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RAINFALL AND SALINITY OF A SAHELIAN ESTUARY BETWEEN 1927 AND 1987

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ABSTRACT

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The Saloum river (Sénégal, West Africa) is an inverse estuary, with salinities of more than 80 g l^{-1} reached 100 km from the sea.

Monthly salinity measurements have been done 120 km inland since 1927. Seasonal salinity increase (during dry season) proceeds at a constant rate ($\simeq$ 0.3 g l^{-1} d^{-1}). This would indicate that evaporating water masses are shallow (average depth $\simeq$ 0.4 m).

Since 1950, annual maximum and minimum salinities have been increasing, with decreasing rains, at a rate of about 1.3 g l^{-1} per year. Across the 1927–1987 period, both yearly extremes are well correlated with rainfall in the previous years, indicating a "memory" spanning three years or less.

We have computed a water budget as a function of rainfall with three different hypotheses about the extent of the evaporating surfaces. Comparison with actual data indicate that about 60% of the lowlands are evaporating as shallow open waters would.

We discuss the implications of these results for the possible future of the estuaries in the region, especially in the "green-house effect" hypothesis.

INTRODUCTION

Rivers mirror through their discharge the climatic conditions, and the water balance, prevailing across their catchment (Nemec, 1983). In the particular case of the Sahelian belt, a strong correlation has been shown to exist between rainfall and discharge for the Sénégal river (Palutikoff et al., 1981). The Niger river discharge has been nil in 1985, an especially dry year (Billon, 1985).

A negative water budget has even more drastic effects on smaller rivers: discharge becomes negative, seawater may invade the estuary which becomes hyperhaline. Such a process has been occurring in two coastal "rivers" of Sénégal, the Casamance and the Saloum, both actually tide-influenced "inverse estuaries". In the Casamance river the scattered salinity measure-

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ments seem to indicate that hypersalinity started in 1968 (Brunet-Moret, 1970; Le Reste, 1980, 1984; Pagès et al., 1987). For the Saloum river we could find salinity data stretching back to 1927. Such a body of data had to be studied, since the Saloum river can be considered as a small-scale model for the behaviour of an estuary in semi-arid climate.

MATERIAL, METHODS AND AREA DESCRIPTION

Salinity data

Salinity shall be expressed here in g l^{-1}, in contradiction with present conventions (IAPSO, 1979) because of calculations involving volume changes.

The historical Kaolack data stem from a saltern located about 120 km from the sea (Fig. 1). Samples were taken at the main intake sluice, "around the end of each month" (Pipien, pers. commun., 1987). Salinity was measured in °Bé (n) from 1926 to 1977. Starting in December 1977, density (d) was used. We have converted these data into salinity (S, in g l^{-1}) by using correspondence tables

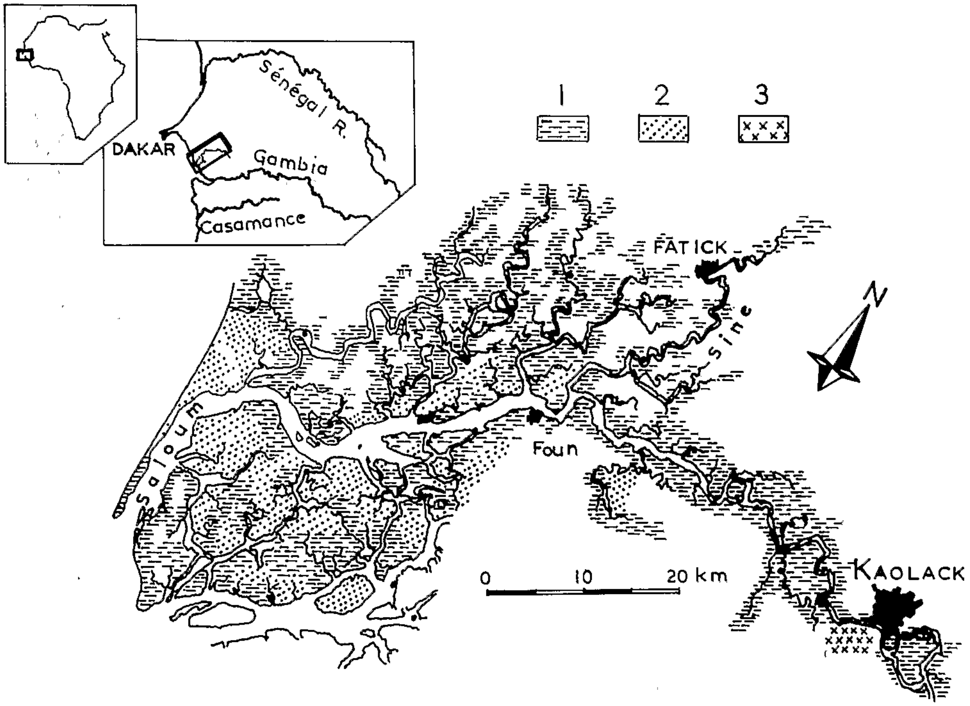

Fig. 1. Situation map of the Saloum estuary and distribution of the main morphological features: (1) inter tidal mud-flats ("humid ground") and mangrove; (2) supra-tidal and extra-tidal lowlands with shallow puddles after rains ("inundable ground"); (3) saltern at Kaolack. "Foun" is Foundiougne, present upstream limit of the mangrove.

