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Hypersalinity: a dramatic change in the hydrology of Sahelian estuaries

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ABSTRACT

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Hypersalinity occurs in estuaries where evaporation exceeds rainfall and runoff. Generally, hypersaline estuaries occur in arid areas and are often used for salt farming. Dramatic ecological changes take place when a normal estuary turns hypersaline. This occurred in the Casamance during the Sahelian drought of the early 1980s. This paper describes the ecological changes that took place and it presents a model which describes the processes involved.

INTRODUCTION

On the 25th anniversary of the International Institute for Hydraulic and Environmental Engineering Course for Hydrologists on 6 September 1991, Professor J.C.I. Dooge (Dooge, 1991), as one of the keynote speakers, expressed his concern for the insufficient knowledge of the effect of climatic changes on rainfall runoff processes and on evaporation. Many of our long-established relations make use of empirical constants that have been calibrated in present climatic circumstances. If the climate changes, these may also change. Dooge emphasized the importance of a better understanding of these processes, so that we can better assess the possible impacts of such important issues as the increase of the carbon dioxide concentration in the atmosphere on rainfall, runoff and evaporation.

But even if we know what will happen to such basic hydrological processes as rainfall, runoff and evaporation, we still have to answer questions such as

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LIST OF SYMBOLS

a	constant
$A(x)$	cross-sectional area (m^2)
b_i	coefficient
C_e	evaporation coefficient
C_p	rainfall coefficient
$D(x, t)$	dispersion ($m^2 s^{-1}$)
$E(t)$	evaporation ($m s^{-1}$)
E_m	mean evaporation ($m s^{-1}$)
$h(x)$	estuary depth (m)
n	constant
N	number of years
$O(x)$	surface area
$P(t)$	rainfall ($m s^{-1}$)
P_m	mean rainfall ($m s^{-1}$)
$Q(x, t)$	discharge ($m^3 s^{-1}$)
Q_f	freshwater discharge ($m^3 s^{-1}$)
$r(t)$	effective rainfall ($m s^{-1}$)
$R(x, t)$	source term ($m^2 s^{-1} kg^{-1} m^{-3}$)
S	salinity ($kg m^{-3}$)
t	time
x	distance
X_i	mean annual runoff ($m^3 s^{-1}$)
Y_n	maximum salinity ($kg m^{-3}$)

how will rivers, lakes, swamps, estuaries, or more generally water bodies, be affected by these changes. For that purpose, we need models which describe the relation between the state of the water bodies (water balance, water quality, environment) and the hydrological processes involved. For some water bodies, such as reservoirs, models exist which relate rainfall, runoff and evaporation to the water balance of the reservoir, but water quality is seldom modelled.

In rivers and estuaries, however, the effect of direct rainfall and evaporation on the water balance of the water body is generally neglected, as their impact is assumed to be small. Although this may be justified in most cases, it has been demonstrated by Savenije (1988) that evaporation and rainfall may have considerable influence on the salinity distribution in estuaries, in particular in semiarid and arid zones.

This paper describes the dramatic effects that climatic changes during the latest Sahelian drought have had on the environment of Sahelian estuaries, and in particular on the Casamance. The model used to simulate these changes incorporates the effects of direct rainfall and evaporation on the salinity of estuaries. This effect is non-linear. The fact that a relatively small decrease in the runoff of an estuary can have such dramatic effects on the environment, should be a warning to hydrologists that we should not take the influence of climatic changes on the state of water bodies too lightly.

The salt intrusion model used in this paper applies to alluvial estuaries in which the salt intrusion is of the mixed type. It is extensively described in Savenije (1986, 1988). Before dealing with the phenomenon of hypersalinity, the model is briefly summarized in the following paragraphs.

THE SALT INTRUSION MODEL

The model is based on the one-dimensional tidal average salt balance equation:

$$A \frac{\partial S}{\partial t} + Q \frac{\partial S}{\partial x} - \frac{\partial}{\partial x}\left(AD \frac{\partial S}{\partial x}\right) = R \qquad (1)$$

where $A(x)$ is the cross-sectional area, $S(x, t)$ is the tidal average salinity, $Q(x, t)$ is the tidal average advective discharge, $D(x, t)$ is the tidal average mean cross-sectional dispersion coefficient, and $R(x, t)$ is a source term. The first term is the rate of change of the salinity in a cross-section. The second term represents the advective transport of salt by the discharge, normally in a downstream direction. The third term represents the net upward transport of salt through dispersion (mixing), and the right-hand member R represents external inputs in the form of a source or sink term. In normal (not hypersaline) estuaries the second and the third term compete for dominance. If the second term prevails, then the first term assumes a negative value, and the salinity decreases. If the third term prevails, then the first term assumes a positive value and the estuary becomes more saline.

The method makes use of geometric schematizations consisting of a constant depth and an exponentially varying cross-sectional area:

$$h = h_0 \qquad (2)$$

$$A = A_0 \exp\left(-\frac{x}{a}\right) \qquad (3)$$

where h is the mean tidal depth, a is a constant called the convergence length and h_0 is the constant depth. The x-axis has the origin at the estuary mouth and points in the upstream direction; hence the negative sign in the exponential function.

In addition, the method makes use of the longitudinal dispersion variation of Van der Burgh (1972), which reads:

$$\frac{\mathrm{d}D}{\mathrm{d}x} = K\frac{Q}{A} \tag{4}$$

where K is the Van der Burgh coefficient. Since the x-axis points in an upstream direction, Q is negative; hence the dispersion reduces in the upstream direction.

Combination of eqns. (1)–(4) yields:

$$\frac{\partial S}{\partial t} + (1 - K)\frac{Q}{A}\frac{\partial S}{\partial x} + \frac{D}{a}\frac{\partial S}{\partial x} - D\frac{\partial^2 S}{\partial x^2} = \frac{R}{A} \tag{5}$$

which is solved numerically in the model through a six-point finite difference scheme.

WHAT IS HYPERSALINITY?

The longitudinal distribution of salinity in estuaries with no significant stratification (partially to well-mixed estuaries) can assume several shapes (see Fig. 1). These shapes can be classified into four types: type 1, recession shape; type 2, bell shape; type 3, dome shape; type 4, humpback shape.

Type 1 is an intrusion curve with a convex shape; at the estuary mouth, the salinity gradient is steep. Examples of this type are: the Tha Chin and the Chao Phya in Thailand, the Lalang and the Solo in Indonesia, the Limpopo in Mozambique and the Rotterdam Waterway in Netherlands, which are all relatively straight and narrow estuaries.

Type 3 is very different. It has a concave shape and the salinity gradient at the mouth is small. Examples of this type include the Delaware (USA), the Gambia (The Gambia), the Pungue (Mozambique), the Thames (UK), and the Westerschelde (Netherlands). These are all wide channels with a profound funnel shape.

Type 2 is not a transition from type 1 to type 3; it is a mixture of the two. At the mouth, it starts concave, but, relatively near to the mouth (within 50% of the intrusion length), it changes into a convex shape. Examples are the Maputo and the Incomati in Mozambique, the Corantijn in Suriname, and the Mae Klong in Thailand. These estuaries are relatively narrow upstream, but strongly funnel-shaped near the mouth.

It appears that these three types of intrusion curve are very much linked to the geometry of an estuary. All estuaries studied appear to have a fixed type of shape irrespective of the hydrological conditions (within the hydrological limits between which mixed salt intrusion occurs). The intrusion may increase or decrease, yet the shape type remains unchanged.

