

# **Salinity in Lake Maracaibo**

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## Summary

Lake Maracaibo, Venezuela is an outstanding example of today's conflict of interests between protection of natural resources and economic development because of the extensive use of the area. The exchange and interaction between the fresh water of the Lake and the saline water from the Gulf of Venezuela is an important mechanism in the development of pollution of the Lake.

For studying the distribution and transport of salt in Lake Maracaibo a three-dimensional numerical simulation model was developed and calibrated, using DELFT HYDRAULICS' hydrodynamic model TRISULA.

With this model the behaviour of the salinity distribution and salt transport was examined under varying hydrological conditions. Because of the very large time-scales of the characteristic physical processes in the system special attention was focused on long-term simulations.

Since the tide is the initiator of the salt transport in the system it is necessary to use small time-steps for an accurate simulation of the tidal dynamics. However this causes problems with the simulation of the salt transport because this is a process of years.

In order to simulate the salt content in the Lake several simulations with constant hydrological conditions were performed and the results were used as input for a box-model. With this box-model the total salt content in the Lake was computed.

Although the box-model was not completely capable of reproducing long-term TRISULA results this approach of modelling the salt transport is still very attractive.

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# 1 Introduction and purpose

Lake Maracaibo, Venezuela is an outstanding example of today's conflict of interests between protection of natural resources and economic development, because a common area is occupied by human concentrations, oilfields and extensive fisheries. The stresses imposed on the biota in the system are manifold.

Many large-scale research programs have been undertaken to identify and evaluate the pollution problems in Lake Maracaibo, and it has been shown that the main problem in the Lake is the accelerated eutrophication. This process is heavily influenced by the transport and the distribution of salt in the Lake.

The most important questions about the Maracaibo system are :

*What will happen with the long term total salinity contents in the Lake in case that a major part of the river discharges will be used for irrigation ? What will be the influence on the eutrophication and other forms of pollution in the Lake ? And how many water from the discharges could be used for irrigation so the damage caused to the ecological system is acceptable ?*

Before one can answer these questions it is necessary to understand the processes involved. From this point of view it is clear that the transport processes in the Lake have to be studied. Before it is possible to make an accurate numerical model of the pollution it is necessary to develop a model of the tidal hydrodynamics, and the transport of salt and the distribution of the salinity in the Lake.

By developing a model to reproduce the tidal dynamics, the salt transport and the salinity distribution a very important fact becomes clear. The time-scales of the processes involved are very different. The tide has a time-scale of approximately half a day, the salinity transport has a time-scale of at least several weeks, and the residence time in the Lake is about 7 years or more.

These different time-scales cause a very significant problem in the modelling of the system. For a good reproduction of the tide it has to be modelled with relatively small time-steps, only a few minutes. For the modelling of the transport of salt it is necessary to simulate several years, and with a small time-step this brings a reasonable amount of computational costs. Nevertheless it seems necessary to make simulations with this small time-step because of the fact that the processes involved - the tide and turbulence - are the originators of the salt transport. These small-time processes are the initiators of the large-time changings in the system

In this thesis the purpose was not to find a strict answer to the questions mentioned above but to study the processes involved in modelling the salt transport and the salinity distribution in the Lake. Our attention was focused on the total salt content in the Lake itself, the seasonal variation in the salt content, the salinity distribution, the behaviour of the salt transport, and the different time-scales involved.

For this purpose the three dimensional numerical model of the Maracaibo system developed by DELFT HYDRAULICS (Bijlsma, 1993) was studied. Many simulations were made to investigate the tidal movement, the salt transport and the salinity distribution in the model. The main purpose of the study was to find out how the system responded to changes in the river discharges and the total salt content in the Lake and how to handle the different time-scales in the system.

In the next chapter the physical aspects of Lake Maracaibo and approaches are described, for example the tide, the hydrological conditions and the climate. In chapter 3 the numerical model and the calibration results are reported, and in chapter 4 simulations focused on the salinity flux and contents are shown. A new approach for simulating the total salt in the Lake with a box-model is given in chapter 5 and overall conclusions are drawn in chapter 6.

## 2 The Maracaibo system

### 2.1 Geography

The Lake Maracaibo system is located in the north-west corner of Venezuela, and is surrounded by the Sierras de los Motilones and the Venezuelan Andes. It consists of an oceanic water body, the Gulf of Venezuela, connected through a partially mixed estuary, Tablazo Bay and the Strait of Maracaibo, to a salt-stratified lake, Lake Maracaibo. Figure (2.1)

Lake Maracaibo is an oval-shaped lake with a length of approximately 150 km and a width of 110 km. It averages 25 m depth reaching a maximum of about 35 m. With a total area of 12,000 km<sup>2</sup> the total volume of water is almost 280 km<sup>3</sup>.

The Strait of Maracaibo, which is from 5 to 15 km wide and 40 km long, connects the Lake with Tablazo Bay. Tablazo Bay has trapezoidal form with a length of 30 km and a width of 15 km. The bay is very shallow with averaged depths of 2.5 m. The area of the Strait and the Bay together covers 1,100 km<sup>2</sup>. Tablazo Bay is connected in the north with the Gulf of Venezuela by two narrow inlets, Boca Cañonera and Boca Cañonerita.

The depth in the western part of the Gulf of Venezuela averages 20 meter. The Gulf is roughly rectangular and is approximately 180 km long and 75 km wide. In the north-east it flows into the Caribbean Sea.

From every side rivers flow into Lake Maracaibo. An area of about 90,000 km<sup>2</sup> drains into the Lake. The greatest rivers - Rio Santa Ana, Rio Catatumbo, Rio Escalante - stream from the mountains through the swampy low lands before they reach the Lake in its south-eastern part. The other rivers are mostly short and relatively steep. Marshlands are also located on both sides of Tablazo Bay. A few rivers run into the Bay, from these Rio Limon is the most important one. The coasts in the system are generally low, except the coasts in the Strait of Maracaibo and the coasts of some islands in Tablazo Bay.

The bottom sediments in the system consist mainly of fine erosion material, descended from the mountains. The supply of these sediments still takes place.

A shipping channel has been dredged through the entire Maracaibo system. This 100 km long, 14 m deep channel begins in the Gulf and leads through Tablazo Bay, the Strait of Maracaibo into the Lake. Its existence makes it possible for large oil-carriers to navigate into the Lake, in spite of the very shallow depths in the system. Especially in the north-eastern part of the Lake very large amounts of oil are produced.

### 2.2 Hydrodynamics

The first description of the hydrodynamics in the Maracaibo system was made by Redfield (1955, 1961). After the construction of the navigation channel Brezina (1975) made a hydraulic model of the system including the Lake, the Bay and a part of the Gulf. Further 2Dh and 3D hydrodynamic analyses were made by Molines et al. (1989), and Lynch et al. (1986, 1990).

The tidal characteristics in the estuary system are induced by tide, wind, river inflows, and by density currents due to differences in the salt content of the water of the Gulf and the fresh river inflows.

### 2.2.1 Vertical Tide

A mixed but predominantly diurnal tide with an amplitude of 0.3 m exists in the north-east of the Caribbean sea, close to Aruba. Only very small semi-diurnal components of the tide exist here. The tide reflects in the Gulf of Venezuela and causes an amplification of the semi-diurnal tides. The amplitude increases toward the end of the Gulf, and by the tide gauges between the Gulf and Tablazo Bay the tide is mainly semi-diurnal with a maximum observed amplitude of 1.6 meter.

Further south the vertical tide decreases to 0.70 m in the middle of Tablazo Bay and to about 0.40 m and less at the southern end of the Strait of Maracaibo. In the north of the Lake the vertical tide is almost reduced to zero, but the amplitude increases a little further southward. It nevertheless remains very small, with a magnitude of about 10 cm.

From in situ observations and the tidal analyses of Redfield, Molines and Lynch it is known that a standing (tidal) wave exists in the system. A node for the semi-diurnal constituents occurs in the northern part of Lake Maracaibo. The tidal waves propagate in the system from the Gulf, through the Bay and the Strait to the Lake. In the Lake the waves rotate anti-clockwise around the amphidromic point. In Figure (2.2) co-tidal charts are given for the  $M_2$  and  $K_1$  constituents.

Because of the very weak astronomical tide variations in windspeed and direction can cause significant fluctuations in the waterlevel of the Lake.

### 2.2.2 Currents

The currents in the northern part of the Maracaibo system are dominated by the tide. The standing wave, its amphidromic point in the Lake, and the 'anti-node' in Tablazo Bay cause the bay to fill and empty by currents from the North and from the South simultaneously. This means that the currents in the Strait and the tidal inlets Boca Cañonerita and Boca Cañonera are very often in opposite directions. The northern half of Tablazo Bay receives most of its water from the Gulf, the southern half is filled by water from the Lake. See Figure (2.3). In this part of the system mean velocities of 0.5 m/s occur.

The flow pattern described above is slightly disturbed by diurnal constituents of the tide, by density effects, fresh water inflow from rivers and the wind.

The tidal influence on the currents in Lake Maracaibo itself is very small. The astronomical tide only generates a small north south current. The major cause for the stream pattern in the Lake is the windfield. The wind generates a counter-clockwise vortex movement in the Lake.

## 2.3 Windfield

A northwesterly trade-wind blows above the Maracaibo area for the main part of the year. This wind blows from the Gulf to the Lake, and the surrounding mountains force the wind to rotate more or less anti-clockwise, Figure (2.4). In the northern region of the Lake, predominant winds come from NNE, NE and ENE. Near the centre of the Lake and toward the northwest of the Lake predominant winds are from NNW, N and NNE. In the south-western part predominant winds originate from WSW, WNW and NW. On the eastern coast they usually come from ESE and ENE. (See Parra-Pardi, 1983)

This rotating windfield forces the waterbody to rotate anti-clockwise and these currents reach a speed of about 25 cm/s at the surface to 5 cm/s at the bottom, see Figure (2.5). The wind thus has a very important influence on the salinity structure in the Lake by forcing this stream pattern.

## 2.4 Climate

The Maracaibo system is located between 9° and 12° North-latitude and is undoubtedly tropical, with a very clear dry and wet season. The dry season takes place from November to April, and the wet season from May to October.

### 2.4.1 Temperature

From measurements it is known that the temperature of the water in the Lake doesn't change very much during the different seasons. The mean annual temperature of the Lake water is about 30°C. In the deeper parts of the Lake the temperature is normally 27°C, and at the surface approximately 32°C is not unusual. Further north the temperature decreases slightly.

### 2.4.2 Evaporation

The climate in the system varies from dry and warm in the north to humid and warm in the south. The evaporation increases southwards and measurements showed that reasonable amounts of surface water evaporate from the Lake in the dry season. | ?

### 2.4.3 Precipitation and river discharges

Precipitation enters the Lake in three different manners; there is direct precipitation; there is 'direct run-off' from the shores and precipitation from the hinterland enters into the Lake through the rivers.

The annual averaged precipitation varies from about 400 mm in the north to 2600 mm in the south. The river-discharges vary with the seasons, the average values lay in the range from 400 m<sup>3</sup>/s (dry season) to 2600 m<sup>3</sup>/s (wet season). The largest river, Rio Catatumbo, alone supplies around 70 % of the total discharge.

#### 2.4.4 Hydrological balance

In the past a lot of hydrological balances have been made for the Maracaibo system. See e.g. Carter (1955) Corona (1964), Parra-Pardi et al. (1979) and Belkis et al. (1986).

Hydrological balances were made with the equation :

$$V_{sea} = V_{rivers} + V_{precipitation} - V_{evaporation} \quad (2.1)$$

where  $V_i$  = volume<sub>*i*</sub> in m<sup>3</sup>/year.

The river discharges  $V_{rivers}$ , the evaporation  $V_{evaporation}$  and the precipitation  $V_{precipitation}$  have been calculated out of large data sets of measurements. With these data the annual outflow from the Lake to the sea  $V_{sea}$  has been calculated using Eq. (2.1).

The annual outflow from Lake Maracaibo to the Gulf of Venezuela between 1958 and 1977 has been varying between 19 and 54 km<sup>3</sup>/year, with an average value of 40 km<sup>3</sup>/year.

Taking into account the seasonal variations it is clear that the monthly hydrological balance can become negative in extremely dry periods. In that case the evaporation is larger than the precipitation and the river discharges together. More salt will penetrate into the Lake because of the nett inflow of water from the Gulf to the Lake. (See Redfield, 1955; Belkis, 1986; Parra-Pardi, 1991) A table with the monthly hydrological balance for the years 1973 - 1983 is given in Appendix A.

### 2.5 Residence time

The residence time in the system is very long, because of the very large dimensions and the small velocities. With a volume of 280 km<sup>3</sup> and an annual outflow of 40 km<sup>3</sup>/year it takes at least 7 years before all the water in the Lake has been refreshed. The outflowing water is mainly descended from the fresh upper layers, and because of the small exchange between the upper layers and the more saline under layers the actual residence times can be much longer.

### 2.6 Salinity

A lot of measurement campaigns were held in the past decades in which hydrodynamic and water quality data was collected. From the analyses of Redfield (1955,1961), Rodríguez (1973), Sutton (1974) and Parra-Pardi (1977 until 1986) a global view of salinity distribution and penetration is derived.

To understand the water quality processes in the Lake it is very important to know the salinity distribution in the system, and which processes influence this distribution.