(available from "Salines du Midi") from which we computed the conversion equations

$$S = -5.975 + 11.565\,n$$

$$S = -1.424 + 1.4803\,\sigma, \text{ with } \sigma = (d - 1)\,10^3$$

The resulting raw data are given in Appendix A.

Several surveys were made on the Saloum and its tributary, the Sine (Fig. 1), in 1967 and 1969 (Lhomme, 1974). Another survey was made in 1982 (Saos, 1982). All data were in $g\,l^{-1}$; most had been measured with a hand-held field refractometer.

Climate data

We used the daily rainfall data compiled from 1918 to 1965 for Kaolack (anon., 1976) and calculated from these the monthly rainfall. Data covering the more recent period (1966–1984) were copied from the ASECNA files in Dakar. Rainfall data used here are given in Appendix B.

The other climate data for Kaolack are averaged across the period 1945–1959. We also used some data covering the period 1972–1974 (ASECNA, Dakar).

Hypsometry

The hypsometric profiles of the Saloum and Casamance river were estab lished from 1/200,000 maps. We used published data for the Gambia river (Michel, 1973; Lesack et al., 1984) and for the Sénégal river (Michel, 1973; Rochette, 1974).

Area description

We shall here briefly recall the general climatic and geographical background, which explains some of the hydrological characteristics.

Climate is tropical dry (Fig. 2). Yearly averaged temperature is about 28 °C; highest values are observed in May, when average maximum can reach 38 °C. A single rain season stretches from June to October, with wide variations. To exemplify these, we have selected dry years (with less than 550 mm) and humid ones (more than 1,000 mm); both groups happened to number 11 years. The overall distribution of monthly rain amounts (Fig. 2) is identical, but the deficit in dry years is highest in August. The same difference has been shown in the neighbouring Gambia (Hutchinson, 1985). Evaporation (pan) averages 2400 mm per year, i.e. about 5 mm per day for effective evapotranspiration.

The Sine–Saloum hydrological system (Fig. 1) has shrunk after the last pluvial episode around 10,000 years BP (Maley, 1981; Petit-Maire, 1986). An extensive network of fossil, dried-out thalwegs stretches north- and eastward.

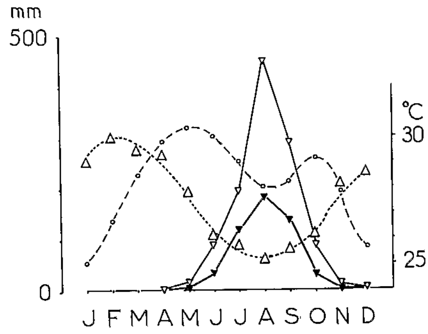

Fig. 2. Climate characteristics at Kaolack: monthly evaporation (△) and mean air temperature (○) (both averaged 1951–1974), the rainfall (mm per month) during dry years (▼) and humid years (▽) (see text).

Discharge is "temporary" (anonymous, non-dated) at the gauging of Kaolack.

Altitudes are low throughout the whole catchment (maximum height is 50 m) and longitudinal slope of the river course is correspondingly low (Fig. 3), becoming nil across the lowermost 150 km. Tide is still felt at Kaolack. Tidal currents maintain a relatively deep central channel (2–5 m), while shallows, mud flats and salt marshes make up most of the wetted area (Fig. 1). The supratidal barren mud-flats (locally called "tannes") correspond to the european "schorre" (Marius, 1985).

The earliest water-salinity data available show that the Saloum "river" was an "inverse estuary" (Pritchard, 1967), at least in its upper reaches, in 1967

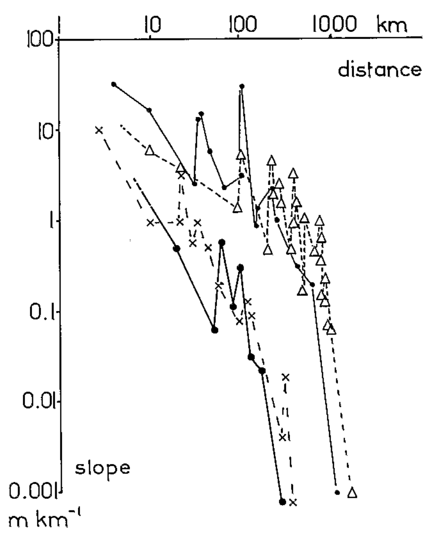

Fig. 3. Slope of the Saloum river channel (thick lines) against distance from origin. For comparison are shown data for Casamance (× --- ×), Gambia (●—●) and Sénégal (△– – –△).