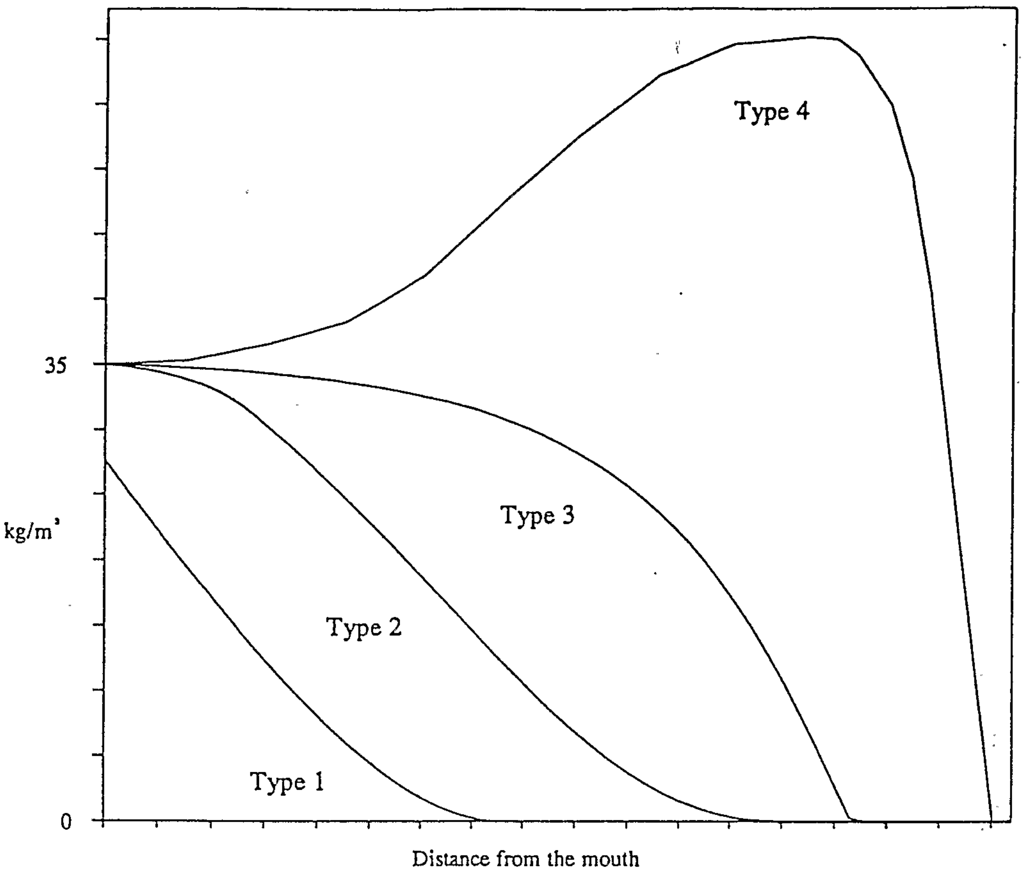


Fig. 1. Four types of salt intrusion curves.

The fourth type is an exception in this respect. A humpback shape is entirely the result of a rainfall deficit or an evaporation excess. Evaporation can change a bell-shaped intrusion into a dome-shaped intrusion and eventually into a hypersaline intrusion.

The salt balance equation, eqn. (1), is in two ways affected by rainfall and evaporation. One is through the source term R and another is through the advective discharge Q. The source term reflects the process of dilution and condensation, which would also occur in stagnant water with a given salinity under the influence of rainfall and evaporation. But the discharge Q is also affected by evaporation: because the total volume of water in the estuary remains constant, the discharge compensates for the rainfall and evaporation. The outflow to the sea increases due to rainfall and decreases due to evaporation. If the total amount of evaporation is more than the inflow of fresh water from the rivers, then sea water is drawn into the estuary.

Incorporation of these two processes into eqn. (5) yields:

$$\frac{\partial S}{\partial t} + (1-K)\left(\frac{Q_{\mathrm{f}}}{A} - \frac{ra}{h_0}\right)\frac{\partial S}{\partial x} + \frac{D}{a}\frac{\partial S}{\partial x} - D\frac{\partial^2 S}{\partial x^2} = -\frac{Sr}{h_0} \qquad (6)$$

where $Q_f(t)$ is the freshwater inflow into the estuary (a negative value) and $r(t)$ is the rainfall (negative in the case of net evaporation). In the source term, it can be seen that the effect of evaporation is large if the estuary is shallow and if the salinity is high. This means that dome-shaped, shallow estuaries are most sensitive to the source term. In the advective term, the effect of evaporation is largest if the estuary is shallow and if the convergence length is large. This is the case when estuaries are intruding far inland.

Depending on the relative size of each term in this equation, the effect of rainfall and evaporation is large or small. The relative size of each term depends on both hydrologic and geometric parameters which can vary strongly from estuary to estuary. In most estuaries, however, the significance is small, which is one of the reasons that not much attention is given to this issue in the literature. Savenije (1988) showed that in the Gambia evaporation played an important role. Although the evaporation terms were not particularly large in comparison with other estuaries (in fact they were relatively small) they were large compared with the advective and dispersive terms, which, in the Gambia, were exceptionally small compared with other estuaries.

For the Gambia, the author developed a dynamic salt intrusion model based on eqn. (6). In the application of the model the effect of rainfall and

