Port Botany, New South Wales

PART IV

COASTAL, ESTUARINE, AND ENVIRONMENTAL PROBLEMS

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Separation of climatic fluctuations and impacts of engineering activities in estuaries

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Abstract

Using salinity as an example of dissolved substances in estuarine waters it is shown how the long term trend of concentrations can be split up into a man-made and a climatic contribution. The understanding of long term mixing processes and adequate sampling techniques are essential for this purpose. The physical state of the estuary can be described in terms of 3 basic variables, the river discharge, the filtered water level and the filtered salinity. The river discharge represents the climatic fluctuations in the catchment area, and the filtered water level is a record of the large scale weather pattern over the adjacent ocean basin. Salinity trends which cannot be attributed to these two variables must originate from man-made actions, such as dredging or other engineering activities which change the geometry of an estuary.

Two models are used for the trend analysis, the simplest possible mixing equation (which always holds for a sufficiently long time scale), and a salt flux consideration.

1. Introduction

In many cases environmental impacts of coastal engineering activities in estuaries are not easily assessed because it is necessary to separate the man-made changes from climatic fluctuations. Moreover, variables such as water level current velocity and salinity depend not only on tidal conditions and river discharge, but also on external forces like wind set-up, atmospheric pressure gradients, presence of shelf waves and changes of the large scale water circulation of the adjacent ocean basin.

Therefore, methods have to be developed that allow to eliminate all of these natural effects from measured data prior to any trend analysis which aims at assessing human impacts. For the variable salinity suitable methods will be described for a well-mixed estuary. They are derived from a case study using observations of a typical tidal estuary of the North Sea.

2. Area description and observations

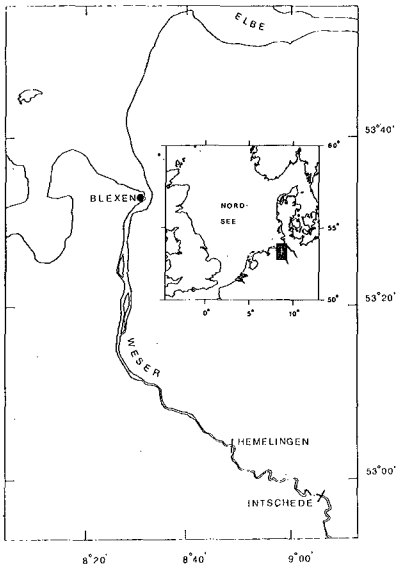


Fig. 1 The river Weser estuary. The tidal range extends up to Hemelingen. The river discharge is measured at Intschede, all other data were obtained from a jetty at Blexen

Fig. 1 shows a map of the river Weser estuary. The mean tidal elevation is 3.40 meters, there are strong tidal currents up to several knots, and a weak stratification of salinity occurs only for two or three hours around slack waters.

The Weser river is an important shipping channel which connects the old Hanse town Bremen with the North Sea. Dredging of the channel has been carried out ever since the introduction of effective techniques.

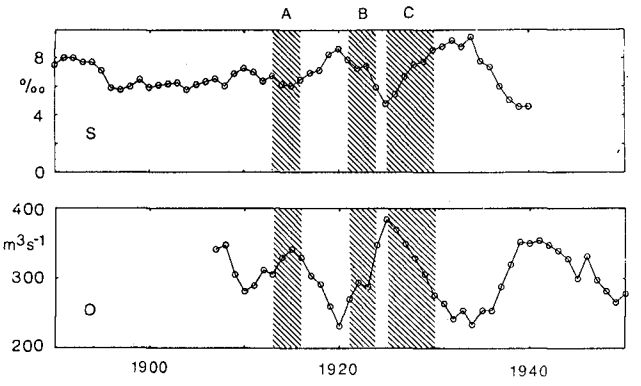


Fig. 2 5 year averaged salinity and river discharge together with major dredging operations A, B and C during which the river was deepened from 5 down to 7 meters

Fig. 2 displays the development of salinity near the mouth of the river (Blexen) together with the river discharge covering the period from 1887 to 1940.