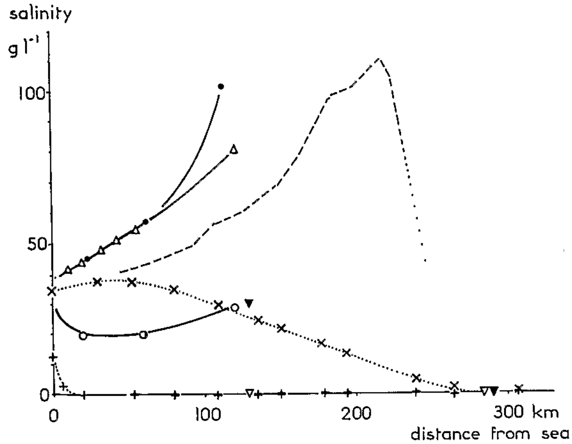

Fig. 4. Geographical distribution of salinity along the Saloum estuary (thick curves), from surveys in January 1967 (○) and June '69 (●) by L'homme (1974) and in April '82 (△) by Saos (1982). For comparison are also shown data for Sénégal river in July '82 (×) and October '82 (+) (Gac et al., 1986), for Gambia river in June '81 (▼) and September '80 (▽) (Lessack et al., 1984), and for Casamance estuary (dashed curve) in May '85 (Pagès et al., 1987).

(Fig. 4). The hyperhaline character becomes more pronounced on the subsequent profiles, with salinity increasing in a roughly linear fashion with distance to the mouth.

Mangrove was the principle ecosystem, and stretched from the sea up to Kaolack, in the 1960s. It is now much degraded, as a consequence of salinity increase and disappears around Foundiougne ("Foun" on Fig. 1) (Diatta et al., 1982).

RESULTS AND DISCUSSION

Seasonal salinity variations at Kaolack

Measured variations

We have selected six series (Fig. 5) to illustrate the case of humid/dry year and before/after 1968 (see below for the choice of this particular year). Minimum values ($S_{\min}$) are found generally in October, at the end of the rains. Salinity then increases monotonically; maximum values ($S_{\max}$) are generally observed in June. As a first approximation, this seasonal increase is a linear function of elapsed time (t, in days), measured from the date of salinity minimum:

$$S_t = S_{\min} + kt \tag{1}$$

The increase rates in successive years are not significantly different (Table 1) and do not depend on the value of $S_{\min}$. Average rate is $0.284\,\mathrm{g\,l^{-1}\,d^{-1}}$.

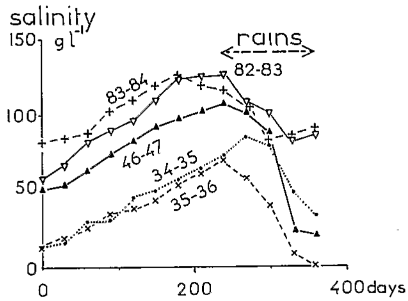

Fig. 5. Annual salinity variations at Kaolack during some typical years. Origin of time is the date of observation of minimum salinity.

TABLE 1

Annual salinity increase during dry season

Year	k	r	b	r	z_1	z_2
1934–35	0.27	0.991	6.61	0.964	0.74	0.26
1935–36	0.24	0.995	6.78	0.989	0.72	0.29
1945–46	0.27	0.980	4.19	0.964	1.16	0.68
1946–47	0.25	0.989	3.24	0.975	1.50	1.02
1971–72	0.27	0.995	7.48	0.944	0.65	0.13
1972–73	0.33	0.998	4.45	0.986	1.09	0.67
1982–83	0.37	0.994	4.51	0.979	1.08	0.69
1983–84	0.33	0.987	2.74	0.985	1.78	1.24

Increase rate k (g l^{-1} d^{-1}) is the slope of the linear regression $S_t = S_0 + k.t$, eqn. (1). Rate b (d^{-1}) is the slope of the regression ln S_t–t, eqn. (2). Average depth z_1 is computed from b, while z_2 is computed from the identity $k \simeq S_0\,E/z$. Evaporation rate E is given the average value of 5 mm d^{-1}.

Since dry season has a nearly constant duration each year, and with a constant increase rate k, we could expect maximum salinity in a given year, $S_{\max,n}$ to be correlated with minimum salinity in the previous year, $S_{\min,n-1}$. We do obtain a good correlation with the available 52 data pairs:

$$S_{\max,n} = 65.9 + 0.86\, S_{\min,n-1}\ (r = 0.90)$$

Theoretical variations

The above relationships are descriptive. Their interpretation must take into account the hydrology of the system. The upstream, or landward, portion of the estuary has a fixed level since communication with the sea is free. We would then be in the well-studied case of a "terminal lake" (Jauzein, 1982; Gonfiantini, 1986), losing water through evaporation and replacing it by inflowing water. In fact, though, the classical analytical solutions do not apply in the present case, since — among other reasons — the inflowing waters closely follow the considered "terminal" portion in its seasonal salinity variations.