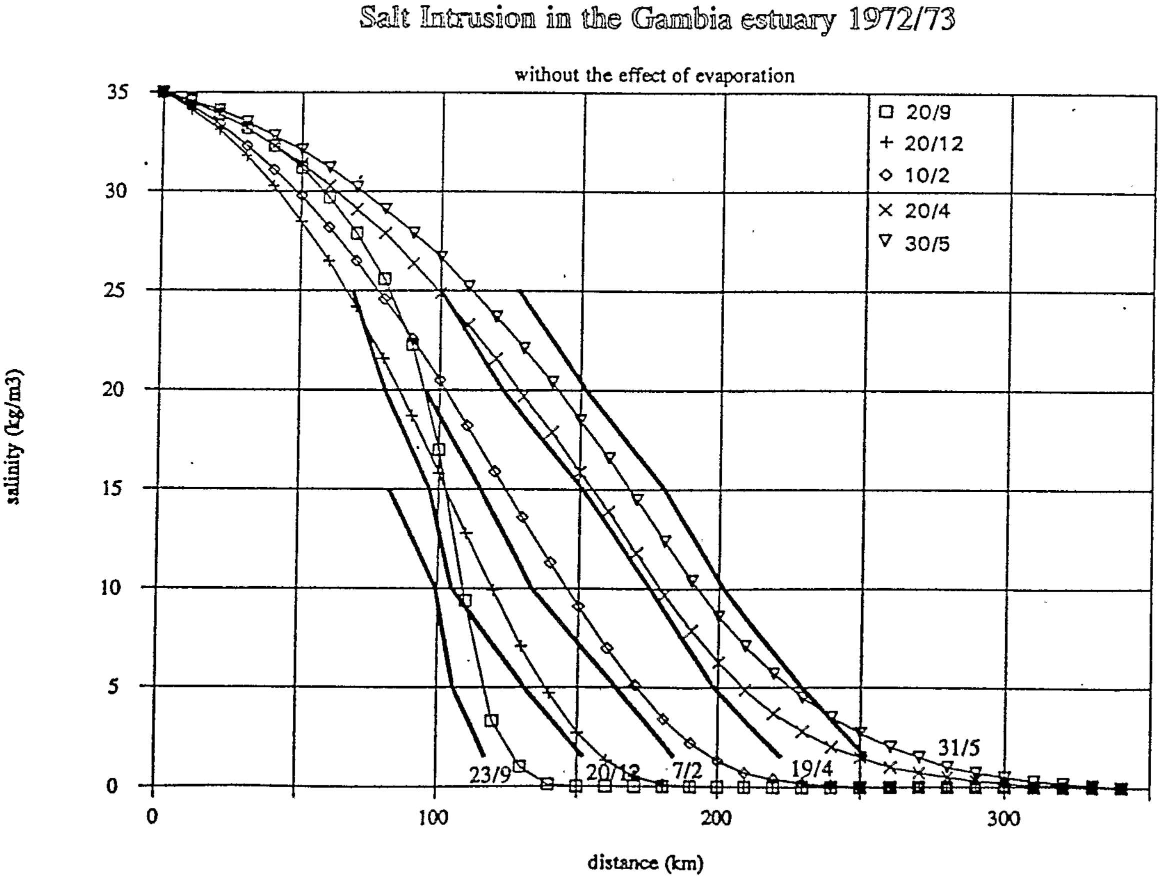


Fig. 2. Computed and measured intrusion curves in the Gambia, no evaporation (after Savenije, 1988).

evaporation appeared noticeable, but not at all dramatic (see Figs. 2 and 3). After inclusion of the effect of evaporation the longitudinal fit was somewhat improved. Pagès and Citeau (1990), however, showed that in the nearby Saloum and Casamance (see Fig. 4) the effect was of a completely different scale, leading to hypersaline conditions. It was decided to investigate whether the Gambia model could be used to simulate these hypersaline estuaries as well.

In hypersaline estuaries the two evaporation-driven mechanisms are much more important than the two hydraulic mechanisms of dispersion and advection. The lack of inflow of fresh water into the system and the high rate of evaporation, combined with a relatively shallow geometry, can lead to a situation where the salinity reaches a level of several times ocean salinity. In an extreme situation, the salinity may even reach saturation level.

An estuary may become hypersaline if the net downstream salinity flux is not sufficient to evacuate the accumulation of salt due to evaporation. In the Gambia, the freshwater discharge is still too high for the estuary to become hypersaline. However, the two estuaries that border the Gambia in the north and in the south, the Saloum and the Casamance (see Fig. 4), are strongly hypersaline.

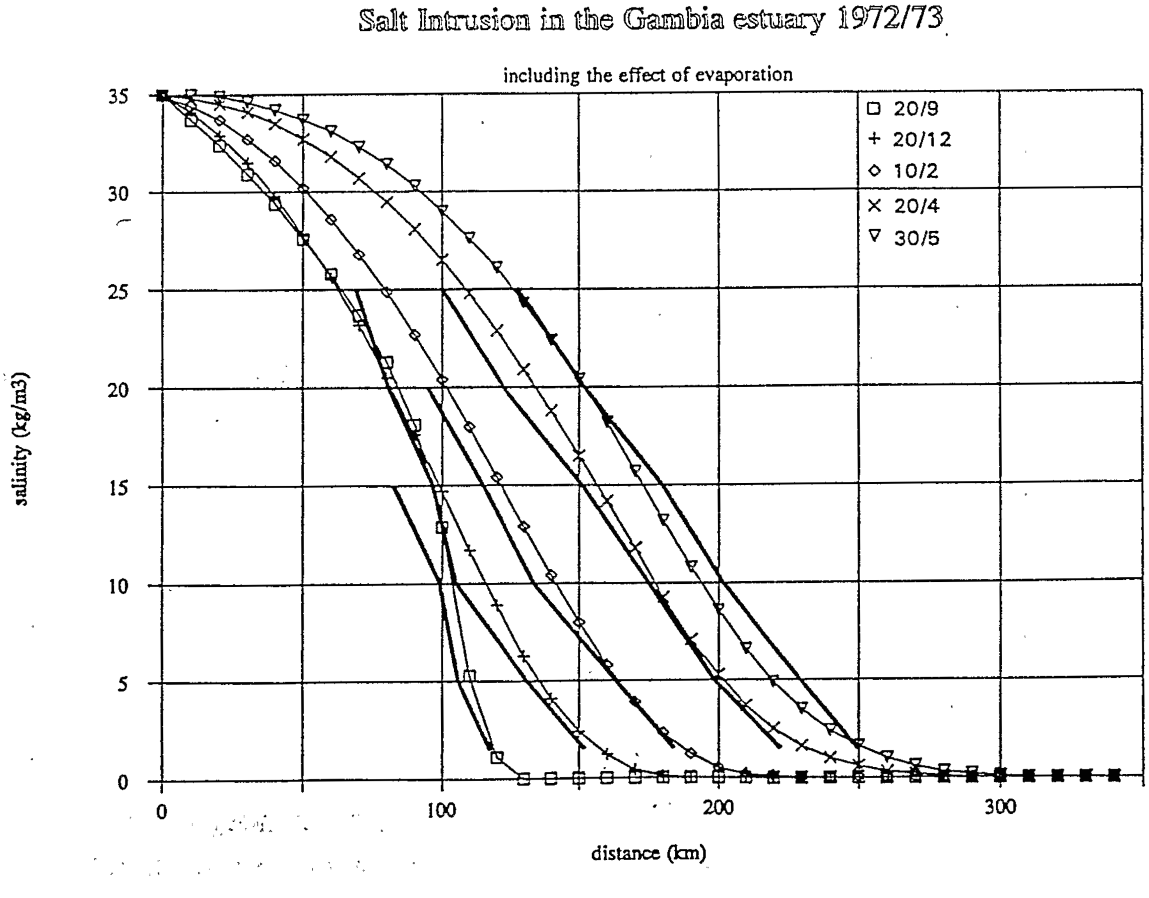


Fig. 3. Computed and measured intrusion curves in the Gambia, with evaporation (after Savenije, 1988).

THE SALOUM

The Saloum has always been known to be strongly hypersaline. Measurements in the Saloum near a salt production farm go as far back as 1927 (Pagès and Citeau, 1990).

Figure 5 shows model results of the Saloum against measurements at three locations along the estuary. It can be seen that pronounced hypersaline conditions have always existed due to the ephemeral character of the rivers entering the estuary. The fit of the model is not perfect. This is largely due to the lack of data on freshwater discharge into the estuary. A simple hydrological model had to be made on the basis of rainfall data at Kaolak to simulate inflow series. Moreover, hydrographic data on cross-section and depth were scarce. Since evaporation depends, to a large extent, on the depth, this lack of information strongly limits the accuracy of the model. In qualitative terms, however, the model is quite reliable, as can be judged from the longitudinal profiles presented in Fig. 6, where a comparison is made between measured and modelled salinities. The correspondence with measured data proves that the model accurately describes the dynamics of the system.

THE CASAMANCE

The Casamance, although always under the influence of evaporation, only became clearly hypersaline during the Sahelian drought which started in the late 1970s.

Figures 7(a) and 8 show similar graphs to those for the Saloum. Figures 7(b), 7(c) and 7(d) show enlargements of Fig. 7(a) which emphasize the different periods of the late 1960s, late 1970s, and early 1980s, respectively. It can clearly be seen that, starting in the late 1970s, the environment in the Casamance has completely changed from a normal estuary into a hypersaline estuary, as a result of the Sahelian drought. Until 1981 the estuary, at a distance of 180 km from the mouth, turned fresh annually. Since that time serious salinization took place, as is dramatically illustrated by Fig. 8 in the longitudinal profile. The difference between the situations of 1978 and 1984 is striking.