### 2.6.1 Stratification

Tablazo Bay and the Strait of Maracaibo are partially mixed due to the sea water intrusion, but Lake Maracaibo itself has a two-layered stratification. In the fresh upper layer, the so called *epilimnion*, the salinity is low and doesn't vary much with position and depth. In the lower layer, the *hypolimnion*, the water is considerably more saline, and the salinity also varies more with place and depth.

The entire Lake can be characterized as a water body with low salinity percentages. The epilimnion has an averaged salinity value of 2 to 5‰. The hypolimnion has a value of around 10‰ but in certain conditions a salinity of 20 to 25‰ can occur at the bottom. The epilimnion contains normally 75 to 90 % of the total volume of the Lake. The almost uniform salinity distribution in the epilimnion makes clear that the fresh river discharges and the more saline Lake water are mixing well as a result of turbulence caused by (wind) waves and the currents.

As mentioned before the actual amount of salt that enters the Lake is mainly determined by the hydrological balance of the Lake, but also depends on the tide (neap/spring) and the wind. The exchange of water and salt at the outlet of the Lake depends on the balance between the non-tidal flow of water escaping from the Lake as a hydraulic current and the action of tidal currents which mix the sea water and the Lake water in Tablazo Bay. During the greater part of the year the outflow from the Lake is sufficient to prevent the penetration of salt water across Tablazo Bay, and the Strait is filled with typical Lake water (low salinity). During the dry season the flow slackens and the salt water works across Tablazo Bay to sink into the deeper layers of the Strait, from where some of it flows into the Lake basin to contribute to the hypolimnion.

### 2.6.2 Salinity cone

A very special physical feature in the Lake is the formation of a very consistent hypolimnetic cone, with its base in the central area of the lake bottom and its apex in a variable point near the centre of the lake, at 5 to 15 meters. Driven by the wind the anti-clockwise rotation of the water in the Lake generates this salinity cone, and as a result of these currents the hypolimnion comes closer to the surface of the water, Figure (2.6)

As mentioned before the total volume of the hypolimnion and thus the salinity cone varies throughout the year, Figure (2.7). In the dry season the hypolimnion has a larger volume than in the wet season, due to the higher intrusion of saline water from the Gulf. Not only the season but also the input of fresh water from the tributaries plays an important role in this process. The influence of the river Catatumbo is very important and can be recognized in the large scale turbulence effects in the measurements, Figure (2.8).

Erosion of the cone is caused by turbulent interaction between the epilimnion and the hypolimnion. Only by mixing up the salt is it possible to remove salt from the Lake, Figure (2.9). As a consequence it is easier to transport salt into the Lake than out of it.

From observations it is known that sometimes the salinity cone completely disappears. Most likely this is an effect of very strong wind which mix the epilimnion and the hypolimnion. (Parra-Pardi, 1983)

## 2.7 Water quality problems

Like many places in the world the pollution of the surface water in the Maracaibo system is increasing. Pollution can lead to a situation in which it is no longer possible for the Lake to fulfil its essential functions. The regional developments may be adversely influenced because of the poor water quality in the Lake.

Water quality problems of the Lake are concerned with salt intrusion, anoxic conditions in the hypolimnion, release of nutrients from the bottom sediments, excessive algae blooms, oxygen deficit that may result from decay of algal material and local bacterial pollution may play a role.

### 2.7.1 Salt intrusion

Due to the fact that Lake Maracaibo is connected with the Gulf of Venezuela by the Tablazo Bay and Maracaibo Strait an exchange between the fresh water of the Lake and the saline water of the Gulf takes place. Of course this is no pollution, but a certain equilibrium state exists. In case that through human interference the salt penetration into the Lake increases and the equilibrium is disturbed than one can conceive this as a form of pollution.

As a result of a larger salt intrusion the hypolimnion become more saline, and the relative density differences between the epilimnion and the hypolimnion become larger leading to less exchange between the epilimnion and the hypolimnion.

Increased salinity levels result in changes in the ecological system of the Lake.

### 2.7.2 Eutrophication

The most important problem in Lake Maracaibo is the eutrophication of the water, see Parra-Pardi (1983).

The suspended organic and anorganic matter in the water column may be trapped in the salt water layer and settle out on the bottom where it will decompose using oxygen. Due to this oxygen demand the hypolimnion will suffer reduced oxygen contents and this may accelerate the release of phosphorus and ammonia from the sediments, which can be used as algal nutrients in the water column: eutrophication.

The circulation in the Lake may transport nutrients to the areas in the Lake with lower flow rates, where algal blooms can arise. Especially in the North-Eastern part of the Lake algae blooms are observed. Blue green algae blooms are unaesthetic, cause a high turbidity, green colour and high pH of the water which can be very detrimental to the recreational use of the water. Especially, blue greens can produce toxics leading to skin and eye irritation by swimmers whereas the water becomes unsuitable as potable water for cattle.

The sudden decay of algal material and the possible mixing of the stratified system at increased wind velocities may seriously effect the oxygen content as well as the conditions for the flora and fauna in the Lake as a whole.

### 2.7.3 Floating debris and oil pollution

As a result of the large production of oil in the Lake and the highly frequent ship movements other regular forms of pollution include visual pollution by floating debris and pollution resulting from spills of oil and other substances.

All forms of pollution mentioned above are perceived as problems for the ecological system of the Lake, and can damage it seriously. It is necessary to stop the pollution of the Lake to preserve the Lake for nature, and assure that it is possible for the Lake to fulfil its (ecological) functions.

It is clear that for modelling the water quality in the Lake it is necessary to know the salinity distribution, the stratification and the tidal dynamics. Only then is it possible to make reliable simulations of the water quality.

## 3 Simulations with TRISULA

### 3.1 Numerical model for Lake Maracaibo

In 1993 a three dimensional numerical hydrodynamic model of the Lake Maracaibo system was developed by Bijlsma (1993) using TRISULA, DELFT HYDRAULICS' simulation program for hydrodynamics in two and three dimensions. See TRISULA User Manual, 1994, and Appendix B.

The numerical model covers the Maracaibo system, including the Lake, the Strait, the Bay and the south-western part of the Gulf, and has been developed to simulate:

- the water movement due to tide, wind fields, and density gradients,
- the transport of saline and fresh water through the system,
- the stratification of the salinity in the system.

The next sections describe the numerical model as it was developed by Bijlsma (1993).

#### 3.1.1 Schematization

The model employs a curvilinear orthogonal coordinate grid, which is defined in UTM with geodetic reference spheroid of Hayford, Figure (3.1). The model covers an area of 120 km by 300 km in east-west respectively north-south direction. The model comprises a grid of 16 by 64 grid cells with 576 active computational grid points, and with 13 non-equidistant layers.

The grid has been designed to provide an efficient coverage of the area with a relatively small number of computational points. The grid cells have a high resolution in the Strait (approximately 0.5 by 1.5 km) and become coarser towards the Lake and the open boundary (about 10 by 10 km). Some details of the model layout, like tidal inlets, islands and headlands were schematized by definition of dry cells and so-called thin dams. The open sea boundary is situated in the Gulf of Venezuela.

A time integration step of 2.5 minutes was selected on the basis of a maximum Courant Number of 6 in the Strait. This ensures accurate computations in a numerical sense.

#### 3.1.2 Boundary conditions

The tidal dynamics in the numerical model are generated by prescription of the tidal water levels at the open boundary. The water levels are predicted on the basis of the nine most relevant tidal constituents (e.g.  $M_2$ ,  $S_2$ ,  $O_1$ ,  $K_1$ ). The used boundary condition was based on information of tidal constants.

During the simulations the salinity at the sea boundary was described with a constant value of 33‰, the salinity of the attributes (fresh river water) was defined as 0‰.

### 3.1.3 Parameter settings

In the numerical model the water temperature is set at 27°C, and the acceleration of gravity at 9.813 m/s<sup>2</sup>. The coriolis parameter is set at a value belonging to the latitude of 10°50'N,  $2.74 \cdot 10^{-5} \text{ s}^{-1}$ .

A value of 0.01 m<sup>2</sup>/s is used for both the uniform horizontal eddy viscosity and diffusivity. For the calculation of the vertical eddy viscosities and diffusivities the algebraic turbulence closure model is used.

The bottom roughness is modelled with the Manning's formula, a uniform value of 0.026 for the Manning's friction coefficient is used. In the computation of the wind shear stresses at the water surface, the density of the air is taken equal to 1.2 kg/m<sup>3</sup> and the drag coefficient is equal to  $1.0 \cdot 10^{-3}$ .

### 3.1.4 Calibration

The model has been calibrated in two steps. First the calibration was performed for the tidal dynamics only. Secondly, the calibration was performed for the stratification and salt transport.

- After the calibration for the tide the model reproduced the tidal dynamics in the system in a very satisfying way.
- The salinity distribution and transport was calibrated for dry and wet conditions. Although the results for both conditions showed general agreement with the salinity distributions observed during the measurements campaign in December 1992 and March/April 1993 they were not completely satisfying.

In the next section these difference will be discussed.

## 3.2 Salt transport and salinity distribution

As mentioned before, the calibration of the model for stratification and salt transport was not completely satisfying. The two major differences are:

- Compared with observations of the stratification in the Strait it is mixed too highly in the vertical, see Fig. (3.2). This is a result of the turbulence closure model selected.
- The salt transport towards and out of the Lake is too small. The transport from and to the Lake is at least a factor 5 too low, compared with observations. Fig. (3.3).

The salinity cone in the Lake itself is very well reproduced by the model, nevertheless it is very interesting to investigate the behaviour of the salinity distribution in the Lake under different wind-conditions.

To improve the numerical model described above further investigations were carried out to the salt transport. Two parameters were examined, the windfield and the turbulence closure models.

### 3.2.1 Windfield

A *uniform* windfield (5 m/s, NNE) could not generate the generally observed current pattern of the Lake. The uniform windfield introduced two large circulation cells in the Lake instead of one. To reproduce the counter-clockwise rotation of the currents it turned out that a *non-uniform* windfield was necessary.

A schematized windfield with a value of 5 m/s was prepared that met the observations with respect to the spatial variation of the wind (see Parra-Pardi, 1983). In Figure (3.4) this windfield is shown, and this windfield did indeed reproduce the counter-clockwise rotation with reasonable velocities. After about 20 days of computation this current pattern introduced the salinity cone in the Lake.

To investigate the influence of the windspeed and direction on the salinity distribution in the Lake several simulations with higher and lower windspeed, and with slightly different wind-directions have been made. Lower windspeed showed no better results, the salinity cone was less explicit. Higher windspeed caused the salinity cone to mix up, and if the windspeed is too high, e.g. 15 m/s, the salinity cone completely disappears because of the turbulent mixing.

A remark related to the windfield has to be made. The windfield defined above has to be treated as a sort of 'background' wind. This windfield is only defined to generate the observed currents in the Lake and it is assumed constant throughout the entire simulations. It is evident that this windfield has very little to do with the actual wind above the Lake, and it is also clear that the actual wind can disturb the salinity distribution, and can even force the salinity cone to disappear (Parra-Pardi, 1983).

### 3.2.2 Turbulence closure model

#### Description

Because of the 3-dimensional sub-grid turbulence effects in TRISULA it is necessary to use a *turbulence closure model* for solving the hydrodynamic flow equations. A turbulence closure model is used to calculate the vertical eddy viscosities and only then is the system of equations complete and can it be solved.

When the Maracaibo model was developed in 1993 only one turbulence closure model was available in TRISULA. Nowadays in TRISULA three turbulence closure models are implemented, all based on the so-called eddy viscosity concept of Kolmogorov (1942) and Prandtl (1945). The eddy viscosity has the following form:

$$\nu_V = c_\mu' L \sqrt{k} \quad (3.1)$$

where

- $c_\mu'$  a constant determined by calibration, derived from the constant  $c_\mu$  in the  $k$ - $\epsilon$  model;  $c_\mu' = c_\mu^{1/4} \approx 0.5477$ ,
- $L$  is the mixing length, and
- $k$  the turbulent kinetic energy.

The turbulence closure models differ in their prescription of the turbulent kinetic energy  $k$ , the dissipation of energy  $\epsilon$ , and/or the mixing length  $L$ .

The *first* turbulence closure model, the algebraic model, is a combination of two zero order closure schemes. The schemes use algebraic/analytical formulas to determine  $k$  and  $L$ .  $k$  depends on the (friction) velocities or velocity gradients and for the mixing length  $L$  the following function of the depth is taken (Bakhmetev, 1932).

$$L = \kappa(z+d) \sqrt{1 - \frac{z+d}{H}} \quad (3.2)$$

Parameter  $\kappa$  is Von Kármán's constant,  $\kappa \approx 0.41$ .

In case of vertical density gradients, the turbulent exchanges are limited by buoyancy forces and the mixing length  $L$  of Eq.(3.3.22) must be corrected. This correction involves a so-called damping function  $F_L(\cdot)$  which depends on the gradient Richardson number  $Ri$  (Simonin et. al., 1989).

$$L = \kappa(z+d) \sqrt{1 - \frac{z+d}{H}} F_L(Ri) \quad (3.3)$$

The gradient Richardson number,  $Ri$  is defined by:

$$Ri := -\frac{g}{\rho} \frac{\frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \quad (3.4)$$

See e.g. Richardson (1920), Taylor (1931) and Miles (1987).