We are thus led to consider that the terminal portion around Kaolack behaves like a "reduced volume basin". The piston-flow behaviour of the water masses allows us to neglect lateral advection such as modeled by Savenije (1988). In such an isolated basin submitted to evaporation, salinity increase is exponential (Roche, 1980; Guelorget and Perthuisot, 1983):

$$S_t = S_0 \exp(Et/z)$$

where S_0 is salinity at time zero, and z is averaged water depth (in m). Evaporation rate, E (in $\mathrm{m\,d^{-1}}$), is implicitly constant in the above equation. This approximation is tolerable, since the negative feed-back effect of salinity increase upon evaporation rate (Salhotra et al., 1985, 1987) remains negligible across our actual salinity range.

A regression of $\ln S_t$ versus time would then yield an experimental equation in the form:

$$\ln S_t = a + bt \qquad (2)$$

where the slope, b, has the value of E/z. With the same years taken above as example (Table 1), we get values of b around $0.004\,\mathrm{d^{-1}}$. Taking for E an average of $5\,\mathrm{mm\,d^{-1}}$, we obtain mean depth values between 0.8 and 1.7 m.

Plotting the computed regression of S_t (back calculated from $\ln S_t$) against elapsed time indicates that these regressions seriously depart from actual data for $t > 150$ d. We should then use another approach, less sensitive to high t values, i.e. an approach which would avoid the exponential form predicted by the theory.

The serial development of $\exp(E\,t/z)$ may be simplified down to $1 + (E\,t/z)$, with about 15% error, if we consider the numerical values of $E/z = b$ (see above). We then have the approximation $k \sim S_0\,E/z$. Taking again an average E value of $5\,\mathrm{mm\,d^{-1}}$, we obtain for z a range of 0 to 1.04 m; the median S_0 ($22\,\mathrm{g\,l^{-1}}$) gives a median z value of 0.38 m. This means that evaporation occurs across waters with a very shallow *mean* depth.

Long-term variations (Fig. 6)

Recent trends

While yearly rainfall (R) has decreased during the last years, salinities (both maximum and minimum yearly values) have increased. If we consider that the present trend started in 1950, we get the regressions:

$$R = 970 - 16.6\,T \quad (r = -0.78) \qquad \text{(Regr. 1)}$$

$$S_{min} = 11 + 1.31\,T \quad (r = 0.70) \qquad \text{(Regr. 2)}$$

$$S_{max} = 71 + 1.29\,T \quad (r = 0.74) \qquad \text{(Regr. 3)}$$

with T being the time (in years) elapsed since 1950.

The climatic turning point has been fixed between 1965 and 1970 by several authors (Sircoulon, 1976; Hubert and Carbonnel, 1987). Inspection of other data

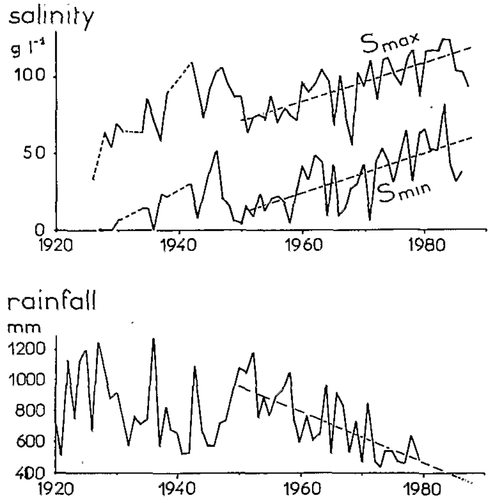

Fig. 6. Long-term variation of salinity (S_{max} and S_{min}) and rainfall at Kaolack.

for whole West Africa show that the present trend started around 1952 (Lamb et al., 1986). Our choice of 1950 as time origin is hence justified.

We may use the above regressions to extract descriptive equations between salinities and rainfall:

$$S_{max} = 146 - 0.078R \qquad \text{(Regr. 4)}$$

$$S_{min} = 87 - 0.079R \qquad \text{(Regr. 5)}$$

Overall relationship between salinity and rainfall

We have correlated S_{max} for a given year, n, with rainfall in the previous years, $n - i$; the multiple correlation analysis was carried out 5 years back (Table 2). The correlation does not significantly improve beyond three years back ($n - 2$). For S_{min}, the memory of the system stretches only two years back ($n - 1$). Salinities in a given year n may then be modeled as functions of past rainfall by the simplified regressions:

$$S_{max(n)} = 152 - 0.063R_{n-1} - 0.019R_{n-2} \quad (r^2 = 0.766) \qquad \text{(Regr. 6)}$$

TABLE 2

Correlation between salinities and past rainfall; variation of correlation coefficient (squared) with increasing number of previous years ($n - i$) from which rainfall has been correlated with salinities in the year (n)

	n	$n-1$	$n-2$	$n-3$	$n-4$	$n-5$
$S_{max,n}$		0.716	0.766	0.763	0.773	0.775
$S_{min,n}$	0.751	0.770	0.767	0.762	0.782	0.786