ENVIRONMENTAL CHANGES IN THE CASAMANCE

The changes in the salinity have had serious consequences for both the aquatic and terrestrial environment of the Casamance. Some spectacular adaptations were observed at the level of phytoplankton, and in chemical processes (Pagès et al., 1987). But here we shall concentrate on the economic consequences.

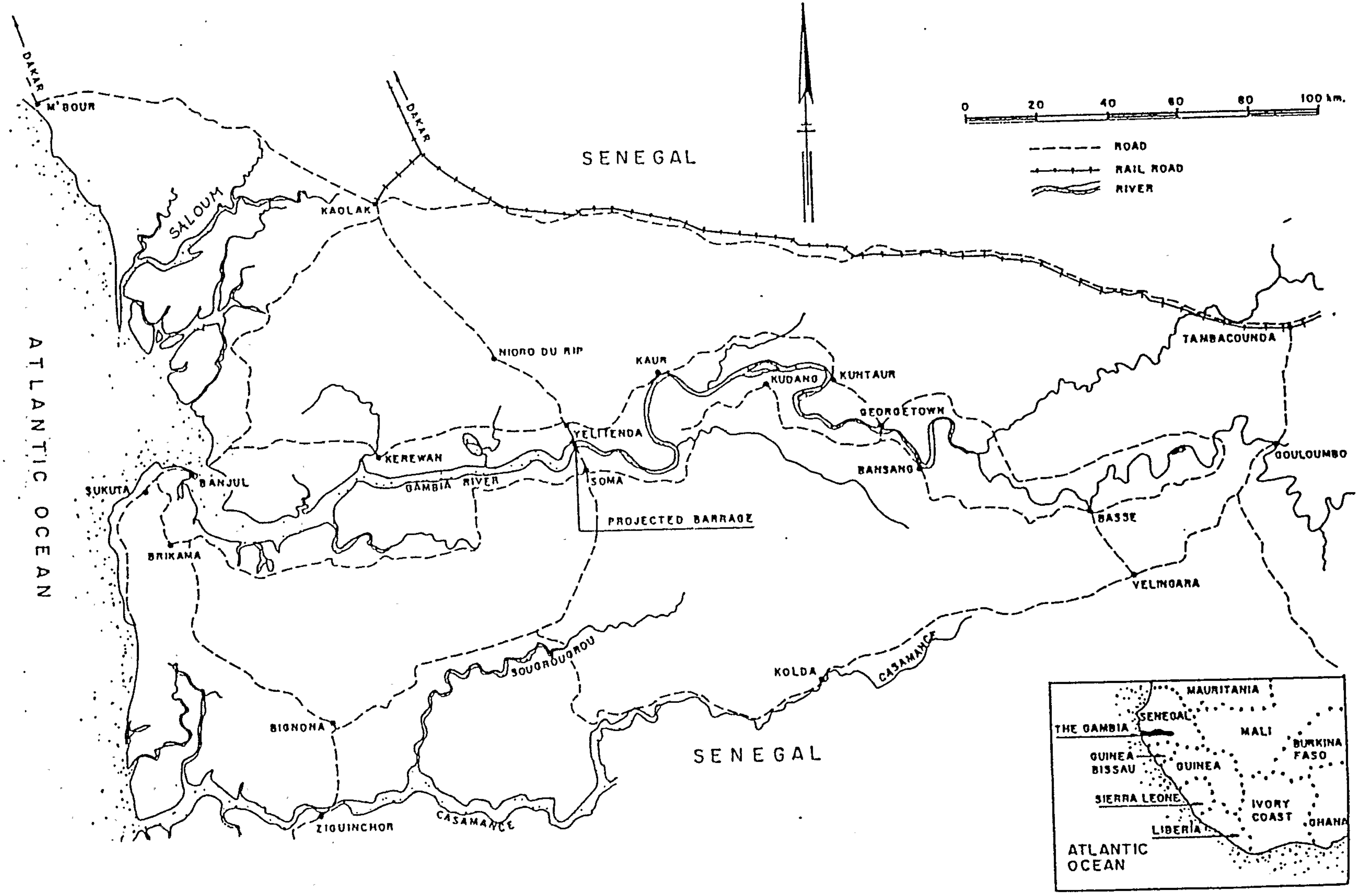


Fig. 4. Situation sketch of the Sahelian estuaries.

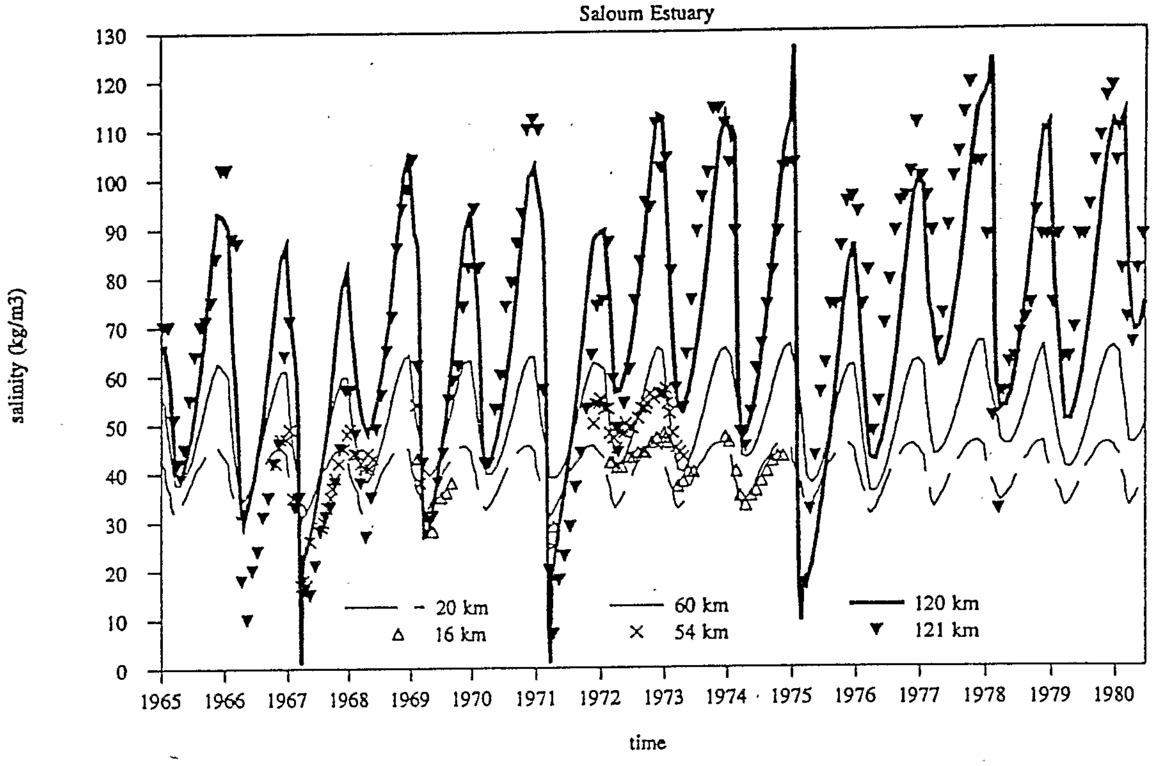


Fig. 5. Computed and measured salinity variation in the Saloum estuary.