People were alarmed by the increase of salinity which followed the first extensive period of dredging, but it is seen that salinity just reflects the influence of the variable river discharge whereas effects of dredging are not obvious from the data.

However, there is biological and other evidence that salinity must have changed especially after deepening the river further upstream. Obviously, the large fluctuations of the river discharge mask the effects of dredging. It could also be the case that salinity sampling was not adequately carried out with respect to the problems to be studied. The old data set of fig. 2 just served as an in-

troduction into the problem of a long term trend analysis. The intention of this paper is to outline a method how man-made changes and natural fluctuations of salinity can be separated.

For this purpose another data set will be used which is represented in fig. 3. It was measured at a rather high sampling rate (Δt = 1 hour), and it covers 368 days of salinity, water level and river discharge observations.

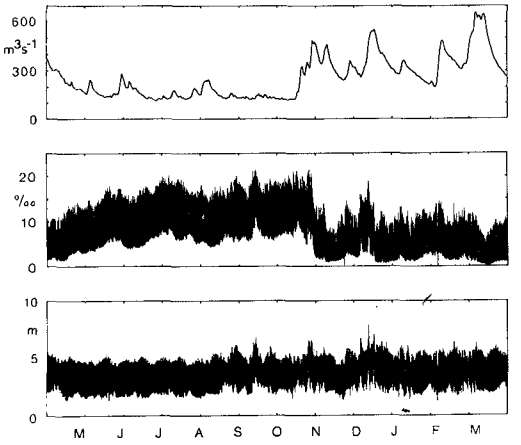


Fig. 3 The data set (river discharge, salinity, water level) used for this investigation. Time scale is one year, sampling interval is one hour

3. Fundamentals of trend analysis of salinity

3.1 Scale considerations

The duration of a tidal cycle can be considered as a basic estuarine time scale. Mixing of river and sea water appears as a very complicated process within this scale. It involves turbulence, density effects, bottom friction, river discharge and many others amongst which are the water depth and other geometrical properties of the channel.

In order to predict salinity changes as a result of dredging the complicated mixing process is usually modelled, and respective parameters are systematically changed.

This usual engineering approach will not be adopted here. Man-made changes to salinity distributions in estuaries occur not only by single operations but also by many minor actions in the course of years or decades, and on these very long time scales one cannot consider all the details of mixing which take place within a single tidal cycle.

If a long term observer looks upon salinity in an estuary, the time averaged salinity $\bar{S}$ can only be a function of the averaged volume ratio of fresh water to sea water $\bar{q}$, and the salinity of the adjacent ocean water S_o, i.e.

$$\bar{S} = S\ (S_o,\ \bar{q}) \qquad (1)$$

The volume ratio $\bar{q}$ depends on the position within the estuary, on the geometrical dimensions, and on the amount of fresh water which is given by

$$F = Q + (P - E) \qquad (2)$$

where Q is the river discharge, P is precipitation and E stands for evaporation.
Restricting the discussion to one fixed position, assuming a channel-like estuary, neglecting (P-E) compared with Q, and assuming salinity of the ocean water to be constant, then eq. (1) reduces to

$$\bar{S} = f\ (Q,\ \bar{h}) \qquad (3)$$

where $\bar{h}$ is the mean water depth. Eq. (3) indicates that the averaged salinity is a function of climatic fluctuations in the catchment area, and that it is also dependent on all external processes that change the mean water level. Such processes can be wind set-up, seiching, presence of shelf waves or atmospheric pressure gradients. Eventually, the mean water depth depends on the dredging operations in the area.

No particular mixing process has been assumed. If data are sufficiently averaged it does not matter how river and sea water is mixed, whether this is due to tidal or other currents or whether there exists a stratification or not for some periods of time. The basic question is only over what period of time the averaging procedure has to be extended so that the above arguements will hold. This can only be answered with the aid of observations, and the data set of fig. 3 serves for this purpose.