For stable stratifications the Richardson number is positive and the mixing length must be decreased. For unstable stratification  $Ri < 0$ , the buoyancy forces destabilize and enhance vertical exchanges. As a result the mixing length must be increased.

$$F_L(Ri) = \begin{cases} \exp(-2.3 Ri) & ; Ri \geq 0 \\ (1 - 14 Ri)^{0.25} & ; Ri < 0 \end{cases} \quad (3.5)$$

The *second* model is a first order turbulence closure scheme. The mixing length  $L$  is prescribed analytically and the same formulation, including damping functions, is used as for the algebraic turbulence model. However, to find the kinetic energy  $k$ , a transport equation is solved. This turbulence closure model is known as the  $k$ - $L$  model.

The *third* model is the  $k$ - $\epsilon$  model which is a second order turbulence closure model. In this model both the turbulent energy  $k$  and dissipation  $\epsilon$  are calculated by a transport equation. From  $k$  and  $\epsilon$  the mixing length  $L$  and viscosity  $\nu_t$  are determined. The mixing length is now a property of the flow, and in the case of stratification no damping functions are used.

For a more detailed description of the turbulence closure models is referred to the TRISULA Users Manual (1994) and to Uittenboogaard et al. (1992).

## Comparison

To make a choice between the turbulence closure models several simulations were made with the algebraic and  $k-\epsilon$  turbulence closure model.

Only these two turbulence closure models were compared with observations because the algebraic model was used by Bijlsma (1993), and the  $k-\epsilon$  turbulence model is known to give in general better results than the  $k-L$  turbulence model.

Compared with measurements it is obvious that the  $k-\epsilon$  turbulence closure model shows better agreement than the algebraic turbulence model, Figure (3.5). In the Strait of Maracaibo the stratification is much better with  $k-\epsilon$ . In the Lake itself the differences are less obvious. Together with the windfield both models reproduce the salinity cone.

Also the salt transport to and from the Lake is better with the  $k-\epsilon$  turbulence model. The amount of transport agrees much better with the transport observed.

## 3.3 Time-scales

From all the simulations made it became evident that in the system three different independent time-scales are present, one for the tidal dynamics, one for the salinity distribution and one for the total salinity contents in the Lake. These time-scales are prescribed below.

### 3.3.1 Tidal dynamics

The tidal dynamics in the system is characterized by the predominant  $M_2$  constituent. This means that the main tidal period in the system is about 12h25'.

The influence of the tide on the salinity distribution is mainly concentrated in the Strait of Maracaibo, and not in the Lake. The salinity stratification here, a kind of salt wedge, moves with the ebb and flood further north or further south in the Strait.

The spin-up time for the numerical solution of the tide is illustrated in Fig. (3.6). It is clear that the spin-up time covers about 10 days. For the salinity stratification in the Strait the spin-up time covers a little bit more time, approximately 20 days.

### 3.3.2 Salinity distribution in Lake

While the salinity distribution in the Strait mainly changes with the tide, the salinity distribution in the Lake itself varies mainly with the season and the wind. The salinity cone in the Lake is generated by the windfield, and a changes in the wind causes different distributions. It is a process of a few days to disturb and to recover the stationary salinity distribution in the Lake.

The numerical spin-up time for the salt cone in the Lake is about 20 to 30 days.

### 3.3.3 Salt content in the Lake

Some simulations carried out for over a year show that the salinity intrusion from the Gulf to the Lake is a process on a time-scale of years. Even with very high advective and gradient transports the total amount of salt that enters and leaves the Lake is very low.

This process of years agrees with the idea that the Lake will never be in a stationary situation. It takes too much time before a stationary state can be reached, the system responds very slow on changing conditions like the discharges, rainfall and evaporation. The system is always on its way to a stationary situation but before it reaches this state, the conditions have changed.

Nevertheless it turned out that the *salt transport* becomes more or less stationary after 35 days of simulation. The transport per second, the *salinity flux*, is not really stationary because the flux varies with the total salinity contents of the Lake and with the discharges but it is a feature worth taking a look at.

So in the next chapter we will take a closer look at the behaviour of the salinity fluxes under influence of changing hydrological circumstances, and the assumption of the 'stationary' fluxes will be well illustrated. With the assumption of 'stationary' fluxes it is interesting to see whether or not it is possible to predict the total salinity in the Lake without using TRISULA for long-term simulations.

## 4 Salinity flux

### 4.1 Purpose of the simulations

Earlier long term simulations showed that the salinity flux becomes constant after 35 days of computation. In figure (4.1a) one can see that the total salinity in the Lake shows a constant increasing level. Besides the tidal fluctuations it looks like that the total salinity contents in the Lake increases with a constant in the time. In Figure (4.1b) total salinity flux is presented, in kg/s. After averaging over one tidal cycle the salinity flux looks like Figure (4.1c). For this simulation it is clear that you can make the assumption that the salinity flux is constant after 35 days of computation.

The following remark has to be made: although we assume that the salinity flux is a 'stationary' flux it is obvious that this cannot be true.

Only in the case that a long-term simulation with constant hydrological circumstances is made - that means with constant discharges, evaporation and precipitation - will a real stationary salinity flux be reached. Only when the water in the Lake is completely fresh or completely saline is the salinity flux constant in time with a value of 0 kg/s.

In this chapter it is described how the assumed 'stationary' salinity flux reacts on different hydrological conditions and different amounts of total salinity in the Lake.

### 4.2 Simulation framework

For the further simulations we start with the following remarks:

- all simulations are made with a very fast research version of TRISULA. This means besides minor differences that the advection is calculated with the Van Leer scheme.
- because of less computational efforts 8 layers are used.
- the  $k-\epsilon$  turbulence model is used.
- the horizontal dispersion coefficients are constant with a value of  $0.01 \text{ m}^2/\text{s}$ .
- the background vertical viscosity is  $5 \cdot 10^{-4} \text{ m}^2/\text{s}$ , so uncoupling of horizontal computational layers will not take place.
- the windfield with a value of  $5 \text{ m/s}$ , is used.
- because of the disturbing effects of the day to day variations in tidal boundary conditions a characteristic fourier tidal boundary condition is used. A single  $M_2$ -tidal wave with a period of 12h25' and an amplitude of 0.45 m is used.
- for the dry and the wet conditions the values of Bijlsma are used. See Appendix C and the next section.
- all other definitions and parameters, like grid, bathymetry, time-step, background temperature, boundary conditions for salinity etc. are all the same as mentioned in section 3.3.1, 3.3.2 and 3.3.3.

### 4.3 Simulations

Several simulations have been made to investigate the behaviour of the salinity flux in the model. As said before the purpose was to discover in what way the flux would respond on the changing of the discharges and the total salinity in the Lake. To investigate this response the hydrological conditions and the initial conditions - this is the total amount of salinity in the Lake - have been varied.

For reaching a 'stationary' salinity flux it is necessary to make computations of 70 days, 40,320 time-steps. During the simulations the hydrological conditions were not changed, and each hydrological state represented another month.

#### 4.3.1 Initial conditions

Three different initial conditions has been defined for the simulations. These initial conditions varied from a very high total salt content, a normal and a very low salt content in the Lake. The normal salt content is of the same order as that of the observations. See Appendix C for a more detailed description of the spatial distribution of the initial salinity condition.

#### 4.3.2 Discharges

For the discharges - including the river discharges, the precipitation and the evaporation - the values for the dry and the wet condition defined by Bijlsma (1993) were used. The values for the minimum and maximum discharges were interpolated with a sine-function to obtain five values in between. These seven hydrological states represented the 12 months of the year. In Appendix C a more detailed description is given for the discharges, evaporation and precipitation.

#### 4.3.3 Salinity fluxes

The salinity flux is calculated from the total salinity in the Lake, and the Lake has been defined as the area covered by  $(M,N) = (1,16;1,23)$ , see Fig. (4.2). The flux itself has been defined as :

$$F_t = \frac{Z_t - Z_{t-1}}{\Delta t} \quad (4.1)$$

where

|            |                                               |
|------------|-----------------------------------------------|
| $F_t$      | salinity flux in [kg/s] at time-step $t$      |
| $Z_t$      | total salinity in the Lake at time $t$ , [kg] |
| $\Delta t$ | time increment ( $t - \{t-1\}$ ), in [s]      |

To eliminate the influence of the tide, the salinity fluxes are averaged over the last 12h25', thus over the last 298 time-steps.

To find the average flux belonging by the initial conditions and hydrological state the salinity flux has been averaged over a period of 35 days, from day 35 till day 70. The flux obtained is used for further investigations.

With the three initial salinity conditions and the seven different hydrological conditions twenty-one simulations have been made.

## 4.4 Results

In general the spatial distribution of the salinity in the Lake agrees with the observations, the stratification in the Strait and the Lake are present and the salinity cone is very clear to see.

The simulations all showed all a good result for the tidal dynamics, the differences between the tidal movements for the different initial conditions are not very large.

In Figure (4.3) the total salinity in Lake Maracaibo is represented for the first initial condition and the seven hydrological states. The influence of the tide is obvious. In Figure (4.4) the averaged total salinity in the Lake is represented for each of the initial conditions. Figure (4.5) shows the twenty-one simulations in one picture, the similarity is clear.

In Figure (4.6) the salinity flux is given, and also here the similarity is clear. For each March - the dry season - there is a salinity flux from the Gulf to the Lake, and for each September - wet - there is a flux from the Lake to the Gulf. The months in between vary with the season.

It appears that each combination of initial condition and hydrological state has its own 'stationary' salinity flux. In Fig. (4.7) the averaged 'stationary' salinity fluxes for all simulations are given as functions of the discharges  $Q$  ( $\text{m}^3/\text{s}$ ) and the total salinity in the Lake  $Z$  (kg).

By interpolation in Fig. (4.7) it is possible to obtain salinity fluxes for every hydrological state and total salinity in the Lake. In the next chapter we will try to simulate the total salinity in the Lake by using Figure (4.7).

## 5 Box-model approach

Because of the very large computational times for long term simulations it is very attractive to use a simple and fast box-model for simulating the total salinity in Lake Maracaibo. If you are capable of doing, it is possible to make a lot of simulations for different hydrological scenarios, and you can answer the questions asked in chapter 1.

By using the information obtained from the TRISULA simulations it should be possible to give a good description of the salinity fluxes in the system and thus of the total salinity.

In this chapter this box-model approach is described.

### 5.1 Box-model

#### 5.1.1 Differential equation

To describe the total salinity in Lake Maracaibo the following Equation is used:

$$Z = \sum_{t=0}^{t_{end}} F(Q,Z,t) \Delta t \quad (5.1)$$

where

|            |                                                                                                              |
|------------|--------------------------------------------------------------------------------------------------------------|
| Z          | total salinity in the Lake, in [kg]                                                                          |
| F          | instantaneous salinity flux, dependent on time, discharges Q and the total salinity in the Lake Z, in [kg/s] |
| $\Delta t$ | time increment, in [s]                                                                                       |

The salinity flux F is described by the differential equation:

$$T(Q,Z) \frac{dF}{dt} + F = F_{stat}(Q,Z) \quad (5.2)$$

where

|            |                                                                                        |
|------------|----------------------------------------------------------------------------------------|
| T          | relaxation time, dependent from Q and Z, in [s]                                        |
| $F_{stat}$ | 'stationary' salinity flux, obtained from Figure (4.7), and also dependant of Q and Z. |

This differential equation has been discretized as:

$$T(Q,Z) \frac{F^{t+1} - F^t}{\Delta t} + F^t = F_{stat}(Q,Z) \quad (5.3)$$

Together with the data obtained from the simulations in chapter 4 a program has been written to calculate the flux and the total salinity.

### 5.1.2 Relaxation time

Because of the spin-up time in the Maracaibo system it takes some time before the salinity flux becomes 'stationary' and the first time the flux is time-dependant. In Eqs. 5.2 and 5.3 the relaxation time determines how long it takes before the momentary salinity flux becomes stationary. The relaxation time is most likely dependent on the total salinity in the Lake and on the hydrological conditions.

To find out the relations between the relaxation times and its dependence upon the discharges and the total salinity in the Lake, the box-model was calibrated for the simulations made in chapter 4.

The results of the calibration are given in the Figures (5.1, 5.2, 5.3 and 5.4), and as one can see the box-model represents the total salinity in the Lake for all the different conditions very well. The results of the calibration were used in the simulations.

## 5.2 Simulations

### 5.2.1 Simulations with box-model

The box-model is used to simulate the total salinity in the Lake for five different scenarios. Each scenario represented a different hydrological state, like a very dry year, a very wet year and some years in between.

In every scenario there is an obvious seasonal change of the hydrological conditions present, and the conditions were assumed constant during each month. In Appendix D these scenarios are described in more detail.

### 5.2.2 Simulations with TRISULA

For the verification of the simulations made with the box-model some TRISULA simulations have been made with the same hydrological scenarios. All these simulations also lasted thirteen months. See Appendix D for more details.

## 5.3 Results and conclusions

In Figure (5.5a) the total salinity in the Lake is shown for the TRISULA simulations, the total salinity is averaged over one tidal cycle of 12h25'. The simulations with the box-model are shown in Figure (5.5b). Although the simulations with the box-model and with TRISULA do seem to agree reasonably for the first 6 or 7 months, the results become worse in the following period, Figure (5.6).

Examining the salinity fluxes it is clear that the fluxes are not the same at all, Figure (5.7). Although the forms of the curves are similar, the figure shows that the values of the fluxes are truly different. Apparently the TRISULA simulations with changing hydrological conditions do responds different then the TRISULA simulations with constant conditions (represented by the box-model).