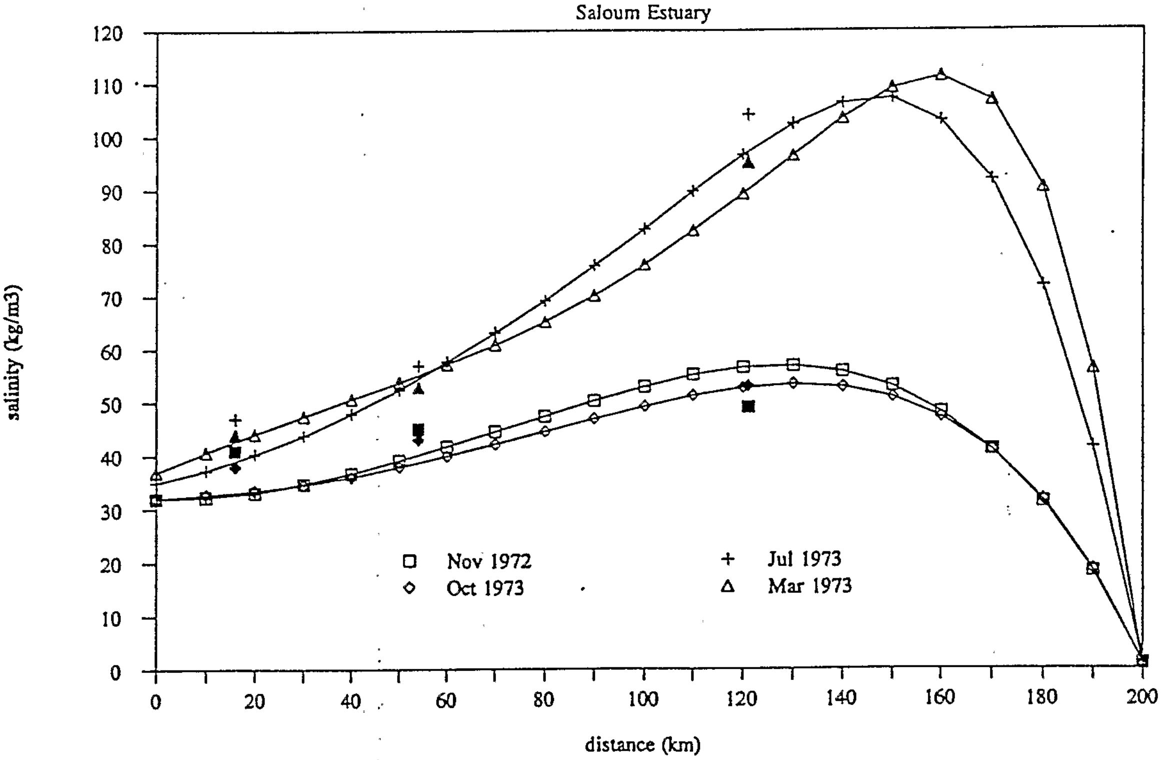


Fig. 6. Computed and measured longitudinal salinity distribution along the Saloum estuary.

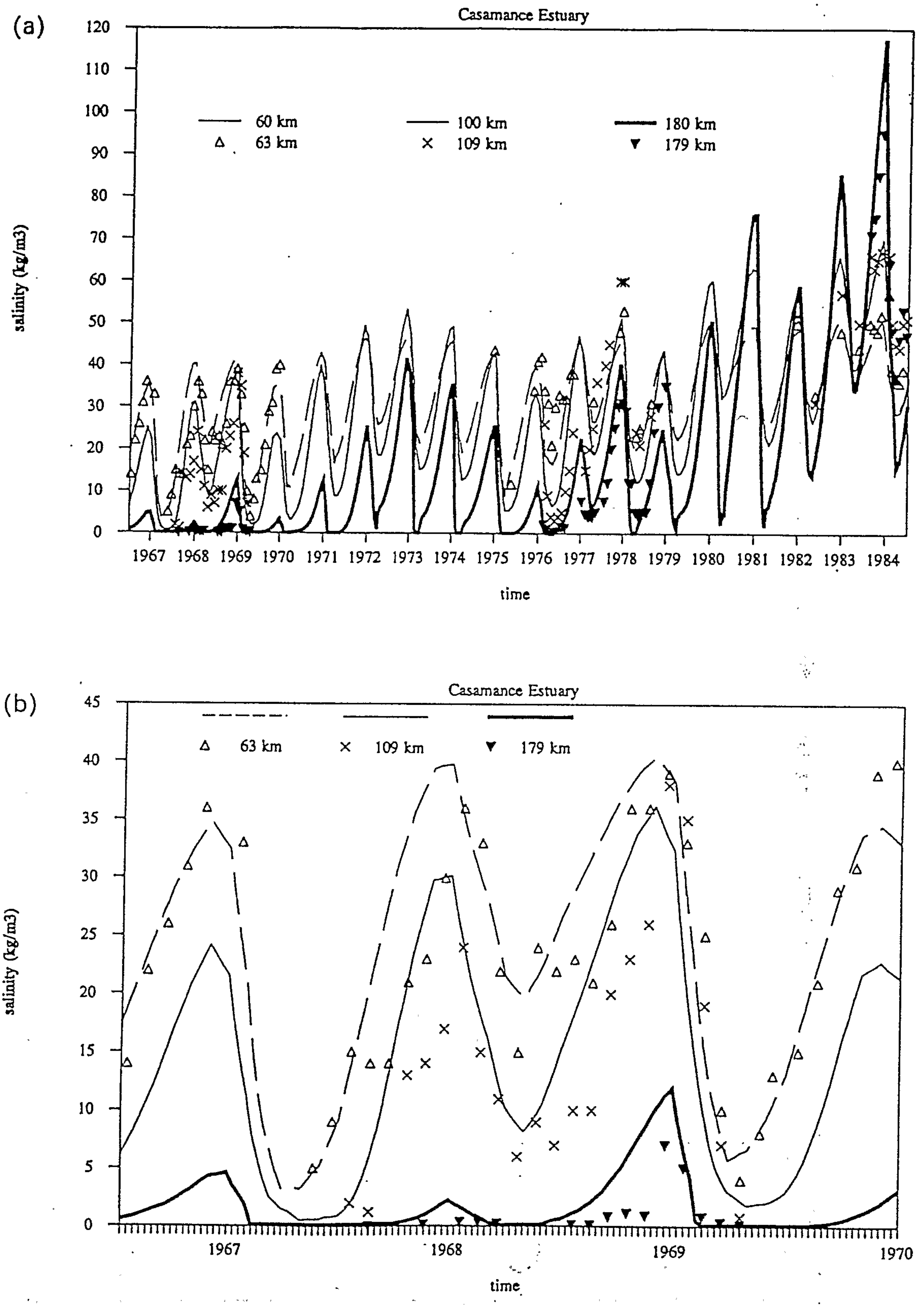
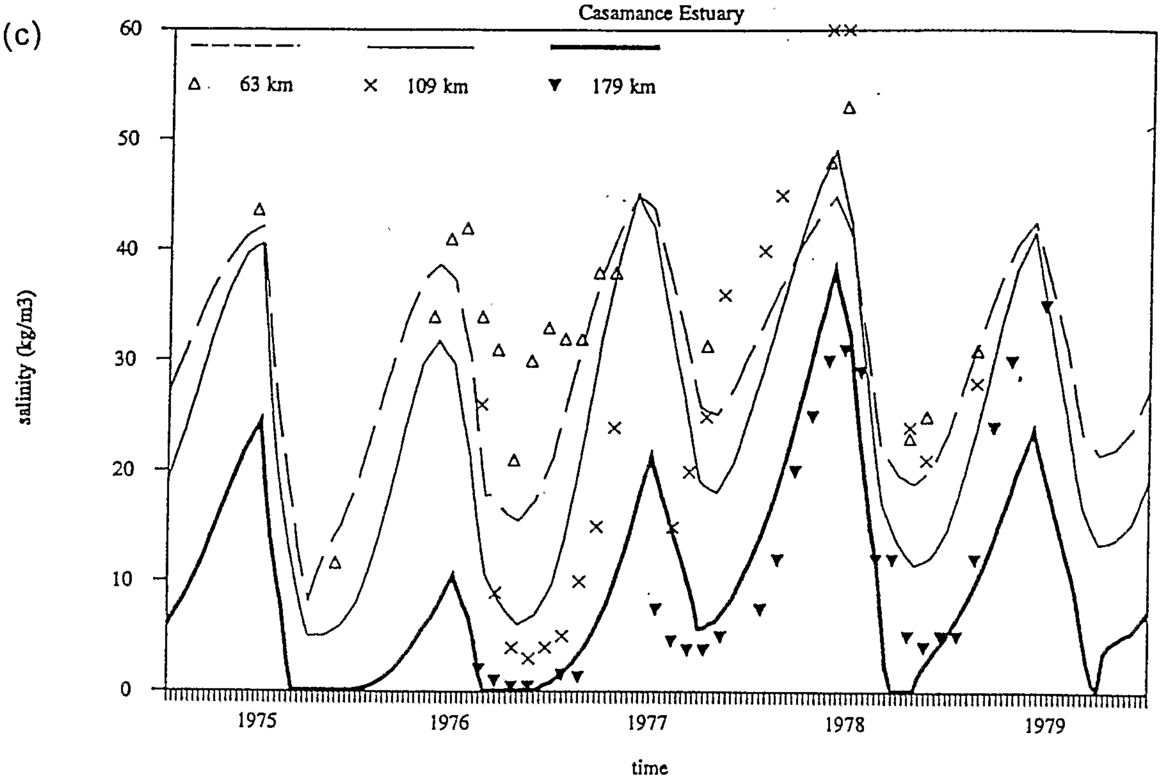