3.2 Selecting the time scale

The result of the previous discussion can also be put this way: Whenever the mean water level changes sea water is moved into or out of the estuary in addition to the tides. Given enough time this additional water mass will be mixed completely with the estuarine water.

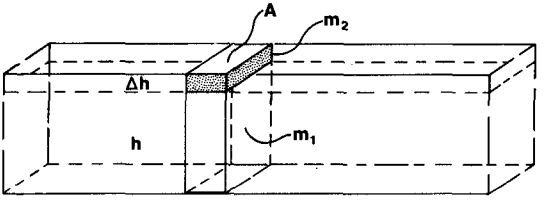


fig. 4

If m_1 denotes the mass of water in a control volume and m_2 an additional water mass, then the equation

$$m_1 S_1 + m_2 S_2 = (m_1 + m_2) S \qquad (4)$$

must hold after complete mixing. S_1, S_2 and S are the respective salinities. Relating the masses to respective water levels (fig. 4) yields for small changes

$$\Delta S = \frac{S_2}{h} \Delta h \qquad (5)$$

Near the mouth of the river S_2 can be considered constant (ocean salinity), it varies very much less than the salinity in the estuary. Therefore, one should expect a linear relationship between mean salinity and mean water level fluctuations. This can serve as a criterion for finding the characteristic time after which complete mixing has taken place.
With the frequently sampled time series available, the most obvious averaging procedure is filtering by a low pass filter.

For the river Weser estuary it was found (KRAUSE 1979) that mean data of salinity and water level satisfy eq. (5) after being filtered with a pass band between 35 h and 3000 h. The filtered time series are shown in fig. 5.

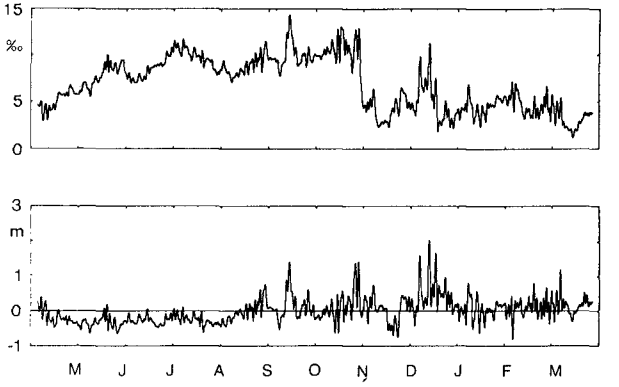


Fig. 5 Filtered salinity and water level

Fig. 6 shows an enlarged section of the filtered time series, and in fig. 7 the same data are plotted against each other.