Another reason for the worse results is the fact that the system is non-convergent. The differences between the results of the box-model and the TRISULA results grow during the simulation. If the salinity flux used is too high then this will lead to a salt content in the Lake that is also too high. Because of this, in the next time-step the salinity flux that will be used is too high again. The system doesn't converge to the solution wanted.

So the results of the box-model are less accurate when compared with the TRISULA results. Evidently the Maracaibo system is much too complex to be described with the simple box-model. With this box-model it is not possible to give a good prediction of the total salinity in Lake Maracaibo.

## 6 Conclusions and recommendations

### Conclusions

Although the policy-questions mentioned in the introduction about changes in the river discharges are not really answered in the thesis the following conclusions about (the modelling of) Lake Maracaibo were reached:

- In the Maracaibo system three different time-scales are present. One of the tide, 12h25', one of the influence of the windfield, a few days, and one for the transport of the salt in the system, and this is a process of years.
- The TRISULA model of Lake Maracaibo, the Strait of Maracaibo, Tablazo Bay and the Gulf of Venezuela reproduces the tidal dynamics - waterlevels and currents - in a very satisfying way, as long as an anti-clockwise windfield is used for producing the anti-clockwise rotation of the waterbody in the Lake itself.
- With the parameter settings used (e.g.  $k-\epsilon$  turbulence closure model) the TRISULA model is able to simulate the salinity distribution and transport in the system very well, the results however are very much dependent on available observations, and with little data it is hard to calibrate the model for the salinity.
- Because of the very different time-scales the tidal dynamics and the wind-driven salinity distribution in the Lake are simulated within a simulation time of a month with a small time-step (2.5 minutes). The simulation of the long-term salt transport however, has to last at least a few years, and with a small time-step this requires high computational effort.
- A box-model was used to reduce the computational efforts. Unfortunately the box-model, that simulated the total salinity in the Lake, was not capable of describing the complex salt transport to and from the Lake. Nevertheless using a slightly more sophisticated box-model seems to be very attractive.

In general this study has increased our knowledge of the behaviour of the Maracaibo system, as far as salt transport, stratification and the influence of several related parameters are concerned.

## Recommendations

- For the simulation of the salinity distribution in the Lake it is highly recommended to use more layers in the vertical and to decrease the horizontal size of the gridcells. With only 8 layers and the very coarse grid used the salinity cone is reproduced, but undoubtedly the results will improve whenever a more refined grid in the horizontal and vertical direction is used.
- Although the simulations with the box-model failed, the box-model approach is still very attractive to simulate the long term variations in the salt content in the Lake instead of using TRISULA. Maybe a somewhat more sophisticated box-model is capable of describing salt transports in the Maracaibo system.
- For examining 3-dimensional simulations the use of animations and a 3D visualization program are very well recommended. These are very effective tools in analyzing the results of the simulations.

In the near future estuaries and other systems with small tidal influences and large interaction between fresh and saline waterbodies are threatened in their ecological functions if nothing is undertaken to stop the process of pollution. Because of this much attention has to be paid on the modelling of these weak-dynamic systems, in order to help to try to solve the problem of environmental pollution.

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# A Hydrological balance

Discharges in m<sup>3</sup>/s

HYDROLOGICAL BALANCE per month, from : Belkis et al., 1986.

|      | Jan. | Feb. | Mar. | Apr. | May  | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | sum   |
|------|------|------|------|------|------|------|------|------|------|------|------|------|-------|
| 1973 | -492 | -576 | -515 | 198  | 263  | 1215 | 930  | 2029 | 3063 | 3139 | 4644 | 3355 | 17253 |
| 1974 | 2052 | 1716 | 1578 | 1960 | 2612 | 1575 | 1254 | 1397 | 2650 | 3109 | 3958 | 1819 | 25680 |
| 1975 | 914  | 399  | 562  | 725  | 1195 | 1015 | 1677 | 2032 | 3056 | 3594 | 3884 | 4964 | 24017 |
| 1976 | 2541 | 2435 | 2142 | 1886 | 2037 | 1953 | 1840 | 1214 | 1340 | 2703 | 1950 | 924  | 22965 |
| 1977 | 395  | -154 | -77  | 53   | 1322 | 1287 | 999  | 1224 | 1431 | 2125 | 2014 | 541  | 11160 |
| 1978 | 50   | -163 | 658  | 2730 | 2232 | 2170 | 1982 | 1771 | 1708 | 2462 | 2008 | 1609 | 19217 |
| 1979 | 391  | 11   | 903  | 1862 | 2390 | 3324 | 2337 | 2129 | 2868 | 3457 | 3549 | 2643 | 25864 |
| 1980 | 1289 | 633  | -86  | 136  | 1078 | 909  | 710  | 1411 | 1616 | 1640 | 1637 | 1188 | 12161 |
| 1981 | 612  | 1011 | 544  | 3855 | 4572 | 4292 | 3031 | 3158 | 3268 | 3251 | 2980 | 2157 | 32731 |
| 1982 | 1310 | 1452 | 970  | 2929 | 3569 | 2500 | 1985 | 1176 | 1842 | 2643 | 1728 | 1407 | 23511 |
| 1983 | 570  | -84  | -266 | 1663 | 2494 | 1967 | 1713 | 1657 | 1560 | 1971 | 1272 | 915  | 15432 |
| avg. | 876  | 607  | 583  | 1636 | 2160 | 2019 | 1678 | 1745 | 2218 | 2736 | 2693 | 1957 | 20908 |

## **B Conceptual description of TRISULA**

### **B.1 Introduction**

Reliable information on water quantity, water quality, sediment transport and morphology can be obtained from appropriate mathematical models. In general the first step in these modelling activities concerns the simulation of the flow itself. Whether the problem is related, for example, to the stability of a hydraulic structure, to salt intrusion, to the dispersion of pollutants or to the transport of silt and sediment, flow simulations usually form the basis of the investigations carried out.

At DELFT HYDRAULICS the program package TRISULA is available to provide the hydrodynamic basis for the water quality and morphological computations. For the steady and non-steady modelling of the far-field water quality, TRISULA is coupled with the DELFT HYDRAULICS' water quality program DELWAQ. Non-steady modelling of the mid-field water quality is performed by coupling TRISULA to DELFT HYDRAULICS' program DELPAR. For the interaction between waves and currents TRISULA may be coupled with the short-waves package HISWA. The flow field generated by TRISULA may also be used as input for morphological models or sediment transport models.

This appendix gives some background information on the conceptual model of TRISULA. For a description of the numerical algorithms of TRISULA see the TRISULA User Manual (1994).

### **B.2 General background information**

#### **B.2.1 Range of applications of TRISULA**

The multi-dimensional hydrodynamic program package TRISULA calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing. The main purpose of TRISULA is the two-dimensional (2D, depth averaged) and three-dimensional (3D) simulation of tidal and wind driven flow, including the effect of density differences due to a non-uniform temperature and salinity concentration distribution (density driven flow) in shallow seas, coastal areas, estuaries, rivers and lakes. It aims to model flow phenomena of which the horizontal length scales are significantly larger than the vertical length scale.

Three-dimensional simulations are of particular interest in transport problems where the flow field shows significant variations in the vertical direction. This variation may be generated by wind forcing, bed stress, Coriolis force, topography or stratification. Examples are the dispersion of waste or cooling water in lakes and coastal areas, the upwelling and downwelling of nutrients, the salt intrusion in estuaries, the fresh water river discharges in bays and the thermal stratification in lakes and seas.

### B.2.2 Physical aspects

The multi-dimensional hydrodynamic program package TRISULA solves the unsteady shallow water equations in two (depth-averaged) or in three dimensions. The system of equations consists of the horizontal momentum equations, the continuity equation and transport equations. The equations are formulated either in a Cartesian frame of reference or in spherical coordinates on the globe. In a Cartesian frame of reference the surface level and bed topography are related to a flat horizontal plane, whereas in spherical coordinates the reference plane has Earth's curvature.

The transport of salt and heat can be modelled by a conservative transport equation. Source and sink terms are included to model discharges and withdrawals.

The TRISULA model includes formulations and equations that take into account:

- tidal forcing;
- free surface gradients (barotropic effects);
- the effect of the Earth's rotation (Coriolis force);
- water with variable density (equation of state);
- horizontal density gradients in pressure (baroclinic effects);
- turbulence induced mass and momentum fluxes (turbulence closure models);
- wind shear stress on the water surface;
- bed shear stress on the bottom;
- influence of waves on the bed shear stress (2D only);
- variable atmospheric pressure on the water surface;
- wave induced stresses and mass fluxes (2D only);
- effect of secondary flow (spiral motion intensity) on depth-averaged momentum equations;
- discharge and withdrawal of mass;
- transport of salt, heat and other conservative constituents;
- drying and flooding of tidal flats.

### B.2.3 Assumptions with respect to TRISULA

In TRISULA the flow is modelled by the 2D or 3D shallow-water equations. The following assumptions and approximations are used in formulating these equations:

- The shallow-water assumption: the vertical momentum equation is reduced to the hydrostatic pressure relation. Vertical accelerations are assumed to be small compared with the gravitational acceleration and are not taken into account.
- The fluid (water) is assumed to be incompressible.
- The effect of variable density is only taken into account in the horizontal pressure gradient term (Boussinesq approximation).
- The immediate effect of buoyancy on vertical acceleration is not considered. In TRISULA density differences are taken into account in the horizontal pressure gradients and in the vertical exchange coefficients. So the application of TRISULA is restricted to mid- and far-field dispersion simulations.
- There is no dynamic coupling between changes in topography and flow.

- In a Cartesian frame of reference the effect of the Earth's curvature cannot be taken into account.
- In a Cartesian frame of reference the Coriolis parameter is assumed to be uniform. In spherical coordinates the inertial frequency is dependent of the latitude.
- The gravitational acceleration is taken uniformly, hence the tidal forces are applied only through the boundary conditions.
- The momentum of discharges is neglected.
- The bed stress formulation for combined waves and currents is only sensitive in 2D.
- The total heat flux through the water surface is computed using a temperature excess model. The exchange coefficient is a function of temperature and wind speed and is determined according to (Sweers, 1976). The natural background temperature is assumed to be constant in space.
- In 3D computations the effect of 3D turbulence on the vertical exchange of momentum and mass is modelled through a vertical eddy viscosity and eddy diffusivity coefficient (eddy viscosity concept), by means of an algebraic, k-L or k- $\epsilon$  turbulence model.
- The horizontal viscosity terms are reduced to a biharmonic operator along coordinate lines.
- It is assumed that a velocity point is set dry when the actual waterdepth is below a user-specified threshold and is set wet when the waterdepth is above twice the threshold.
- A continuity cell is set dry when the four surrounding velocity points are dry or the actual waterdepth is below zero (negative volume).
- The tangential shear stress is zero (free slip) for all lateral boundaries.
- At the bed a slip boundary condition is assumed.

## C Discharges, evaporation and precipitation

The data used for the simulations originates from the hydrological balance of Belkis et al. (1986) and were also used by Bijlsma (1993).

To obtain an average seasonal fluctuation in the discharges the data is interpolated with a sine-function between the dry season (March) and the wet season (September). This results in seven characteristic hydrological states.

### C.1 Discharges: dry and wet season

|                 | M        | N        | dry<br>sea.                       | wet<br>sea. | $\frac{1}{2} \cdot \text{diff.}$ | mean   |
|-----------------|----------|----------|-----------------------------------|-------------|----------------------------------|--------|
| source:         | (-)      | (-)      | discharges in (m <sup>3</sup> /s) |             |                                  |        |
| Rio Limon       | 3        | 54       | 50                                | 500         | 225                              | 275    |
| Rio Palmar      | 4        | 17       | 10                                | 40          | 15                               | 25     |
| Rio Apon        | 2        | 11       | 5                                 | 20          | 7,5                              | 12,5   |
| Rio S. Ana      | 5        | 7        | 55                                | 450         | 197,5                            | 252,5  |
| Rio Catatumbo   | 7        | 6        | 280                               | 1000        | 360                              | 640    |
| Rio Escalante   | 7        | 4        | 25                                | 75          | 25                               | 50     |
| Rio Chama       | 10       | 2        | 30                                | 50          | 10                               | 40     |
| Rio Motatan     | 13       | 8        | 10                                | 60          | 25                               | 35     |
| Rio S. Pedro    | 13       | 10       | 5                                 | 20          | 7,5                              | 12,5   |
| Rio Machango    | 13       | 11       | 5                                 | 15          | 5                                | 10     |
| precip. - evap. | M = 1,16 | N = 1,30 | -690                              | 255         | 472,5                            | -217,5 |
| total           |          |          | -215                              | 2485        | 1350                             | 1135   |

## C.2 Interpolated discharges

River discharges and precipitation minus evaporation in the Maracaibo flow model.  
Data interpolated with sine-function between dry and wet season.

|                                 | March<br>dry sea. | April<br>February | May<br>January | June<br>December | July<br>November | August<br>October | September<br>wet sea. |
|---------------------------------|-------------------|-------------------|----------------|------------------|------------------|-------------------|-----------------------|
|                                 | X01               | X02, X12          | X03, X11       | X04, X10         | X05, X09         | X06, X08          | X07                   |
| discharges in m <sup>3</sup> /s |                   |                   |                |                  |                  |                   |                       |
| Rio Limon                       | 50.00             | 80.14             | 162.50         | 275.00           | 387.50           | 469.86            | 500.00                |
| Rio Palmar                      | 10.00             | 12.01             | 17.50          | 25.00            | 32.50            | 37.99             | 40.00                 |
| Rio Apon                        | 5.00              | 6.00              | 8.75           | 12.50            | 16.25            | 19.00             | 20.00                 |
| Rio S. Ana                      | 55.00             | 81.46             | 153.75         | 252.50           | 351.25           | 423.54            | 450.00                |
| Rio Catatumbo                   | 280.00            | 328.23            | 460.00         | 640.00           | 820.00           | 951.77            | 1000.00               |
| Rio Escalante                   | 25.00             | 28.35             | 37.50          | 50.00            | 62.50            | 71.65             | 75.00                 |
| Rio Chama                       | 30.00             | 31.34             | 35.00          | 40.00            | 45.00            | 48.66             | 50.00                 |
| Rio Motatan                     | 10.00             | 13.35             | 22.50          | 35.00            | 47.50            | 56.65             | 60.00                 |
| Rio S. Pedro                    | 5.00              | 6.00              | 8.75           | 12.50            | 16.25            | 19.00             | 20.00                 |
| Rio Machango                    | 5.00              | 5.67              | 7.50           | 10.00            | 12.50            | 14.33             | 15.00                 |
| precip. - evap.                 | -690.00           | -626.70           | -453.75        | -217.50          | 18.75            | 191.70            | 25.50                 |
| total                           | -215.00           | -34.15            | 460.00         | 1135.00          | 1810.00          | 2304.15           | 2485.00               |

### C.3 Precipitation minus evaporation

Precipitation minus evaporation above Lake Maracaibo.