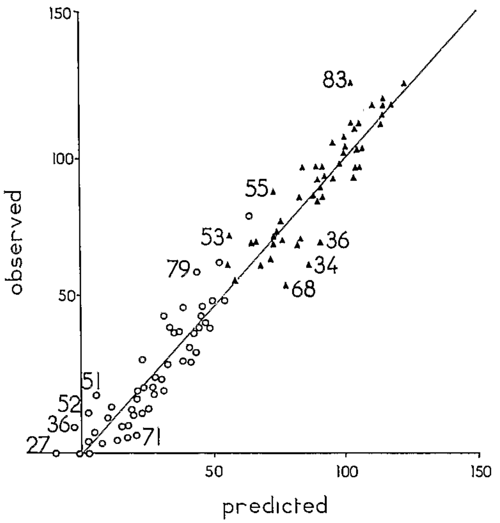

Fig. 7. Fitted models of S_{max} (▲) and S_{min} (○) as functions of rainfall in the previous years: comparison of predicted and observed values ($g\,l^{-1}$). Numerals pinpoint some years for which prediction was less satisfactory.

and

$$S_{min(n)} = 89 - 0.070\,R_n - 0.013\,R_{n-1} \quad (r^2 = 0.770) \qquad \text{(Regr. 7)}$$

In the latter expression, taking into account $S_{max(n)}$ does not significantly improve the correlation ($r^2 = 0.797$).

We have used regressions (6) and (7) for computing salinities (S_{max} and S_{min}) for historical rainfall data (Fig. 7). The "predicted" values agree reasonably with observations aside from two points: (1) some predicted S_{min} values are negative; and (2) for a given predicted S, actual observation show about $\pm$ $10\,g\,l^{-1}$ spread. Nonetheless, about 80% of the variability is explained by rainfall. Most of the "unexplained" variability stems from some abnormal years. The year 1936 is the worst-predicted one, for both S_{max} and S_{min}: this year's record rainfall came amidst a long dry spell. The second most humid year, 1927, also gives a negative predicted S_{min}. Our model is thus obviously "optimistic" for exceptionally high rainfall.

Extrapolations

We can use the relationships found above to compute the probable variation of salinity inside given (hypothetical) scenarios for rain or, conversely, to define the amount of rain which would bring a given salinity.

The most obvious way is to use regressions (6) and (7) with a constant (interannual average) rainfall R. We would then have the two equations:

$$S_{max} = 152 - 0.082\,R \qquad \text{(Regr. 8)}$$

$$S_{min} = 89 - 0.083\,R \qquad \text{(Regr. 9)}$$

We see (Fig. 8) that bringing S_{max} down to zero would demand more than 2000 mm annual rainfall. Since S_{max} is measured at Kaolack, the condition $S_{max} = 0$ does not mean that the whole estuary is desalted. It merely represents the "normal", pre-1968 condition, with a negative landward salinity gradient and an upstream freshwater portion of undetermined extent.

The descriptive regressions (4) and (5) (see above) were obtained from a shorter time span than regressions (8) and (9). They are though much comparable, and the respective plots (Fig. 8) closely parallel the former ones. We may further remark, without any satisfactory explanation, that the slopes of all regressions have a common value of about 0.08 g l^{-1} (mm rain $yr^{-1})^{-1}$. This means that salinities (at Kaolack) decrease by 8 g l^{-1} for an increase of 100 mm in annual rainfall.

A direct confirmation of the predictive value of both sets of equations may be obtained by considering some particular periods. Using actual rainfall data from humid (1950–58) and dry (1978–84) periods and the corresponding average S_{max} and S_{min}, we see that both sets of regressions agree reasonably with observed values, especially for S_{max}. Regressions (5) and (9) underestimate S_{min} by about 5% in humid years and by about 10% in dry ones.

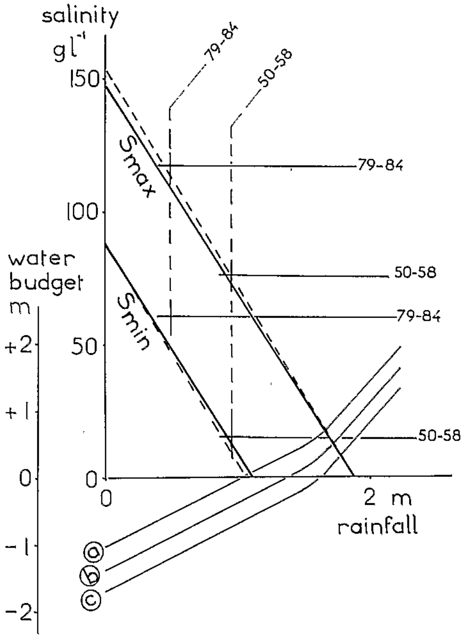

Fig. 8. Effect of annual rainfall upon salinity extremes, S_{max} and S_{min} as calculated from regressions 4–5 (solid lines) and 8–9 (dashed lines). The thin crosses show actual data for two periods (dry and humid; see text). The water budget is computed for three options (see text): (*a*) = "optimistic"; (*b*) = "median"; (*c*) = "pessimistic".