Fig. 7. Computed and measured salinity variation in the Casamance estuary.

(c)



(d)

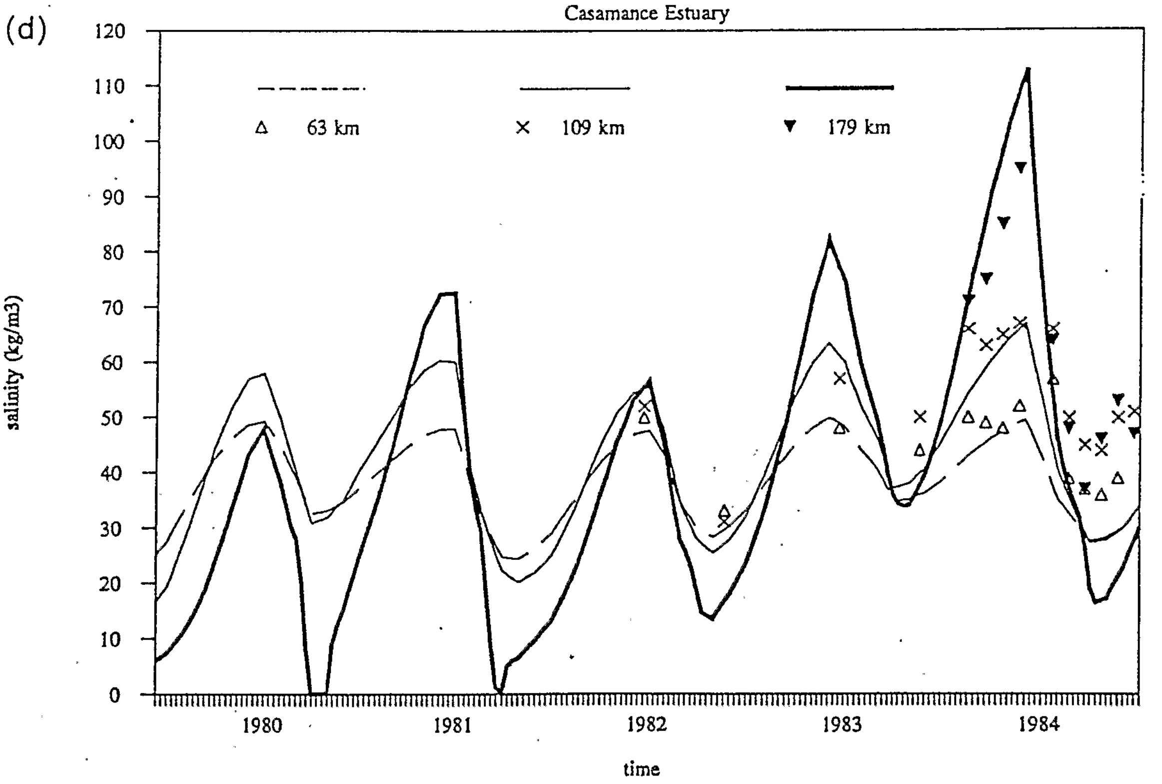


Fig. 7. Continued.

In the aquatic system, fish is the main source of protein. Even the highly adaptable tilapine fish, *Sarotherodon melantheron*, cannot survive 90 kg m^{-3} (Albaret, 1987), which means that one protein source disappears for 4 months of the year. Shrimp, *Penaeus notialis*, has always been an important source of income along the lower half of the estuary. The average weight and number of catches have collapsed since 1980 (LeReste and Collart-Odinetz, 1987). Shellfish were an occasional food supplement; both oyster, *Crassostrea gasar*, and *Anadara senilis* have retreated seaward (Cormier-Salem, 1986). All big vertebrates (hippopotamus, crocodile, manatee) have succumbed due to a combination of food shortage and poaching.

In the terrestrial system, the riparian vegetation is strongly affected. The freshwater reed swamps, with *Phragmites communis*, have retreated some 100 km upstream, depriving birds of their habitat. These reeds were also a source of nutrients for the aquatic system. The downstream mangrove has also suffered. Along some 60 km, *Rhizophora* has been eradicated, while some stunted *Avicennia* manage to survive. Useful fuel wood resources have thus disappeared. Consequently, the pressure has shifted to interfluvial forests, which are also subject to exploitation for timber and clearing for agriculture.