Total (P-E) in (m<sup>3</sup>/s) and (P-E) in (m<sup>3</sup>/s/m)<sup>2</sup>

| Month              | Runid | Precipitation minus evaporation |                                         |
|--------------------|-------|---------------------------------|-----------------------------------------|
|                    |       | (m <sup>3</sup> /s)             | (m <sup>3</sup> /s per m <sup>2</sup> ) |
| January            | X11   | -4,53750e+02                    | -3,69306e-08                            |
| February           | X12   | -6,26700e+02                    | -5,10070e-08                            |
| March              | X01   | -6,90000e+02                    | -5,61590e-08                            |
| April              | X02   | -6,26700e+02                    | -5,10070e-08                            |
| May                | X03   | -4,53750e+02                    | -3,69306e-08                            |
| June               | X04   | -2,17500e+02                    | -1,77023e-08                            |
| July               | X05   | 1,87500e+01                     | 1,52606e-09                             |
| August             | X06   | 1,91700e+02                     | 1,56024e-08                             |
| September          | X07   | 2,55000e+02                     | 2,07544e-08                             |
| October            | X08   | 1,91700e+02                     | 1,56024e-08                             |
| November           | X09   | 1,87500e+01                     | 1,52606e-09                             |
| December           | X10   | -2,17500e+02                    | -1,77023e-08                            |
| Surface Lake (m2): |       |                                 | 12,28655e+09                            |

### C.4 Simulations

In order to investigate the response of the Maracaibo system on changes in the hydrological conditions (the discharges) and the initial salinity distribution several simulations have been made. In the table the river discharges minus evaporation and precipitation, the initial salinity distribution and the salt content for the simulations are given.

| Simulations, X-series |                                                                                                                                                                                                       |                              |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| identification        | initial salinity distribution                                                                                                                                                                         | river discharges (total)     |
| X01                   | $N < 26 : S = 3 \text{ ‰}$ , unless<br>depth > 25m then $S = 10 \text{ ‰}$<br>$25 < N < 53 : S = 10 \text{ ‰}$<br>$N > 52 : S = 33 \text{ ‰}$<br><br>salt content:<br>$967.0 \cdot 10^9 \text{ kg.}$  | in m <sup>3</sup> /s -215.00 |
| X02                   |                                                                                                                                                                                                       | -34.15                       |
| X03                   |                                                                                                                                                                                                       | 460.00                       |
| X04                   |                                                                                                                                                                                                       | 1135.00                      |
| X05                   |                                                                                                                                                                                                       | 1810.00                      |
| X06                   |                                                                                                                                                                                                       | 2304.15                      |
| X07                   |                                                                                                                                                                                                       | 2485.00                      |
| X08                   | $N < 26 : S = 6 \text{ ‰}$ , unless<br>depth > 25m then $S = 12 \text{ ‰}$<br>$25 < N < 53 : S = 12 \text{ ‰}$<br>$N > 52 : S = 33 \text{ ‰}$<br><br>salt content:<br>$1813.5 \cdot 10^9 \text{ kg.}$ | -215.00                      |
| X09                   |                                                                                                                                                                                                       | -34.15                       |
| X10                   |                                                                                                                                                                                                       | 460.00                       |
| X11                   |                                                                                                                                                                                                       | 1135.00                      |
| X12                   |                                                                                                                                                                                                       | 1810.00                      |
| X13                   |                                                                                                                                                                                                       | 2304.15                      |
| X14                   |                                                                                                                                                                                                       | 2485.00                      |
| X15                   | $N < 26 : S = 1.5 \text{ ‰}$ , unless<br>depth > 25m then $S = 8 \text{ ‰}$<br>$25 < N < 53 : S = 8 \text{ ‰}$<br>$N > 52 : S = 33 \text{ ‰}$<br><br>salt content:<br>$528.7 \cdot 10^9 \text{ kg.}$  | -215.00                      |
| X16                   |                                                                                                                                                                                                       | -34.15                       |
| X17                   |                                                                                                                                                                                                       | 460.00                       |
| X18                   |                                                                                                                                                                                                       | 1135.00                      |
| X19                   |                                                                                                                                                                                                       | 1810.00                      |
| X20                   |                                                                                                                                                                                                       | 2304.15                      |
| X21                   |                                                                                                                                                                                                       | 2485.00                      |

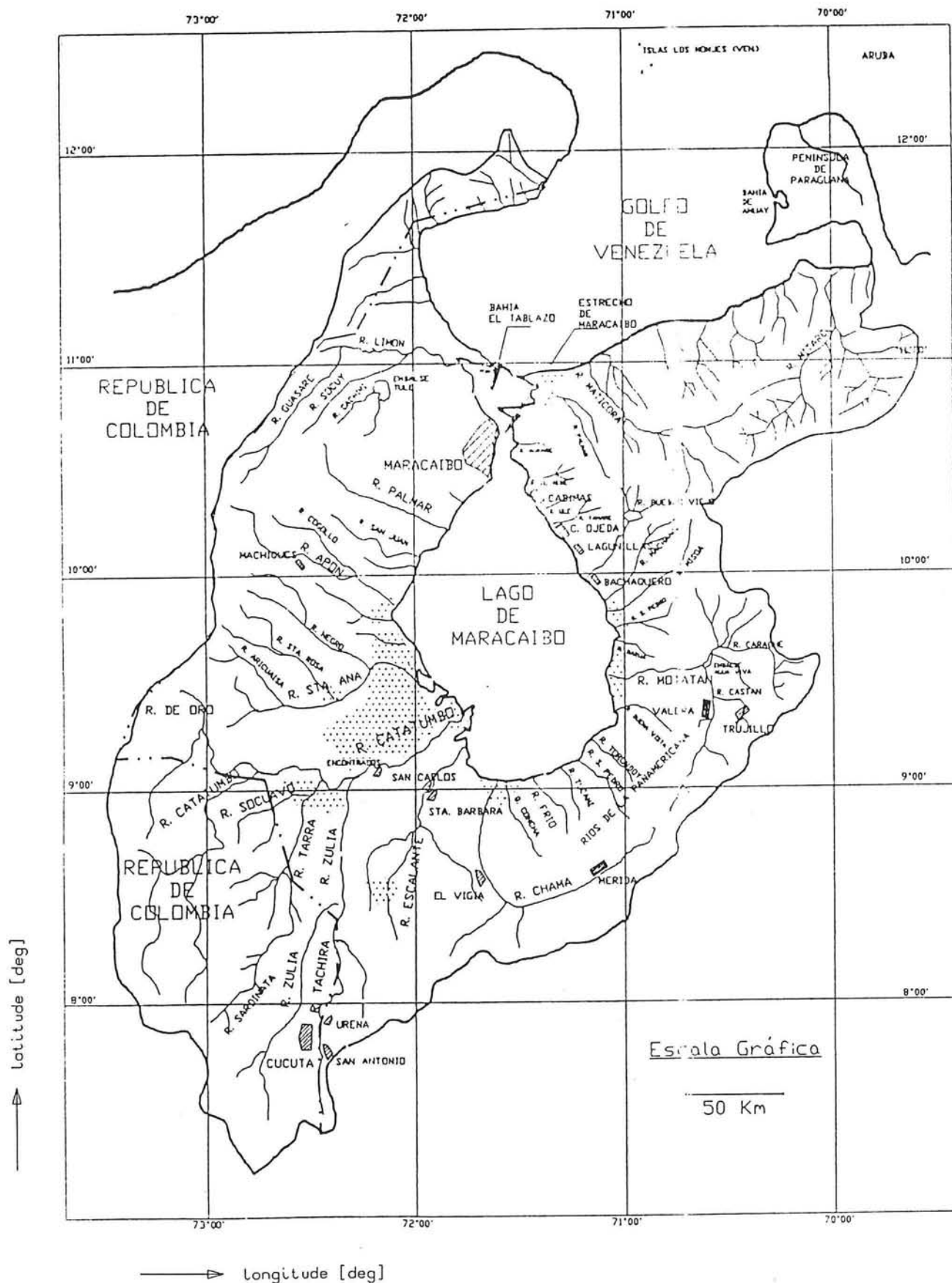
## D Scenarios for box-model

For the long-term simulation Y14 the hydrological conditions of the simulations X01 ... X07 were used. For the simulations Y24, Y25, Y26 and Y27 the river discharges used for Y14 have been increased with respectively 10, 30, 60 and 90 %. All these simulations lasted 13 months.

These discharges were used as well as input for the simulations with TRISULA as for the simulations with the box-model:

| Scenarios for long term simulations with TRISULA and box-model.   |         |         |         |         | discharges m3/s |
|-------------------------------------------------------------------|---------|---------|---------|---------|-----------------|
| identification                                                    | Y14     | Y24     | Y25     | Y26     | Y27             |
| perct.                                                            | 100%    | 110%    | 130%    | 160%    | 190%            |
| March                                                             | -215.00 | -167.50 | -72.50  | 70.00   | 212.50          |
| April                                                             | -34.15  | 25.12   | 143.63  | 321.41  | 499.16          |
| May                                                               | 460.00  | 551.39  | 734.14  | 1008.25 | 1282.39         |
| June                                                              | 1135.00 | 1270.25 | 1540.75 | 1946.50 | 2352.25         |
| July                                                              | 1810.00 | 1989.14 | 2347.39 | 2884.75 | 3422.14         |
| August                                                            | 2304.15 | 2515.38 | 2937.87 | 3571.59 | 4205.34         |
| September                                                         | 2485.00 | 2708.00 | 3154.00 | 3823.00 | 4492.00         |
| October                                                           | 2304.15 | 2515.38 | 2937.87 | 3571.59 | 4205.34         |
| November                                                          | 1810.00 | 1989.14 | 2347.39 | 2884.75 | 3422.14         |
| December                                                          | 1135.00 | 1270.25 | 1540.75 | 1946.50 | 2352.25         |
| Januari                                                           | 460.00  | 551.39  | 734.14  | 1008.25 | 1282.39         |
| Februari                                                          | -34.15  | 25.12   | 143.63  | 321.41  | 499.16          |
| March                                                             | -215.00 | -167.50 | -72.50  | 70.00   | 212.50          |
| for all simulations initial salt content : $967.0 \cdot 10^9$ kg. |         |         |         |         |                 |





Geometry of Lake Maracaibo, Strait of Maracaibo,  
Tablazo Bay and Gulf of Venezuela