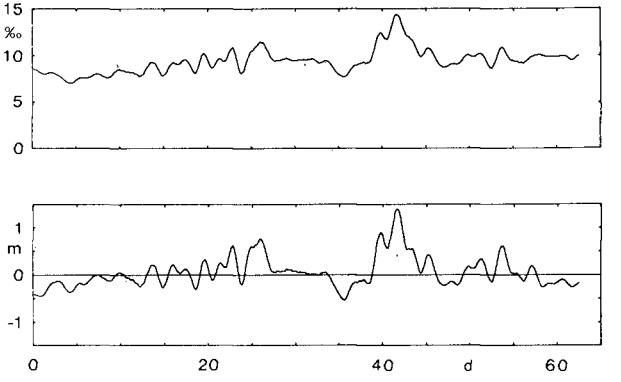


Fig. 6 Filtered salinity and water level during September/October

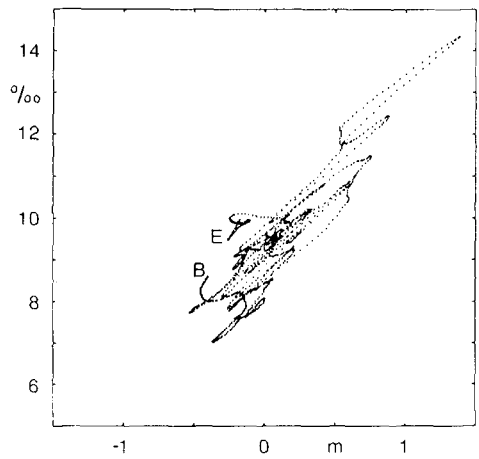
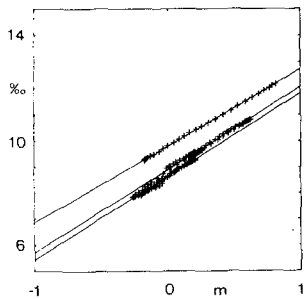


Fig. 7 The data fig. 6 plotted against each other. B: begin, E: end

This picture appears confusing at the first glance, but this results only from the variable river discharge. For short times of almost constant discharge there holds a linear relationship which cannot be better fulfilled as indicated by fig. 8.



$S_F = AH_F + B$

A	B	R	Q (m^3s^{-1})
3.16	8.89	1.00	157
3.18	8.36	0.99	146
2.92	9.74	1.00	130

$\Delta S = 3.08 \; H_F$

Fig. 8 Regression lines through successive data points of fig. 7 (3 examples). R is the correlation coefficient and the last column is the river discharge. S_F denotes filtered salinity, H_F filtered water level and $\Delta S = B \cdot H_F$

It was assumed that the empirical relationship in fig. 8 holds throughout the record.

The physical significance of this result is that in the Weser river a time of about 3 tidal cycles (35 h) is sufficient to mix an additional water mass, associated with a change of the mean sea level, completely with the water already present at the observation site.

3.3 Rejection of external forces

The filtered sea level fluctuations in fig. 5 are closely related to the large scale weather patterns over North Sea and North Atlantic Ocean. However, it is not necessary to elaborate on the mechanism of this response. Whenever the filtered water level changes, water is moved into or out of the estuary. The filtered water level is simply a record of external forces on the estuary. The associated salinity fluctuations can be computed using the empirical relationship given in fig. 8. The result is displayed in fig. 9, and it is seen that the fluctuations are of considerable magnitude.

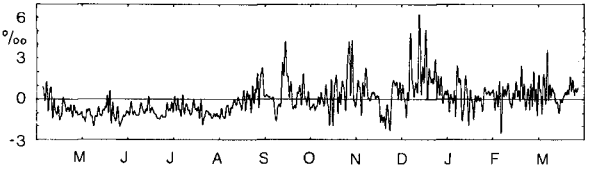


Fig. 9 Salinity fluctuations as a result of external forces on the estuary

They do not contribute to a man-made trend, they only contaminate the data. Therefore, they are subtracted from the filtered salinity time series of fig. 5. The result, presented in fig. 10 is a rather smooth curve which is almost the mirror image of the river discharge.

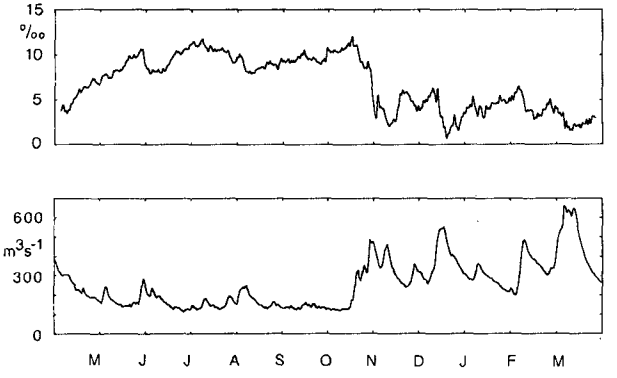


Fig. 10 Reduced salinity and river discharge

3.4 Rejection of climatic fluctuations in the catchment area

Under the assumptions of stationary conditions, constant bathymetry, constant salinity of the adjacent ocean basin and mixing processes being independent of the river discharge Q, the mean in- and outgoing salt fluxes through a cross section of the estuary would be in balance and be constant.
The outgoing salt flux is

$$f_{out} = \varrho U_o \bar{S} \qquad (6)$$

where $\bar{S}$ is salinity averaged over the cross section and over time, ϱ denotes density and

$$U_o = \frac{Q}{A} \qquad (7)$$

is the outgoing velocity according to river discharge Q and cross sectional area A.
Under the above assumptions one has

$$f_{out} = - f_{in} \qquad (8)$$

both being constant. Therefore, the total outgoing flux (mass per second) must also be constant, i. e.