Water budget

We have seen that salinity (at least at Kaolack) is logically governed by rainfall. The negative runoff enables seawater to invade the estuary and become concentrated by evaporation. We can try to quantify this process by computing the annual water budget of the whole Saloum estuary.

Calculations

We may exclude the Diomboss portion, which is hydraulically independent (Barusseau et al., 1986). We shall also admit that tidal exchanges have a null effect when considering a yearly budget (Pagès and Debenay, 1987). The main unknown factor is the evaporative behaviour of the various morphological categories (see Fig. 1), which correspond to bathymetric or hypsometric categories. To quantify this behaviour, we may define an "evaporation coefficient" (Savenije, 1988); this coefficient, C_E, is equivalent, for each category, to a part of its area evaporating at the same rate as open water would. Since the value of C_E is ill-defined (Webb, 1958), we have considered three options (Table 3): (a) an "optimistic" one with low C_E's; (b) a "medium" one; and (c) a "pessimistic" one with high C_E's. We may then compute water budgets for varying rainfall amounts, since runoff coefficients are fairly well known for such grounds (Gallaire, 1980). We obtain three curves (Fig. 8), corresponding to our three options, of yearly water budget as a function of rainfall.

Applications of the results

A balanced budget would mean that rainfall equilibrates evaporation on a yearly basis, so that salinities would be stable between successive years.

TABLE 3

Elements of water budget computation

	Inputs		Losses		
	Area	C_r[a]	C_E[b]		
	(km^2)		a	b	c
Whole catchment	8000	var.[c]	0	0	0
Open waters	228	100	100	100	100
Humid ground	735	90	50	75	100
"Inundable"	195	50	10	30	40
Mangrove	135	90	90	90	90
Dry lowland	614	10	0	0	0
Equivalent area (km^2)		1170	736	968	1176

[a]Runoff coefficient C_r (%).
[b]Evaporation coefficient C_E in the three options a, b, c (see text).
[c]$C_r - 10.9 + 0.0073\ R$ (annual rainfall R in mm). This empirical equation was obtained on the comparable upper Casamance catchment.

Inspection of the actual data (Appendix A) shows that the most stable period for both S_{max} and S_{min} was 1951–1957 (respective averages of 74.3 and 17.0 g l^{-1}). Average rainfall during this period was 929 mm. With this rain amount, the water budget is nearly equilibrated only with option (a) (with a deficit of −85 mm; options (b) and (c) yield respectively −400 and −630 mm). We may then admit that option (a), the "optimistic" one, fairly reflects the actual present distribution of the various morphological features, and of their respective contribution to evaporative losses. This means that about 57% of the total lowlands behave as open water.

A second, perhaps more far-fetched inference can be drawn from our calculations. The much discussed "green-house effect" could bring a sea-level rise of 5.5 cm per decade in the "middle scenario" described by Jäger (1988). Such a sea-level rise would shift the estuary towards our (b) or (c) options, in which 75 or 90% of the lowlands function as open waters in what regards evaporative losses. Moreover, average depth would decrease across these areas, with a rise in water temperature (Howard-Williams, 1982), and also a rise in seasonal salinity increase rates (k or b). The "green-house effect" would thus seriously worsen the situation in the Saloum estuary, even without climate changes, through the mere alteration of sea-level.

We have several times mentioned the other three rivers found in the subregion (Casamance, Sénégal and Gambia). Compared with these, the Saloum river has been the first to show hypersalinity. The main causes for this dubious priority could be (in more or less increasing order): (1) a small catchment, situated in a low-rainfall area; (2) a low hypsometry, causing a very low run-off coefficient, and leading to a negligible fresh-water discharge; (3) a negligible slope of the river bed in the lower part, allowing sea-water intrusion; (4) a very shallow mean depth, amplifying the precipitation deficit; and (5) high evaporation and low rainfall.

All four rivers present to a variable degree these characteristics. They could be ordered in the series Saloum > Casamance > Sénégal > Gambia (see Fig. 3 as an example of the "low slope" character). It is then rather logical — especially by hindsight—that the Casamance river has followed suit in the salination process.

The Sénégal river was beginning to show some salinization (Fig. 4), the extent of which was directly related with rainfall (Gac et al., 1986). A dam has been erected 50 km from the sea, and has been functioning since 1986. It will certainly alter salinity evolution of this river.

In what regards the Gambia, a very deep worsening of the rain régime would probably be necessary before this estuary would become hypersaline, at least in its present state. Salt intrusion is moderate, but the rôle of evaporation has been highlighted and modelled (Savenije, 1988). Some cautionary remarks have been presented about the possible consequences of a dam (van Maren, 1985).

CONCLUSIONS

The Saloum "river" has long been hypersaline, and human settlements reflect this nearly customary condition. The gradual worsening of the water balance has only had relatively few adverse consequences, except in the lower estuary (progressive salination of the aquifers) and upon the mangrove.