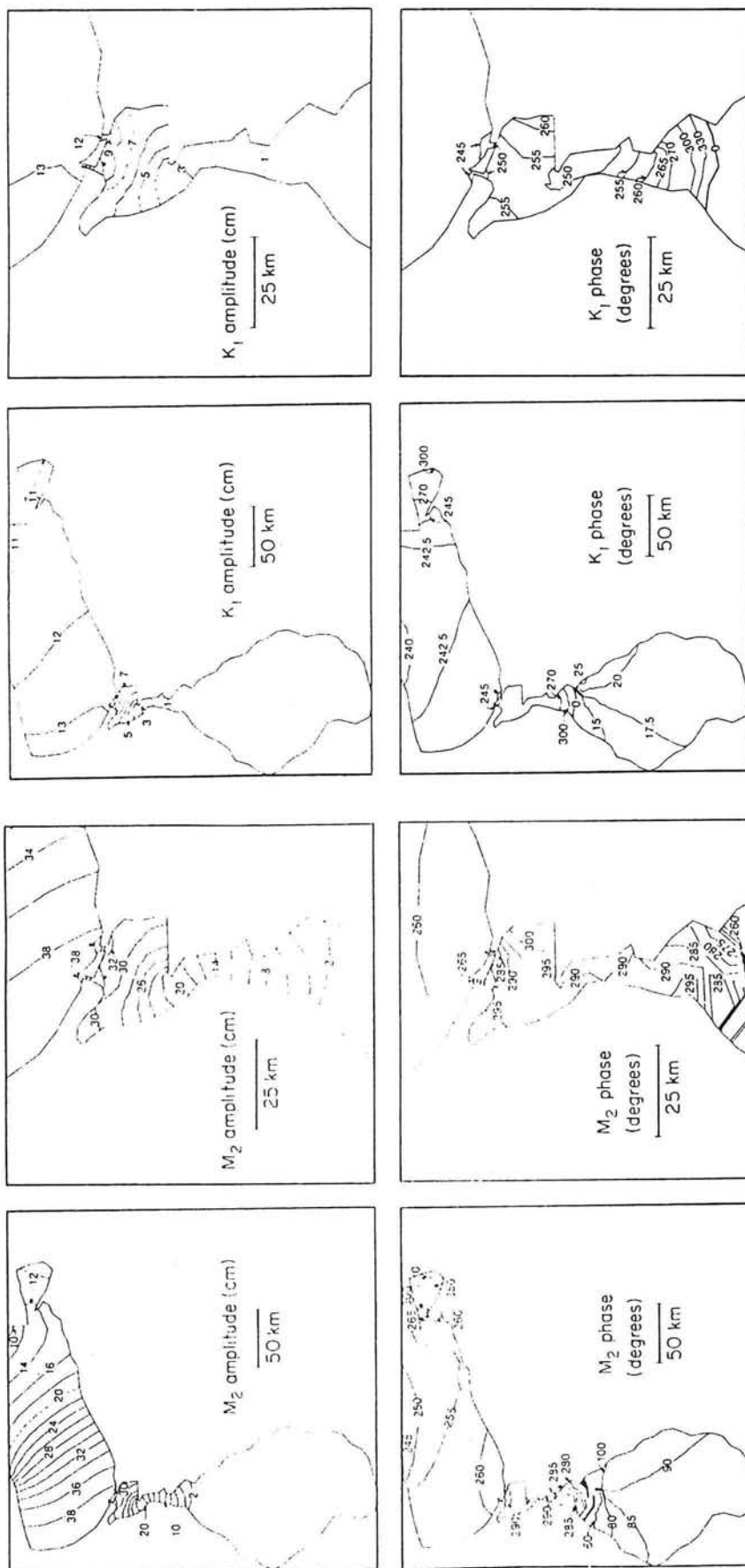
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-01-03

Fig 2.1



1.3 b) co-tidal charts for K<sub>1</sub>-constituent

1.3 a) co-tidal charts for M<sub>2</sub>-constituent

Cotidal maps for constituents M<sub>2</sub> and K<sub>1</sub> from  
From: [Lynch et al.,1990]

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Fig 2.2

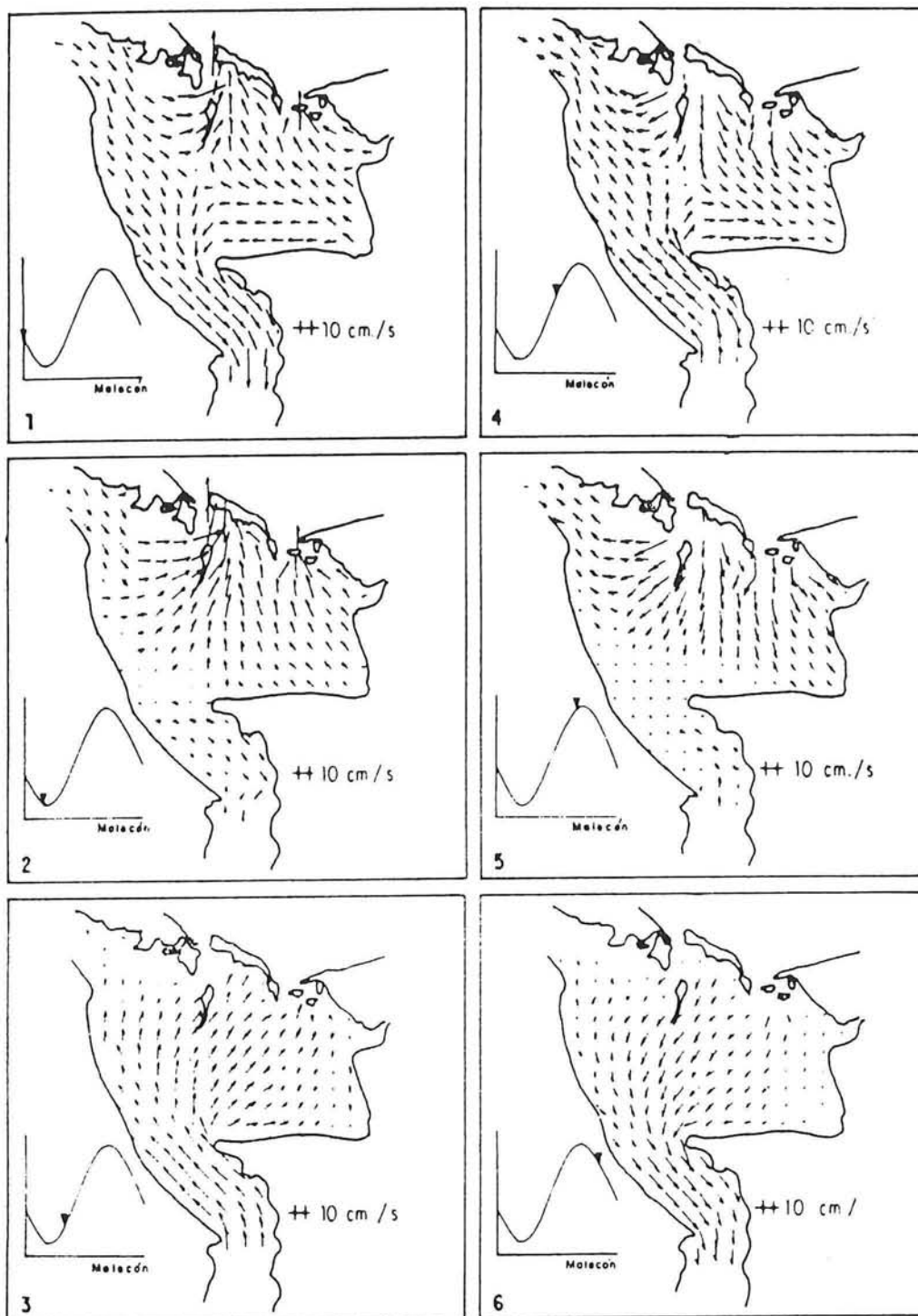


Fig. 12. Instantaneous velocity field in Tablazo Bay during a tidal cycle. Time is referred to the water level at the Malecón tide gauge.

Directions and velocities of water current in  
Tablazo Bay during a tidal cycle  
From: (Molines et al., 1989)

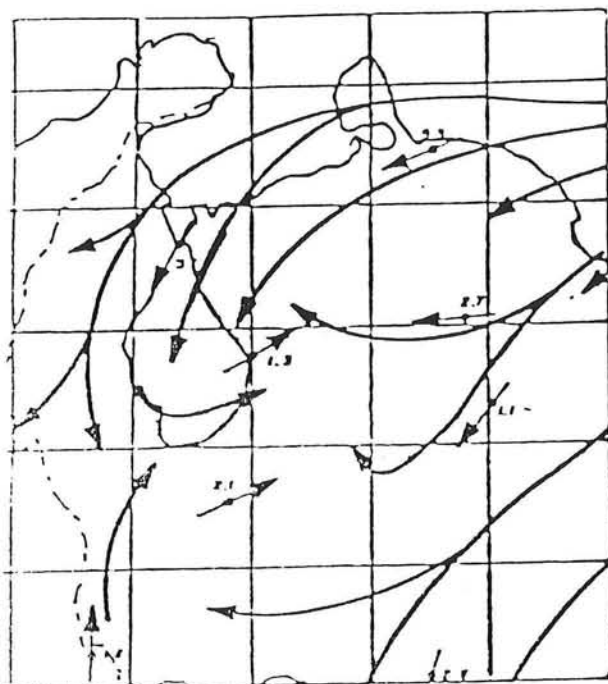
TRISULA

Lago de Maracaibo

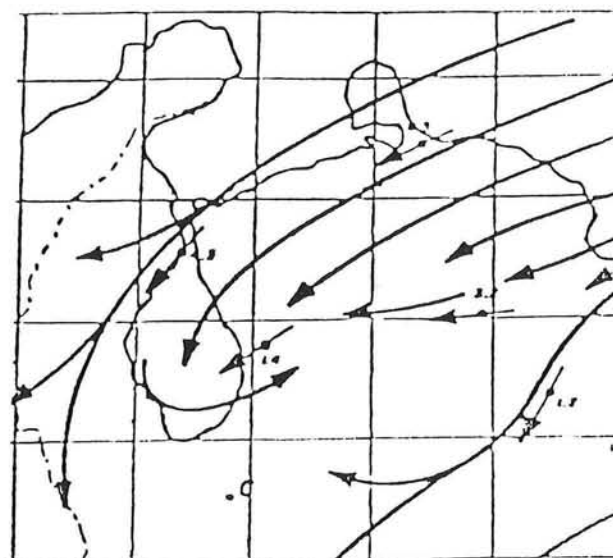
DELFT HYDRAULICS

1995-01-03

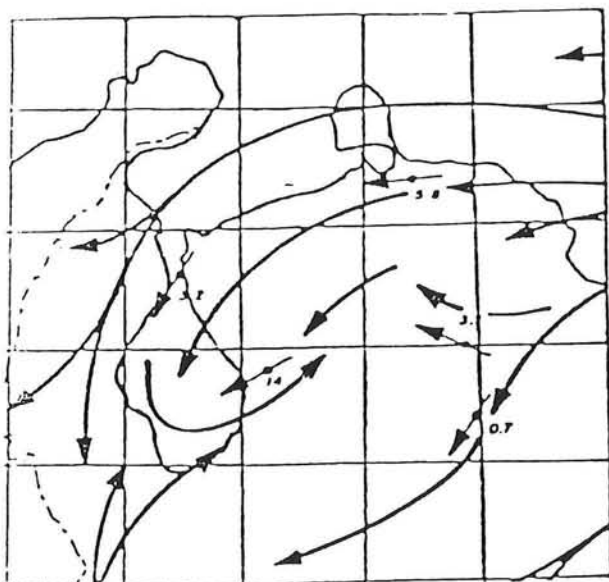
Fig 2.3



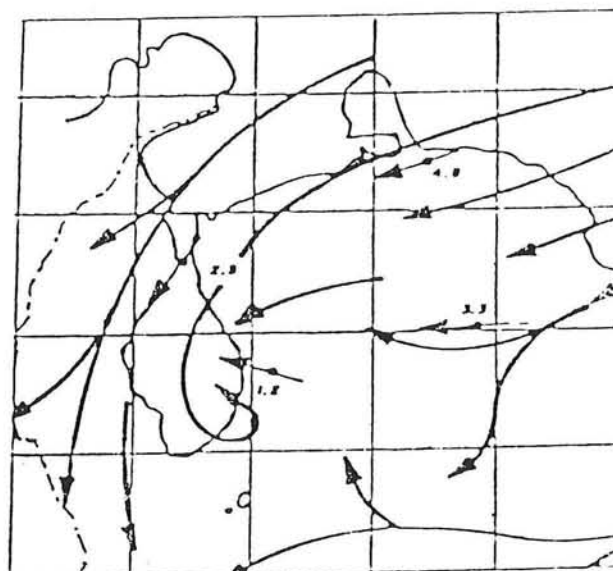
a) January



b) April



c) July



d) October

Windfield above Lake Maracaibo  
From: Atlas Climatologico de la Fuerza Aerea de  
Venezuela, 1984