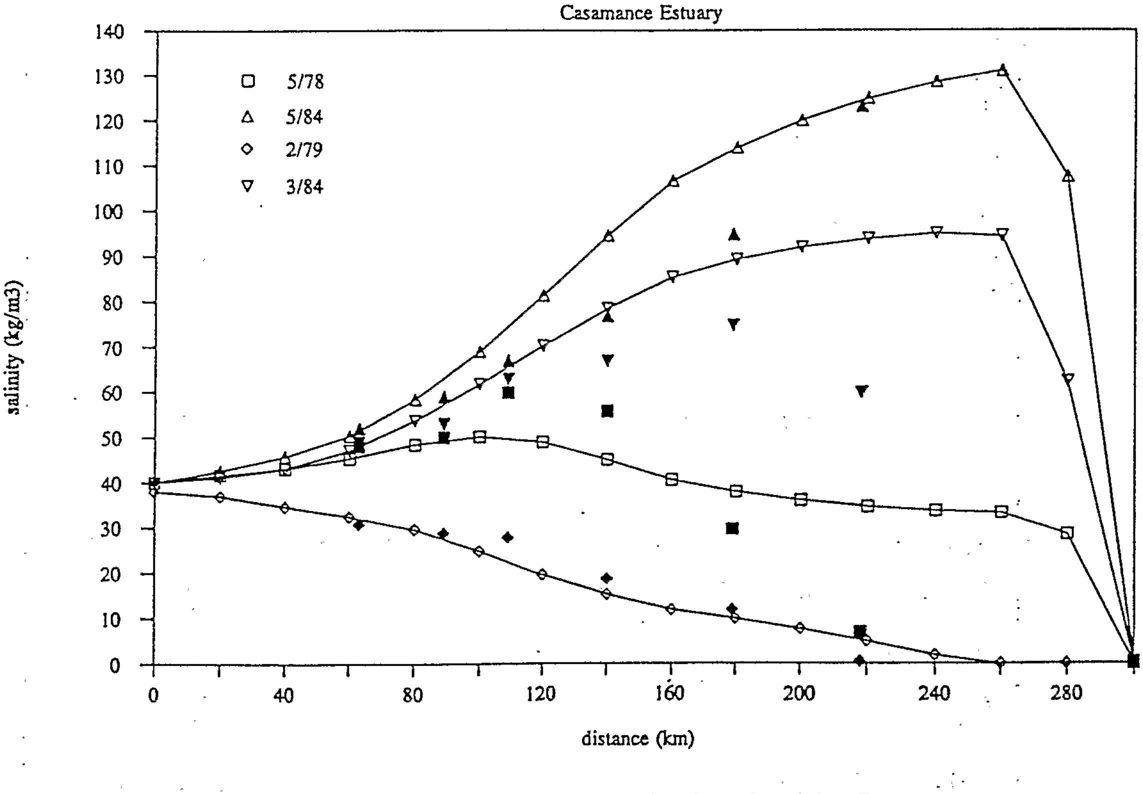


Fig. 8. Computed and measured longitudinal salinity distribution along the Casamance estuary.

Paddy fields have been affected. Along a considerable part of the upper estuary, tidal flats were previously used for rice cultivation. The bunds are still visible, but are now topped with salt crystals. Farmers have built anti-salt dams with moderate results, at best. Salty ground water has destroyed fruit trees and palm trees, *Borassus Aethiopicum*, up to 50 m from the estuary banks.

In the Casamance an ecological disaster has taken place, in which brackish and freshwater habitats turned into hypersaline waters (until 100 kg m^{-3}). In the hypersaline area, dead palms now flank the banks of the Casamance. The hypersaline water has made the growth of otherwise salt-tolerant vegetation impossible. Dead vegetation is surrounded by orange-coloured water. Only a certain orange type of algae is able to survive in this inhospitable environment. Migrant species that previously travelled from the ocean to the head of the estuary and back, now find their way blocked by warm hypersaline water.

The ecological change has seriously damaged the socioeconomic well-being of the population along the Casamance. It is not the hypersalinity in itself which is damaging (the Saloum has always been hypersaline and is known for its salt farms); it is the rapid change from a fresh and brackish environment to a hypersaline environment in a few years that has turned the drought into a long-lasting disaster.

REASONS FOR HYPERSALINITY

What caused the Casamance to become hypersaline during the Sahelian drought of the early 1980s? Since the model succeeds in describing the process, the reason should be found in the hydrological input functions to the model: the recorded upstream fresh discharge Q_f, the rainfall and the evaporation. Continuous records of observations of rainfall and discharge are available from 1967 to 1986. For evaporation, however, observations exist only over the years 1984–1988. The mean pattern of monthly evaporation observed during that period was used to simulate the evaporation for the period of the salinity observations from 1967 to 1984. To accommodate variations in annual evaporation, a simple correlation was established between annual rainfall and annual evaporation which took the form:

$$E = E_m \left(\frac{P}{P_m}\right)^{-0.7} \tag{7}$$

where the suffix m indicates annual mean values. It is realized that this approximation is rough and that it is essential that a better understanding is obtained of the actual evaporation during the period of simulation by a more

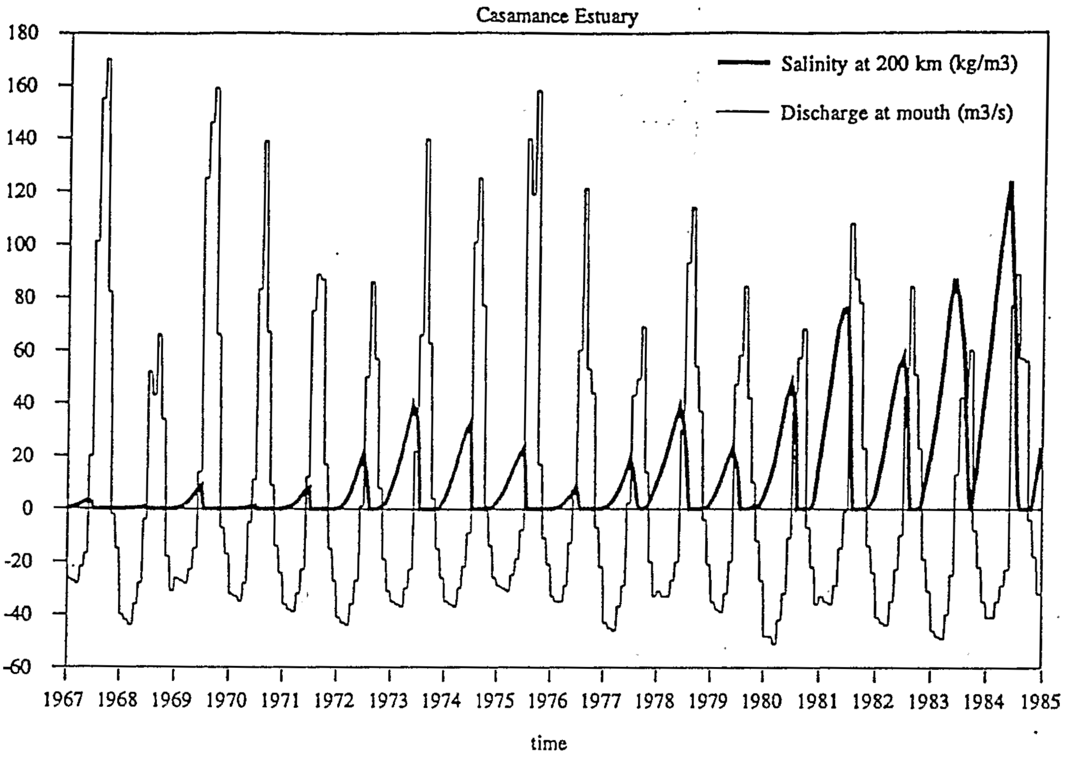


Fig. 9. Relation between runoff at the estuary mouth and maximum salinity at 200 km from the mouth, Casamance estuary.

detailed study of climatic data in the region. This will be a topic for further study.