The hypersalinity of the Saloum would then appear to be of small importance for this particular water body. Conversely, studies of such a natural laboratory may lead to insights in the functioning of other estuaries in the semi-arid belt. Adapting future development strategies to possible stark alterations of the environment could then be facilitated.

Hypersalinity has been described in tropical estuaries (Wolanski, 1986; Ridd et al., 1988) in other parts of the world. It would appear a not-so-seldom feature, which could still become matter-of-fact following some of the possible world-wide climate futures.

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APPENDIX A

Salinity at Kaolack; values in $g\,l^{-1}$

year	J	F	M	A	M	J	J	A	S	O	N	D
1926	--	--	--	--	--	--	--	48	34	43	53	64
1927	64	53	53	72	--	--	--	--	--	--	0	9
1928	18	21	26	36	37	53	64	52	0	0	5	8
1929	12	18	26	31	48	54	53	30	0	3	10	22
1930	31	31	42	55	64	71	55	53	15	5	5	10
1931	22	31	35	42	59	66	64	--	--	--	--	--
1932	--	--	--	--	--	--	--	--	--	--	--	--
1933	--	--	--	--	--	--	--	--	--	16	21	21
1934	42	42	37	58	64	64	--	39	14	16	31	31
1935	47	50	58	65	74	86	81	49	36	14	18	25
1936	33	38	44	55	63	72	59	40	8	0	3	10
1937	14	17	21	29	39	48	59	49	22	23	26	31
1938	44	52	58	69	74	84	90	81	44	22	23	35
1939	--	--	--	--	--	--	--	--	--	--	--	--
1940	--	--	--	--	--	--	--	--	--	--	--	--
1941	--	--	--	--	--	--	--	--	--	42	53	64
1942	79	81	84	97	110	104	104	70	42	--	--	64
1943	67	70	78	93	95	96	59	48	21	8	11	31
1944	24	27	36	41	52	57	74	64	42	23	31	42
1945	50	57	62	72	87	93	93	75	52	37	50	62
1946	69	70	76	88	102	103	98	87	73	51	54	64
1947	75	83	93	88	101	107	101	90	23	21	31	41
1948	55	61	67	81	95	97	84	57	16	21	27	40
1949	48	55	59	70	80	86	87	40	6	12	22	31
1950	37	48	56	64	75	87	87	78	4	4	8	10
1951	19	21	24	31	43	48	54	64	18	15	15	21
1952	27	35	39	48	53	64	72	53	33	10	12	16
1953	28	32	40	43	55	65	74	59	33	23	23	29
1954	37	42	46	53	61	72	70	61	28	13	21	28
1955	41	49	56	70	70	89	75	69	37	20	20	26
1956	36	42	43	53	62	67	70	53	26	21	24	28
1957	37	43	49	56	67	79	75	70	43	23	17	27
1958	35	42	48	56	66	75	75	72	5	7	11	16
1959	23	27	33	37	48	57	64	72	55	26	36	43
1960	53	57	64	75	87	97	94	80	42	42	46	55
1961	67	72	82	82	91	93	89	53	42	33	43	56
1962	61	63	70	75	87	97	97	87	48	49	53	55
1963	69	67	78	79	94	105	101	81	70	53	44	53
1964	62	66	69	82	89	98	98	59	18	10	16	26
1965	35	37	42	55	61	67	70	70	51	42	45	55
1966	64	70	71	75	84	102	102	88	87	18	10	20
1967	24	31	35	42	46	64	71	33	35	16	15	21
1968	28	31	33	38	45	57	57	48	38	27	35	49
1969	56	65	72	86	94	98	104	62	42	31	31	38
1970	44	55	59	62	74	82	94	82	42	42	53	60
1971	74	79	87	93	110	112	110	57	20	7	18	23
1972	29	37	44	53	64	74	75	87	59	44	54	61
1973	75	83	95	94	111	102	104	81	57	53	64	75
1974	89	96	101	114	114	111	103	89	48	45	52	61

1975	66	74	81	89	102	103	103	--	--	32	43	56
1976	62	74	74	86	95	96	93	74	81	48	54	70
1977	79	89	95	96	101	111	100	96	89	66	72	90
1978	100	105	113	119	103	103	88	51	32	56	62	63
1979	68	71	74	93	88	88	74	88	63	63	69	88
1980	88	94	103	108	116	118	103	81	71	66	81	88
1981	96	103	103	103	110	118	118	66	62	53	66	81
1982	76	88	96	103	111	118	118	66	62	51	66	81
1983	88	96	109	122	124	125	103	99	82	85	88	103
1984	110	118	125	118	115	103	81	59	44	48	65	74
1985	79	94	103	106	103	103	65	38	32	44	56	71
1986	79	85	100	103	103	103	96	--	--	38	47	59
1987	71	76	88	94	91	94	.	.	.	.	.	.