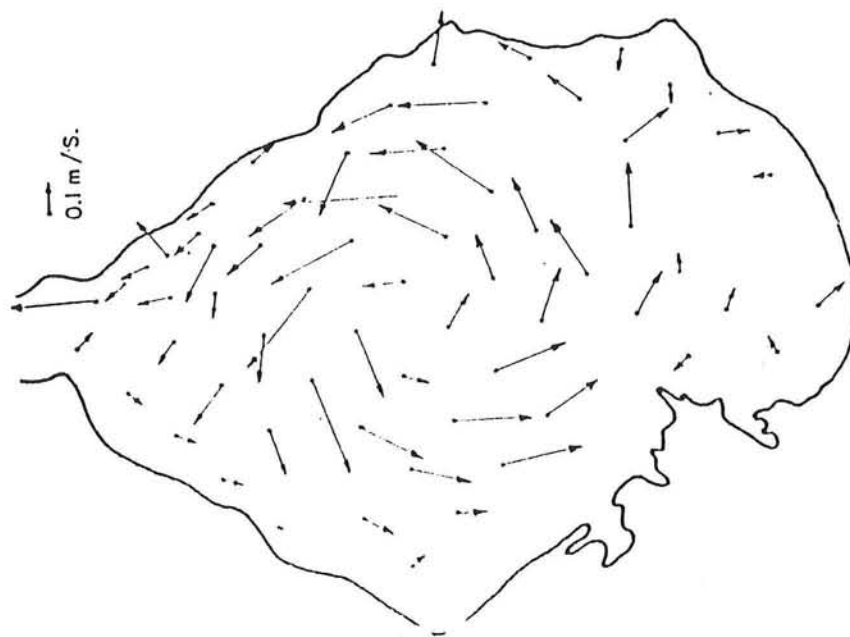
TRISULA

Logo de Maracaibo

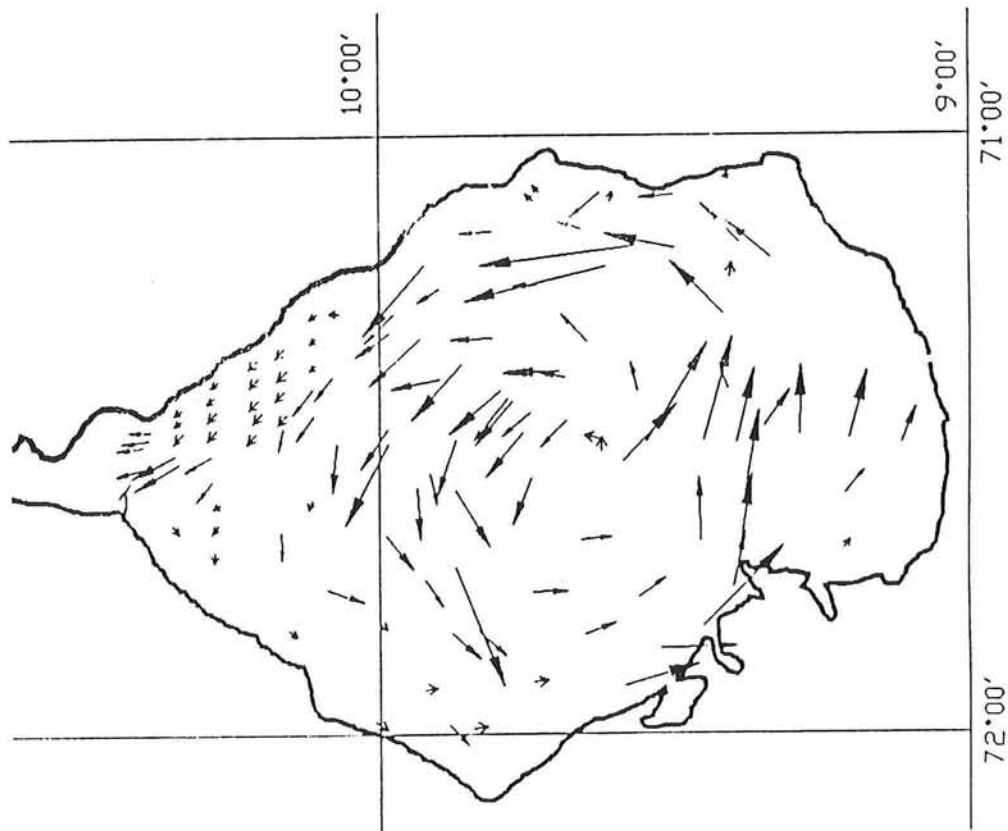
DELFT HYDRAULICS

1995-01-03

Fig 2.4



1.6 a) velocities and directions of water current  
at 5 m depth, measured 24 - 28 October 1977



1.6 b) velocities and directions of water current  
at 1 m depth, measured by ESCAM, August 1982

Lakewide directions and velocities of water current

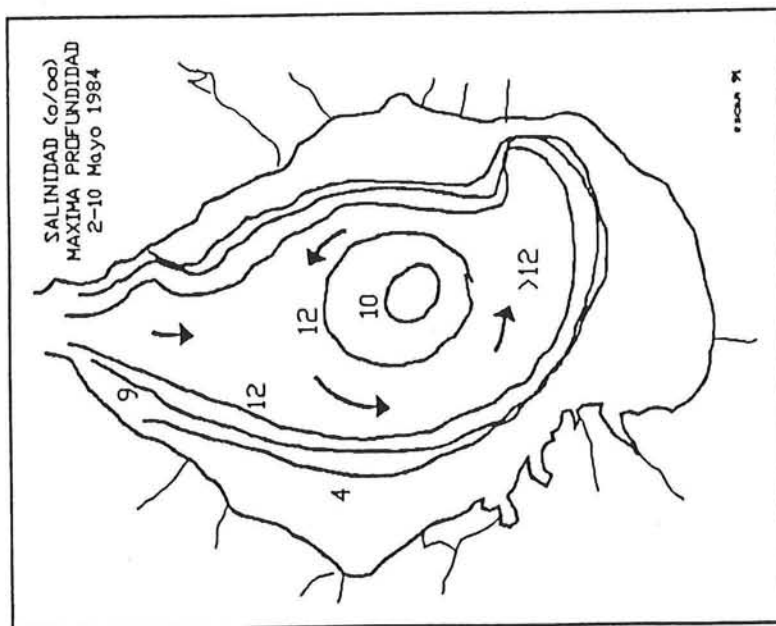
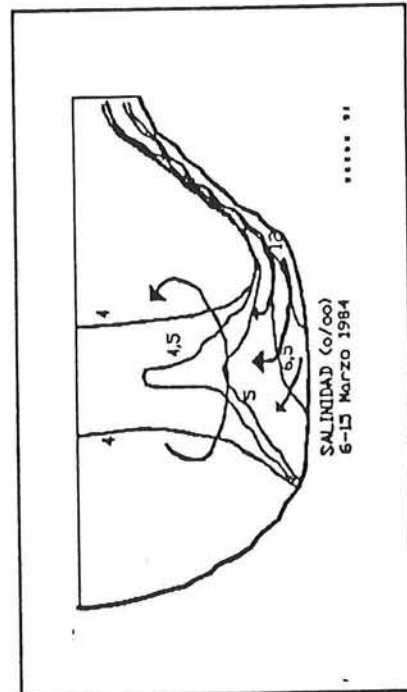
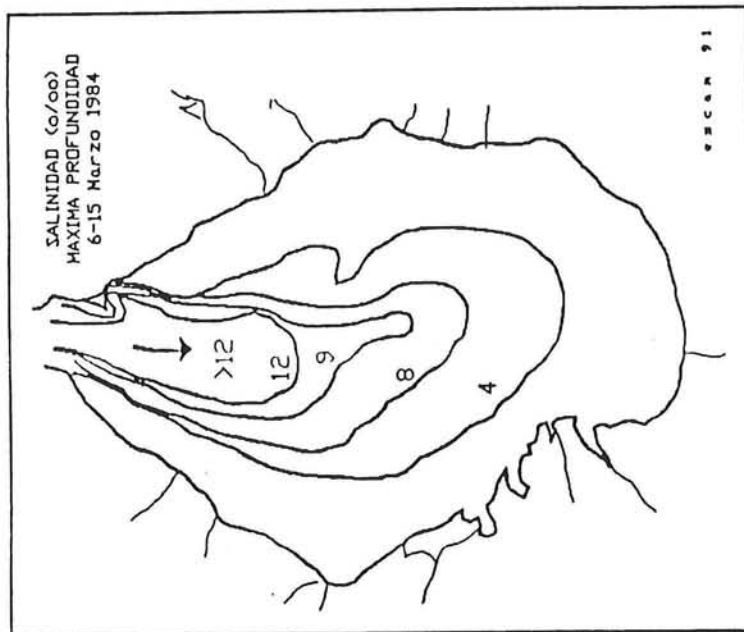
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-01-03

Fig 2.5



Measurements of salinity profiles in Lake Maracaibo  
From: [Parra-Pardi, 1991]

TRISULA

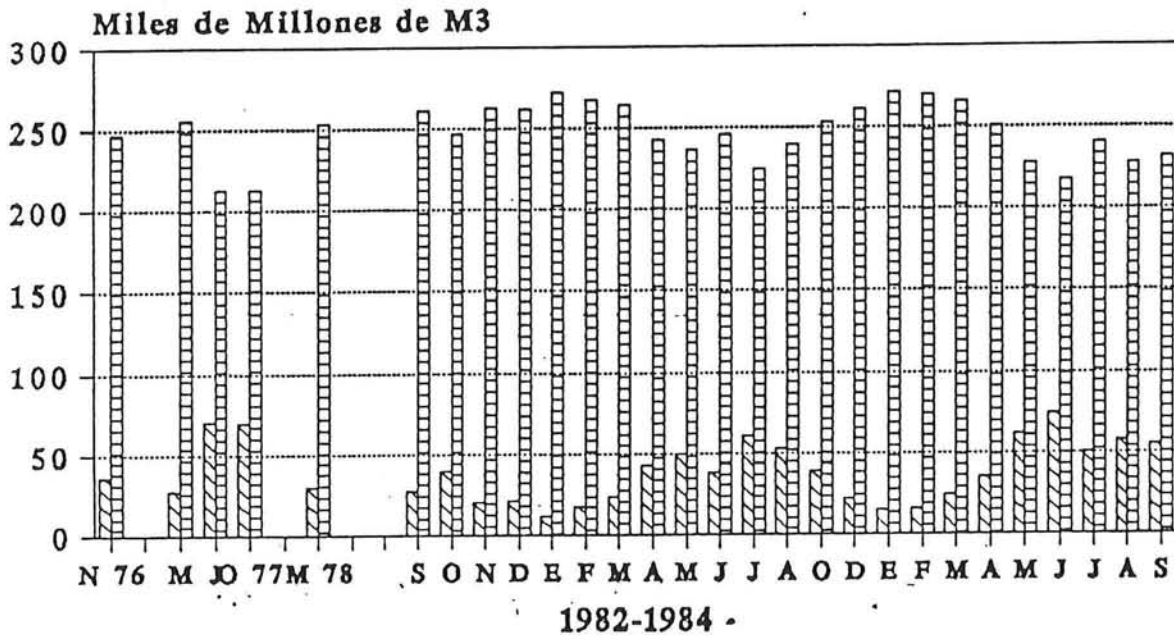
Lago de Maracaibo

DELFT HYDRAULICS

1995-02-03

Fig 2.6

# Lago de Maracaibo Volúmenes observados en el Hipolimnio y Epilimnio



Hipolimnio
 Epilimnio

Observed volume of the hypolimnion and the epilimnion.  
From: (Parro-Pardi, 1991)

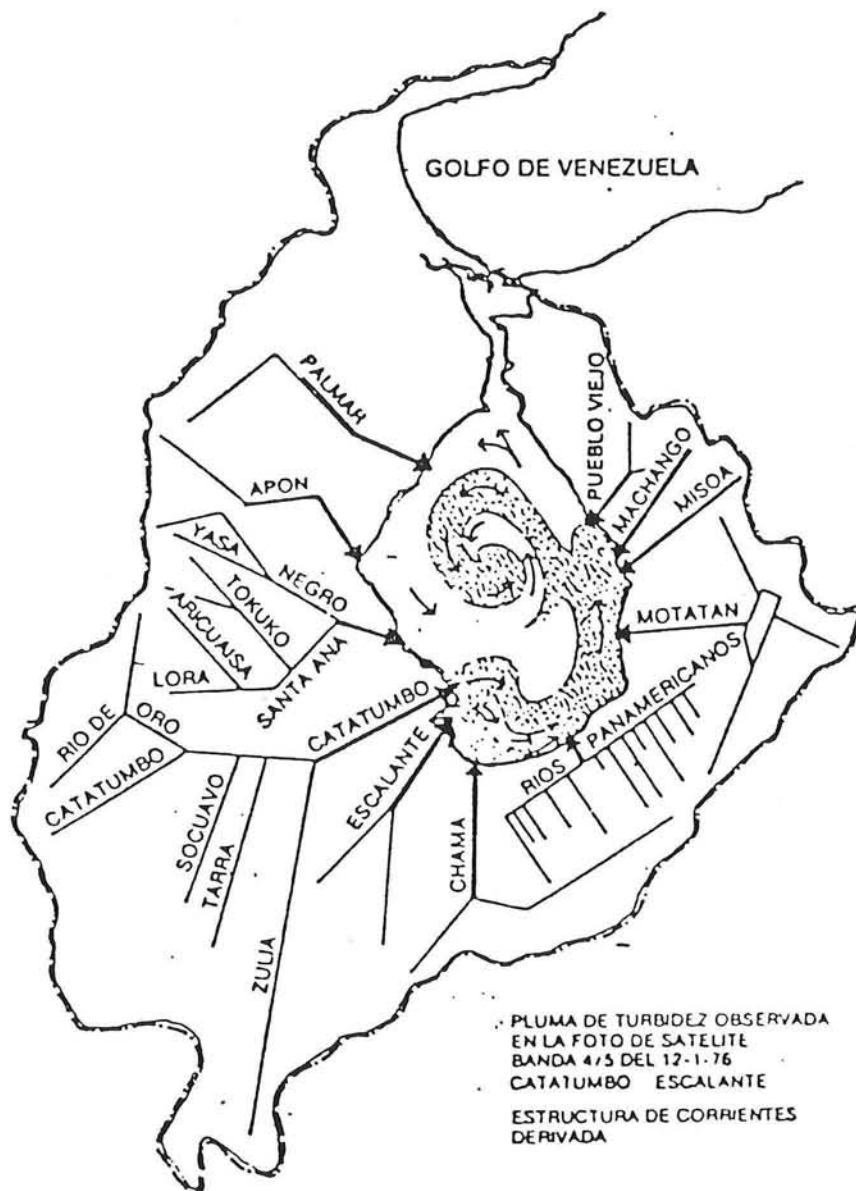
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-02-03

Fig 2.7



Pluma de turbidez observada en la imagen de satélite, banda 4/5 del 12-1-76 (ríos Catatumbo y Escalante) y estructura de corrientes derivada.

