1955–1956. Nevertheless, in spite of the lack of local records, the August 1973–March 1976 La Niña should have been as intense as the 1998–2001 episode. Australian Department of Primary Industries records (http://www.LongPaddock.qld.gov.au) also show that in those years strong La Niña events took place.

The direct correlation between SOI and river streamflow anomalies can be clearly noticed (Fig. 4). Magdalena River and Sevilla streamflows showed the highest correlation with SOI ($R = 0.69$) and a variance of 48% explained by the model. Magdalena River has had a chief importance for interannual hydrological variations in PC. Fundación river correlation follows ($R = 0.61$), with 38% of variance explained; this river has a marked influence in the southwestern Ciénaga Grande. The lowest correlation was found for Aracataca stream ($R = 0.44$) with only 19% of the variance explained by SOI anomaly variation in the model. The latter was due to the likely effect of streamflow regulation on data, as explained above. In all cases the trend of change is very similar, higher annual streamflows correspond with La Niña years (1996, 1999, 2000) and lower annual values with El Niño years, 1992–1995, 1997 and 2002 (Fig. 4).

Magdalena River showed low mean monthly flow values in 1941, 1948, 1952, 1958, 1965, and all El Niño years and high annual streamflows in 1943, 1950, 1956, 1970, and all La Niña years. Kaufmann and Reichelt (1967) showed the existence of a 6–7 year cycle, coincident with the frequency of extreme ENSO events before 1975. However, their 6–7 year interval between extreme flood or drought events seems to have changed in the mid 1970s, both in frequency and intensity as it has been noted by other authors (Overpeck and Webb, 2000). Recent decades, though, show a different frequency of severe ENSO events, and this is likely to be reflected on the Magdalena River and other tributaries’ streamflow values.

4.3. ENSO and salinity trend in the CGSM–PC system

Taking into account the complex processes involved from an atmospheric signal (SOI) up to mean salinity changes in a distant lagoon system as CGSM–PC, it seemed appropriate to use a non-linear expression of the observed variation. For consistency, the same exponential model used before for the streamflow variations in tributaries was selected.

An outlier is often information with extraordinary values that may be of vital interest. As a rule (Draper and Smith, 1981), outliers should be rejected out of hand only if they can be traced to known causes. Therefore, the discrepancy between model predicted and actual mean salinity value in 1997 may be explicated because of the prolonged freshwater retention in the CGSM–PC system after the 1996 flooding due to “La Niña” conditions. The amount of freshwater that entered into the PC system can be thus largely attributed to the opportune opening of the Clarín Channel in a “La Niña” year as 1996.

Heavy rainfall occurred on the tributaries’ watersheds in 1999–2000, causing a rise in their streamflows. This was more important in the case of the Magdalena River, being the one with the largest basin surface. Resulting flooding waters even surpassed the sluice gate structures in the channels. However, due to its high sediment load — about 910 × 10$^3$ tons day$^{-1}$ (Restrepo and Kjerfve, 2000) — and vegetation spreading out, channels became clogged and were inoperative by mid 2000 and just the natural hydrological variation was then observed in the system, beyond any hydraulic control.

The estimated rate of sandy sediment load entering Aguas Negras channel is 108,750 tons yr$^{-1}$, and 88,800 tons yr$^{-1}$.
through Renegado channel (en Deeb Sossa, 1993), which might be underestimated for the 1999—2000 flooding conditions. The impact of these hydrological variations was particularly felt in the PC receiving directly the channels’ inflow.

As observed before with SOI anomaly, the highest correlation found was that with Magdalena streamflow data, followed by that of Fundación’s (Table 4). The influence of the latter is observed to cover the southernmost area of the CGSM, while Sevilla and Aracataca rivers influence just the area adjacent to their mouths. Both correlations are significant ( \( p < 0.05 \) ), indicating the likely participation of these streams on salinity changes in the system. Sevilla and Aracataca rivers seem to affect salinity to a lesser extent, the former because of its smaller streamflow and the latter due to irrigation uses of this tributary as well. Even though the resulting models are mostly hindcast models, since their actual predictive ability is restricted to the forecast of the intensity of an ENSO event, they are useful for analyzing and understanding variations in the hydrology of the CGSM—PC system, as tools for adequate management and risk evaluation facing climate variation.