APPENDIX B

Rainfall at Kaolack; monthly heights in mm

year	J	F	M	A	M	J	J	A	S	O	N	D	total
1918	-	-	-	-	-	38	187	364	264	101	-	-	954
1919	-	-	-	-	6	56	162	130	173	39	-	-	567
1920	-	-	-	0	0	26	113	304	260	66	-	0	769
1921	0	0	0	0	0	27	65	182	208	41	0	0	524
1922	0	0	0	0	10	10	65	391	575	81	1	0	1134
1923	0	0	0	0	0	49	176	266	206	63	0	1	761
1924	0	0	0	0	0	87	360	411	257	0	9	0	1125
1925	0	0	0	0	0	150	212	498	276	66	0	0	1203
1926	0	0	0	0	0	62	147	189	266	8	0	0	672
1927	0	0	0	0	35	99	189	579	221	110	5	14	1253
1928	0	0	0	0	5	41	248	490	160	120	0	0	1065
1929	0	0	0	0	0	110	166	355	208	35	0	4	879
1930	0	3	0	0	1	101	114	335	329	36	0	0	917
1931	0	0	0	2	16	38	358	86	263	12	0	0	775
1932	1	0	0	0	9	86	77	234	164	12	0	0	583
1933	5	0	0	0	0	98	293	222	88	47	31	0	779
1934	0	0	0	0	0	22	168	320	139	62	0	0	710
1935	6	0	0	0	1	44	156	285	165	97	0	0	748
1936	0	0	0	0	8	200	217	485	282	74	8	0	1276
1937	0	0	0	0	0	27	139	209	150	59	1	0	585
1938	0	0	0	0	15	10	113	270	316	107	0	0	832
1939	0	0	0	0	16	106	103	241	120	104	0	2	691
1940	1	0	0	0	0	24	85	352	88	105	0	0	655
1941	0	0	1	0	38	10	123	81	258	13	0	0	524
1942	0	11	0	0	0	39	85	243	135	11	7	0	531
1943	0	1	0	0	19	165	168	329	301	62	0	44	1090
1944	0	0	0	0	0	64	108	238	236	41	1	9	698
1945	0	0	0	0	0	9	123	198	189	50	0	0	568
1946	0	0	0	0	0	24	117	192	202	33	0	0	568
1947	0	0	0	0	0	6	123	390	148	49	0	0	716
1948	0	1	0	0	0	93	180	389	52	41	0	0	754
1949	0	0	0	0	0	62	268	420	66	69	0	16	903
1950	0	0	0	0	4	57	132	424	340	111	17	0	1086
1951	0	0	0	0	71	18	86	413	206	233	40	0	1067
1952	0	0	0	2	9	68	302	306	410	79	0	0	1176
1953	0	0	0	0	0	20	233	223	213	70	0	0	759
1954	0	13	0	0	0	93	148	427	170	41	5	0	899
1955	0	0	0	0	7	81	163	259	264	6	0	0	780
1956	1	0	0	0	0	125	192	339	164	70	0	5	895
1957	2	0	0	0	0	54	189	243	246	197	0	1	929
1958	0	0	0	0	0	61	153	623	183	26	4	0	1050
1959	0	0	0	0	21	47	61	198	291	18	1	0	636
1960	0	0	0	0	0	80	128	213	168	13	0	0	603
1961	0	0	0	0	0	101	295	157	207	6	9	0	775
1962	0	1	0	0	0	72	37	276	53	81	84	0	603
1963	0	0	0	0	0	67	94	186	183	140	0	0	671
1964	4	0	0	0	0	53	232	499	178	24	0	0	986
1965	0	0	0	0	0	73	45	195	173	42	1	0	529
1966	0	0	0	0	0	125	43	227	367	182	0	3	947

1967	0	0	0	0	0	59	214	195	269	108	0	0	845
1968	0	2	0	0	0	72	102	163	155	46	0	0	538
1969	0	0	0	0	0	0	239	219	175	99	0	0	733
1970	0	0	0	0	0	31	99	246	58	41	1	0	476
1971	0	0	0	0	0	19	229	386	200	16	0	0	849
1972	1	0	0	0	0	82	16	164	188	28	0	0	478
1973	0	0	0	0	0	1	166	181	80	12	0	0	440
1974	0	0	0	0	1	4	126	288	117	12	0	0	548
1975	0	0	0	0	0	1	223	127	188	14	0	0	554
1976	1	0	2	0	36	18	108	92	138	76	0	2	470
1977	0	0	0	0	0	14	102	154	180	11	0	0	461
1978	0	0	0	0	1	14	165	281	112	22	41	3	639
1979	18	0	0	0	12	94	112	164	86	17	0	8	492
1980	0	0	0	0	0	13	16	216	148	25	0	0	418
1981	-	-	-	-	-	-	-	-	-	-	-	-	458
1982	-	-	-	-	-	-	-	-	-	-	-	-	654
1983	-	-	-	-	-	-	-	-	-	-	-	-	305
1984	-	-	-	-	-	-	-	-	-	-	-	-	563