$$\S Q\bar{S} = \text{const} \qquad (9)$$

and the ingoing flux needs not to be known.
As indicated by eq. (7) a dredging operation which changes the cross sectional area A would change the constant in eq. (9).
To a first approximation eq. (9) can be used to eliminate the variable river discharge which expresses the climatic fluctuations in the catchment area of the river.
The flux according to eq. (9) has been calculated, and the result is displayed in fig. 11. It is seen that most of the time the assumption of stationary conditions is violated. When a flood wave enters the estuary the flux increases, and salt is washed out of the estuary. Nevertheless, there are also times of almost constant discharge, which enables the observer to determine the constant in eq. (9). In the present case the constant is 1200 kg s^{-1}.

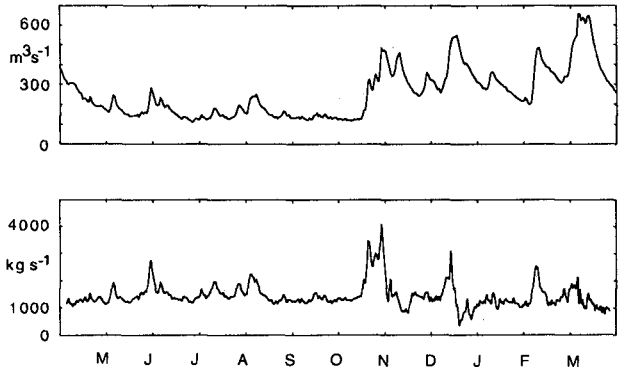


Fig. 11 River discharge and total outgoing salt flux

Observations taken at times of variable discharge cannot be used for the trend analysis under study. Fig. 12 gives some insight into the complicated response of salinity due to variable river discharge, and it supports the above arguement.

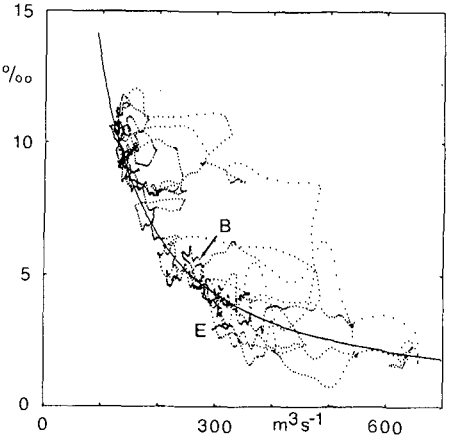


Fig. 12 River discharge - salinity diagram. The solid curve corresponds to a constant flux of 1200 kg s^{-1} which had been determined from fig. 11

3.5 Results

The decisive processes which govern the subtidal variability of salinity in an estuary originate from the adjacent ocean basin and from climatic fluctuations in the catchment area. Resulting fluctuations mask the man-made changes. However, it is possible to recover the very weak signal of human impacts by regarding the other fluctuations as "noise" which contaminates all data gathered.

The salinity fluctuations as a result of external forcing are very well understood. On time scales beyond 3 tidal cycles in case of the Weser, they are linearly related to the filtered (mean) sea level, and corresponding salinity fluctuations are easily removed from observed salinities.

The response of salinity to the variable river discharge involves the previous history of the salinity distribution and depends also on magnitude and time history of the discharge. Only salinity data gathered during periods of almost constant river discharge are reliable for assessing man-made trends.