5. Conclusion

5.1. What is attributable to ENSO and what to the hydraulic works?

Four El Niño events took place in the past decade, in 1992, 1993, 1994 and 1997, recorded as severe drought years in northern Colombia and times of environmental stress for the CGSM—PC system (Mancera and Vidal, 1994; Epstein et al., 1995).

In those years, however, ENSO influence was not yet taken into account for decision making by the agencies concerned, and it was concluded that the increasing salinity trend would continue, unless freshwater entry to the system could be granted. Consequently, the decision to reopen the connecting channels with the Magdalena River was made, beginning with Clarín Channel, delivered in 1996. The PC lagoon system depends largely more on freshwater from the Magdalena River (entering through the channels) than does CGSM, since the latter also receives freshwater from the SNSM tributaries.

Rather than to natural variation, the relatively low mean salinity value in 1997 can be mainly attributed to the opening effect of the Clarín Channel in 1996, opportune enough as to have profited of prevailing La Niña conditions (flooding), also mirrored on high Magdalena River average streamflow in that year (8571.3 m³ s⁻¹). This event lasted up to February 1997. Later, in March 1997 an intense El Niño began that prolonged through June 1998. El Niño atmospheric conditions and low streamflows reduced freshwater supply to the system, and mean salinity rose again until July 1998, just when the other two channels, Renegado and Aguas Negras, were delivered.

The following La Niña, began in July 1998 persisted throughout February 2001, with the exception of June and July 2000, when SOI anomaly was negative and mean salinity in the CGSM—PC system rose above 15. The year 2001 can be regarded as a neutral year and 2002 as a moderate El Niño year. This “bounce” behavior is indicative of the absence of a clear pattern in the rate of recurrence of ENSO events, either extreme or moderate.

Before and after the delivery of the hydraulic works, it is possible to discriminate the occurrence of several scenarios with synergic and antagonistic climatic—hydraulic conditions influencing the system’s salinity:


These outcomes point out that climate variability (ENSO), rather than just anthropogenic perturbations, was largely responsible for high salinity increments, and consequent environmental stress observed in the CGSM—PC system in the first half of the 1990s. On the other hand, it may be assumed that even if the channels had not been reopened, floods in 1996, 1999 and 2000 were severe enough as to have caused a definite lowering effect on CGSM—PC water salinity in those years. The main freshwater source for the system, the Magdalena River, is markedly affected by ENSO variability and its flow depends also on the strength of the events.

Channels are intended to make the system, to a certain extent, independent of the natural variation and thus regulate salinity, avoiding extreme conditions. Therefore, they should be well maintained and operated. The key is to be able to benefit from natural water when it is available. Nevertheless, there would be years when it is unlikely that channels will help much, and because of the drought even the Magdalena River might not reach streamflows high enough to introduce freshwater into the CGSM—PC system, even if channels were in operative conditions. Water salinity values in the system could then become critical, precisely toward the middle of the year, when sun is high for the summer in the Northern Hemisphere.

It is also likely that the sluice gate structures in the channels be surpassed again by flood waters in future intense La Niña events, as in 1999 flooding. In those cases one could just expect that the resilience of the system be effective enough as to overcome the impact of these variations.

On the other hand, uncertainty is high when using data of the past to predict present conditions in streamflows and recent data (though less) should be preferred. Monitoring and time series data analysis are also fundamental to detect suitable patterns in global and local climate variability in the short and long term.

While preparing this paper, streamflow data from Magdalena River and mean salinity in CGSM—PC for 2003 became available. The mean annual flow value for Magdalena River was 6258 m³ s⁻¹, close enough to the value estimated by the
model, 6266 m$^3$ s$^{-1}$ for SOI = −0.6. Mean annual salinity for CGSM—PC system in 2003, computed from field data was 19.6, while the model estimation was 17.5 for an El Niño year as this one. These results show close agreement between model estimations and values calculated from field data.

Continual development of our understanding of the mechanisms driven by climate is required for the mitigation of hazards linked with climate variability. The effects of these changes on water supplies, biotic communities and resources and the response of the human community to climate related threats, demand an integrated approach.

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