The function which incorporates all the effects of inflow, rainfall and evaporation is the discharge Q_0 of the estuary to the sea:

$$Q_0 = Q_f + O_0 r \tag{8}$$

where O_0 is the total surface area of the estuary, and r is the balance of effective rainfall and evaporation:

$$r = C_p P - C_e E \tag{9}$$

where C_p and C_e are coefficients to convert recorded rainfall P and evaporation E to effective open water rainfall and evaporation. The coefficient C_p is higher than unity as a result of direct runoff from tidal swamps (in the Casamance $C_p = 2.0$). The coefficient C_e is to account for the fact that deep water evaporation may differ from recorded evaporation (in the Casamance $C_e = 1.0$). But in practice, the two coefficients are calibration coefficients for the model.

In Fig. 9 a plot is shown of Q_0 against the maximum salinity recorded at 200 km from the estuary mouth. It can clearly be seen that the salinity

TABLE 1

Multiple regression model relating salinity at 200 km to preceding runoff, Casamance estuary

Regression	Memory (years)	R^2	N (years)	a (kg m^{-3})	b_0	b_1	b_2 [(kg m^{-3})/(m^3 s^{-1})]	b_3	b_4
R_1	0	0.55	17	50.9	−2.3				
R_2	1	0.78	16	62.2	−2.3	−1.6			
R_3	2	0.80	15	66.0	−2.2	−1.5	−0.5		
R_4	3	0.88	14	73.3	−2.6	−1.1	−0.9	−0.8	
R_5	4	0.95	13	80.5	−2.5	−1.7	−0.6	−1.1	−0.6

increases as the discharge at the mouth decreases. One can conclude from studying the graph that the main cause for the hypersalinity lies in the reduction of the flood runoff (including the rainfall), rather than a reduction of the dry season flow. Apparently, the total amount of fresh water entering the estuary, and hence the storage of fresh water in the estuary, is the most important factor determining hypersalinity. This is not strange, since the source term of eqn. (6) only becomes powerful when the salinity of the water is high.

A multiple regression model was used to show the dependency between the

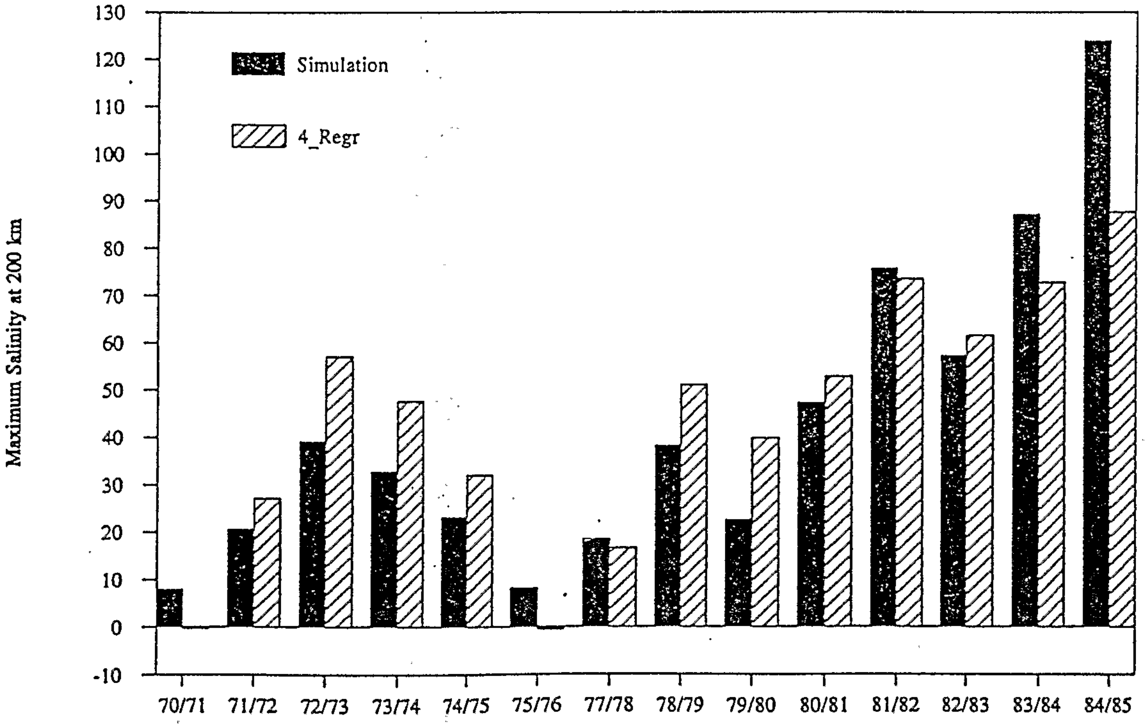


Fig. 10. Comparison of maximum salinity at 200 km computed by the salt intrusion model with the values computed by the multiple regression model, Casamance estuary.

maximum salinity and the mean annual values of Q_0. The general form of the regression formula is:

$$Y_n = a + \sum_{i=0}^{n} b_i X_i \qquad (10)$$

where Y_n is the maximum salinity at 200 km computed with a memory of $n - 1$ years, a is the constant, X_i is the mean annual runoff in a year with lag time i, and b_i are the corresponding coefficients.

Table 1 shows the coefficients obtained in the regressions (R_*n* indicates the regression on the basis of *n* years); and Fig. 10 shows the results. It can be seen that a regression model with a memory of 2–3 years describes the salinity relatively well. The coefficients in Table 1 suggest that a model with a memory of more than 3 years is no longer realistic. It is physically sound to have coefficients b_i that decrease when going back in time, as is the case in the triple (R_3) and quadrupole (R_4) regression. In the R_5 regression, although the correlation coefficient increases to 95%, no physical justification for the coefficients' values can be found.

Hence, hypersalinity is strongly influenced by preceding conditions. A single dry year does not bring on the danger of an estuary becoming hypersaline. It is rather a sequence of consecutive dry years that induces hypersalinity.

In this respect it is interesting to note that the source term in eqn. (6) becomes more important when the salinity increases. As the salinity increases, the rate of change increases as well, resulting in an exponential increase of the salinity. Starting from a relatively fresh estuary, it can take several years before this situation occurs. The hydrological year 1968/1969, for instance, was a very dry year, drier than most of the years in the late 1980s, but it was preceded by wet years, and hence did not cause any hypersalinity. The succession of dry years in the period 1977–1980, however, increased the general level of salinity of the estuary to an extent where the hydrological year 1980/1981 could cause a rapid increase of the salinity, resulting in serious hypersalinity.

The experience in the Casamance should be a warning to those responsible for the management of the Gambia or other Sahelian rivers. An increase in water consumption or water withdrawal in the upper Gambia could lead to similar situations as in the Casamance.

APPLICABILITY OF THE MODEL

In the Gambia, the model performed quite well. In the Gambia reliable information was available on both geometry and hydrology. In the Saloum, the hydrologic information was deficient and geometric information scarce. However, even in the Saloum reasonable results were obtained.

Although in the Casamance data on freshwater inflow were available, the lack of reliable data on depths and cross-sections seriously hampered the calibration. Nevertheless, it appeared possible to apply the model successfully.

The model described by Savenije (1988) has been applied to extreme conditions, for which it had not been developed. Given the limited amount of data available, the model performed well.

One aspect which has not been taken into account is the storage of salt in the estuary bed (after saturation has taken place), on tidal flats and in the soils bordering the estuary. The model has no device for this yet, but the option for salt deposits will be incorporated at a later stage.

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