It is obvious that results derived for salinity will also hold respectively for other dissolved substances, pollutants, turbidity, current velocity and for sediment transport processes. Attention to the difficulties in estimating mean flow conditions in estuaries has been pointed out by WELSBERG (1976).

4. Applications

4.1 Monitoring strategies

With respect to the long-term development of salinity or other variables it is important to realize that inspite of the predominance of tidal variability, a tidal estuary is a meteorologically governed area of the sea. This prescribes the sampling rate to be adopted by monitoring schemes.

In order to demonstrate this more clearly, the salinity data set of fig. 3 (again as an example) can be resampled according to various schemes.

If one assumes an observer who could take a sample at every high water the result would be the trace in fig. 13. In case of pollutants such frequent sampling is beyond any hope of achievement.

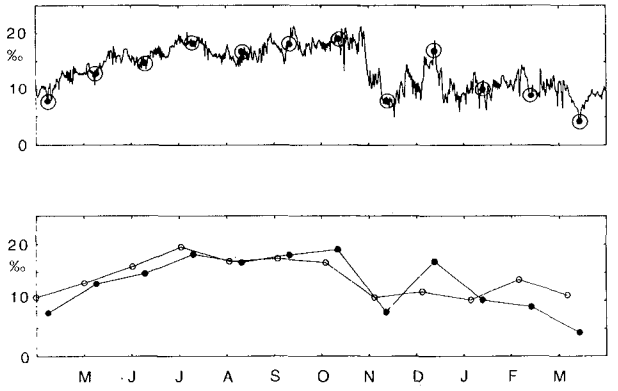


Fig. 13 Results of various monitoring schemes. Trace: Sampling at each high water, dots: sampling on monthly intervals.

Sampling on monthly cruises gives rise to serious errors in trend calculations as indicated in fig. 13. Data of such schemes e.g. depend on the starting time.

A suitable monitoring strategy can only be based on the 3 basic variables water level, salinity and river discharge. They are easy to measure continuously and they characterize the physical state of the estuary. One can apply the reduction procedures outlined before, and this can also be carried out on-line. Based on the results (i.e. stable or unstable conditions due to variable river discharge, mean sea level fluctuations etc.) other measurements can be assessed or perhaps be corrected. One can also adopt a flexible approach. A costly field investigation is only carried out when the conditions are right.

4.2 Assessment of available data sets

The results of chapter 3 enable the assessment of existing data of an estuarine environment also in cases where no salinity measurements have been carried out. It is necessary to know the time history of mean sea level and river discharge to have an indication of the usefulness of data with respect to trend analyses.

4.3 Calibration of mathematical models

Numerical models designed to predict salinities or other variables rely on a data set for calibration that only depends on processes which have been modelled. As has been demonstrated before, estuaries are seldom in a stationary state and field data depend on the previous history. Therefore, great care is necessary to measure a suitable data set that ensures the general validity of the model parameters.

5. Conclusions

(i) The basic element for a long term trend analysis of estuarine variables is the fact that an estuary is a meteorologically governed area of the sea inspite of the predominance of tidal variability.

(ii) The long term trend of the concentration of a conservatively dissolved substance depends only on the large scale weather patterns over the adjacent ocean and the catchment area of the river.

(iii) Whereas other authors (e.g. ELLIOT and WANG, 1978; SMITH, 1978; WANG, 1979) have studied the influence of atmospheric forcing on estuaries in detail, this is not necessary for a long term trend analysis. The filtered (mean) sea level is the record of all external forcing mechanisms.

(iv) In well-mixed estuaries only a few tidal cycles have to elapse until the simplest possible mixing equation describes adequately the response of salinity to external forces which change the filtered water level. Filtered water level fluctuations are natural "experiments" by which the time scale can be determined.

(v) Filtered salinity, filtered water level and river discharge are the basic variables which describe the physical state of an estuary. They can be used to design monitoring schemes and to assess available data, mathematical tidal models and impacts of engineering activities on estuaries which are masked by large climatic fluctuations.

Literature

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