Observed turbulence plume from Rio Catatumbo  
and Escalante, 12/1/1976. From: (Parra-Pardi, 1991)

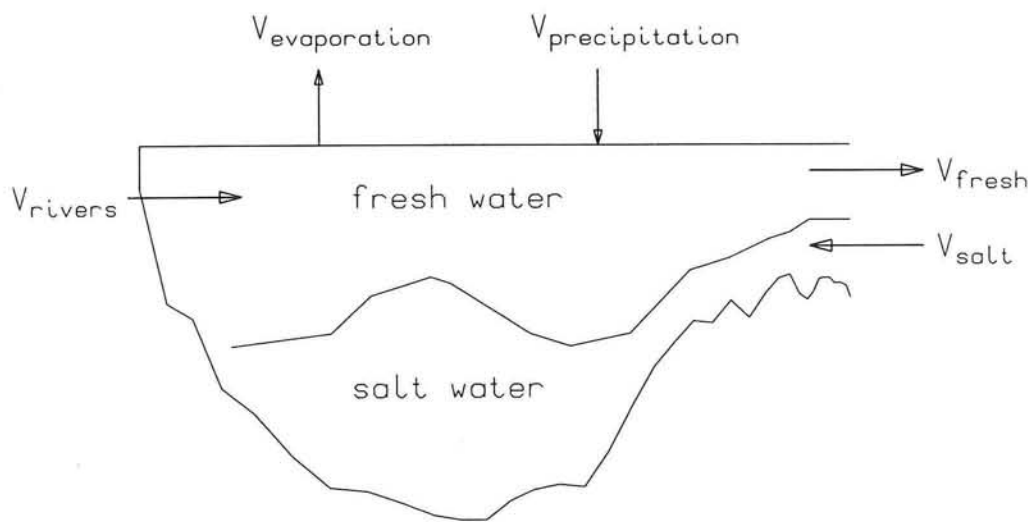
TRISULA

Lago de Maracaibo

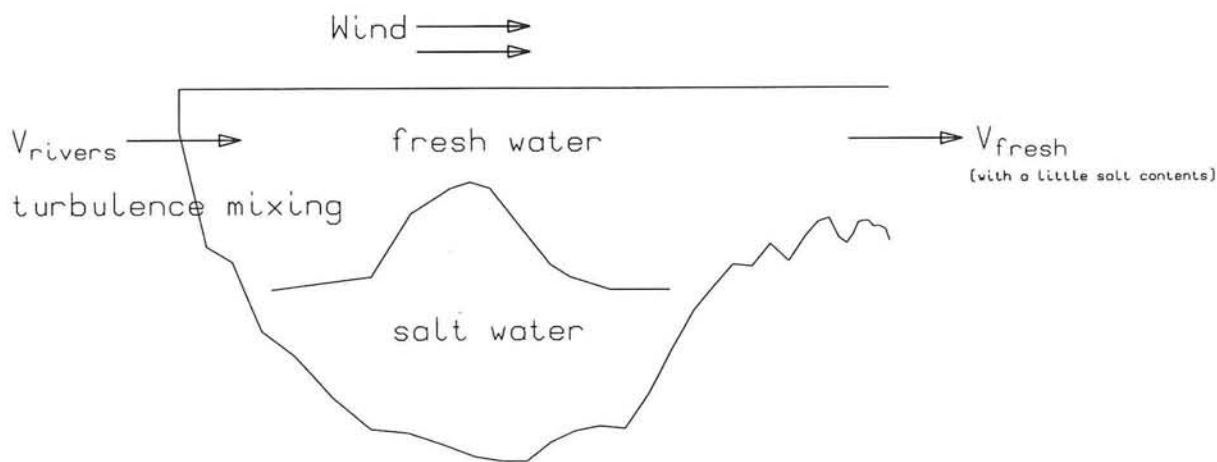
DELFT HYDRAULICS

1995-02-03

Fig 2.8



a) Hydrological balance of Lake Maracaibo



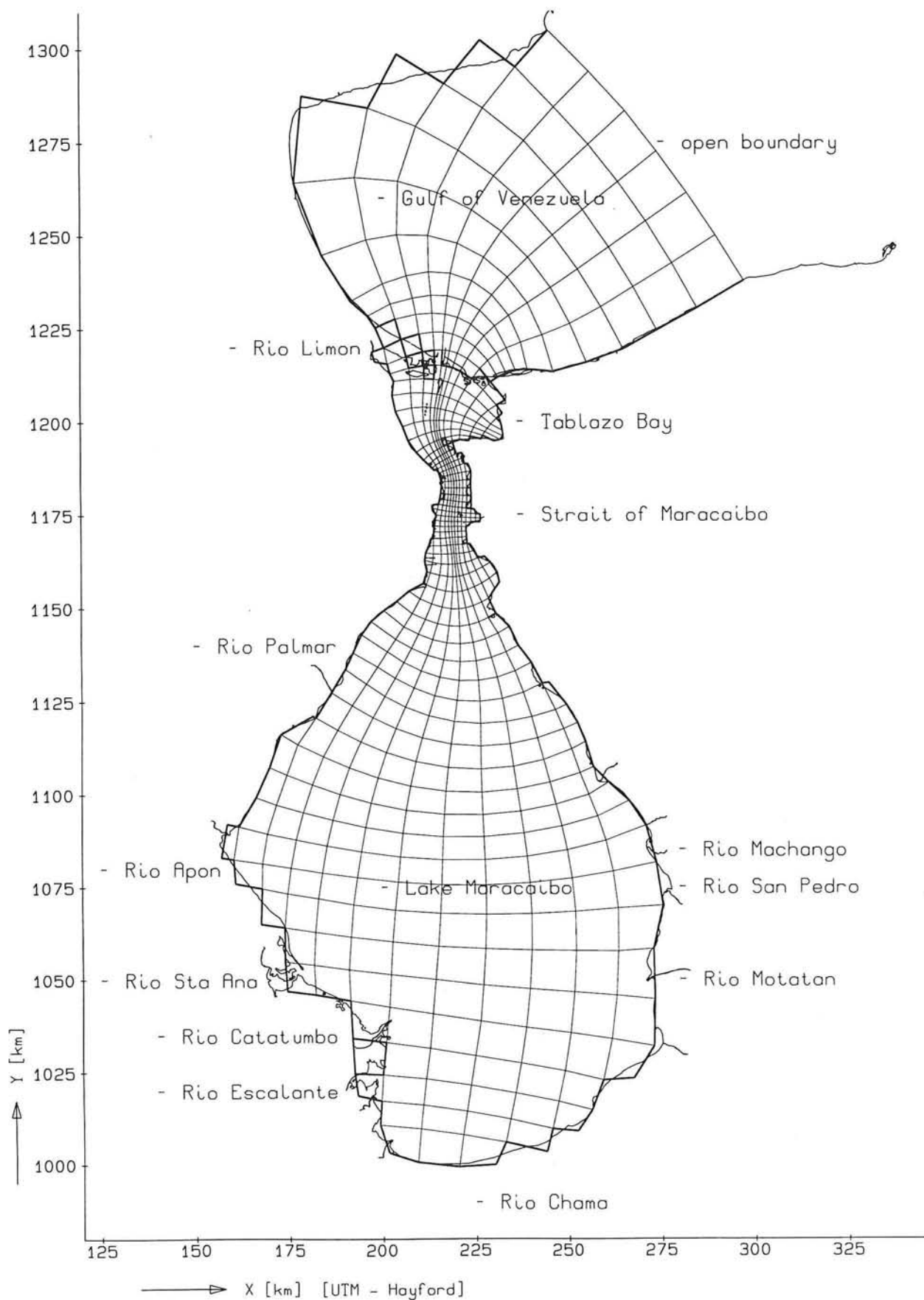
b) Fresh water outflow with extra salinity

a) Hydrological balance of Lake Maracaibo  
b) Salinity outflow caused by turbulence mixing

TRISULA

Lago de Maracaibo





Lake Maracaibo  
Active grid and digitized boundary lines

TRISULA

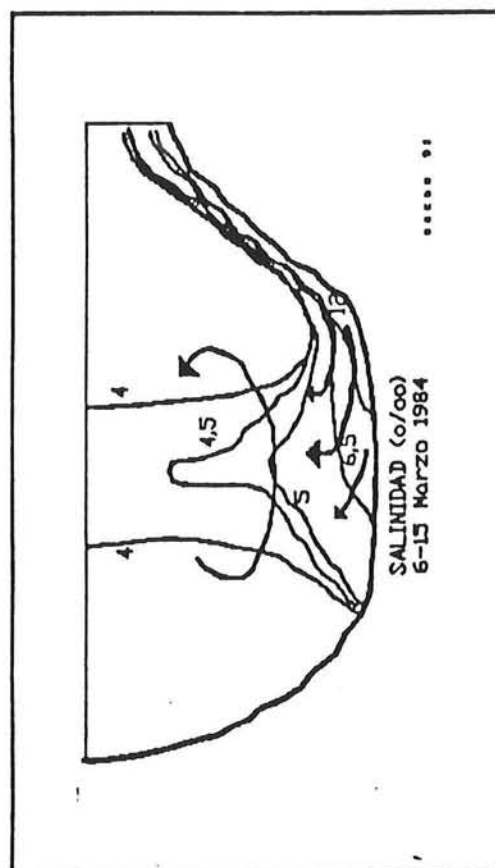
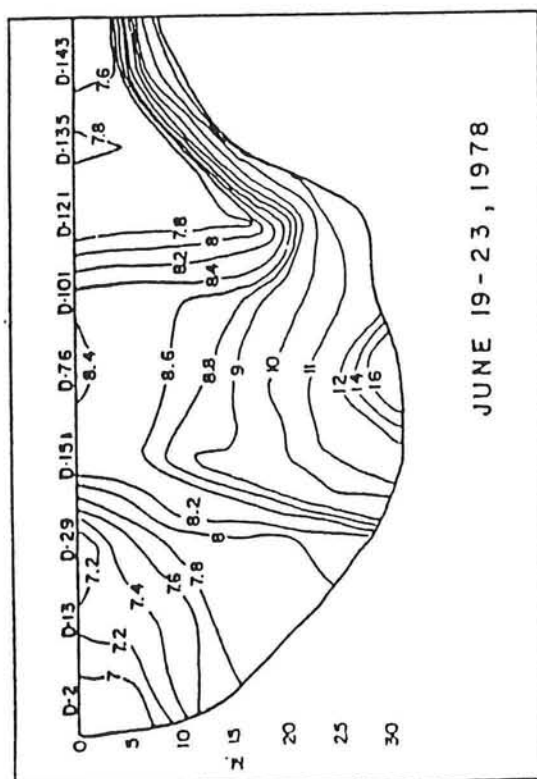
Lago de Maracaibo

DELFT HYDRAULICS

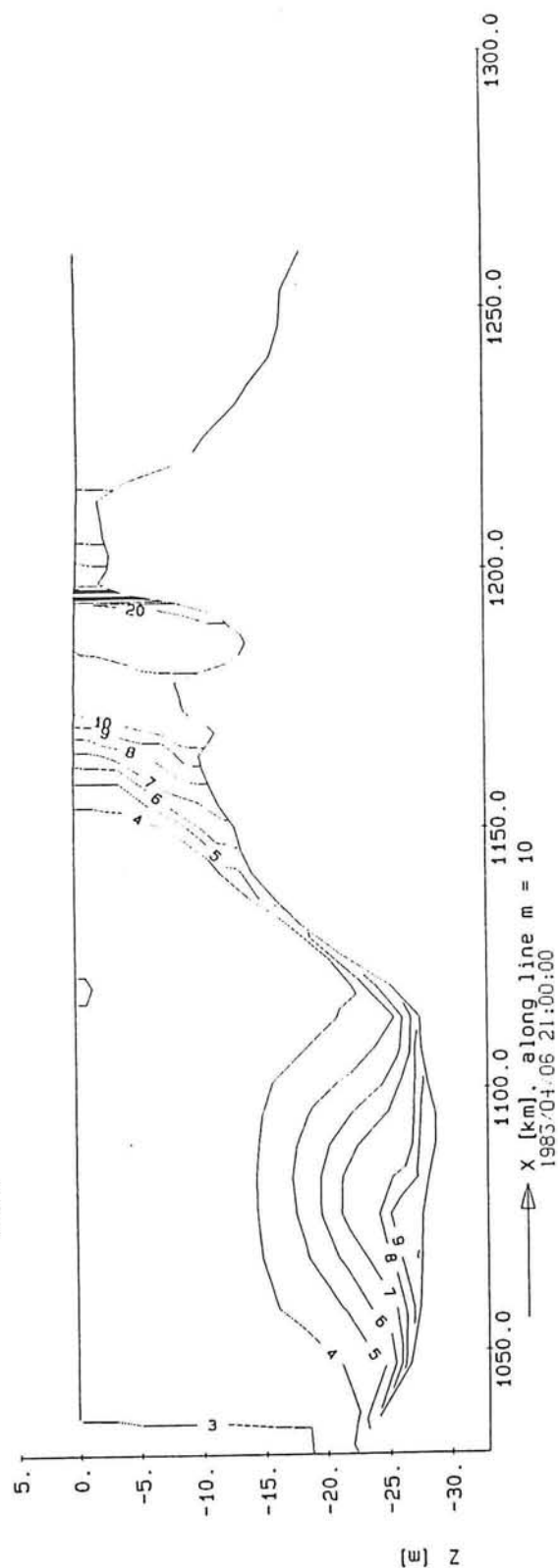
1994-10-03

Fig. 3.1

(a)



(b)



Observed and simulated salinity stratification  
(a) Porra-Pardi 1983, 1991  
(b) Trisula simulation, Bijlsma (1993)

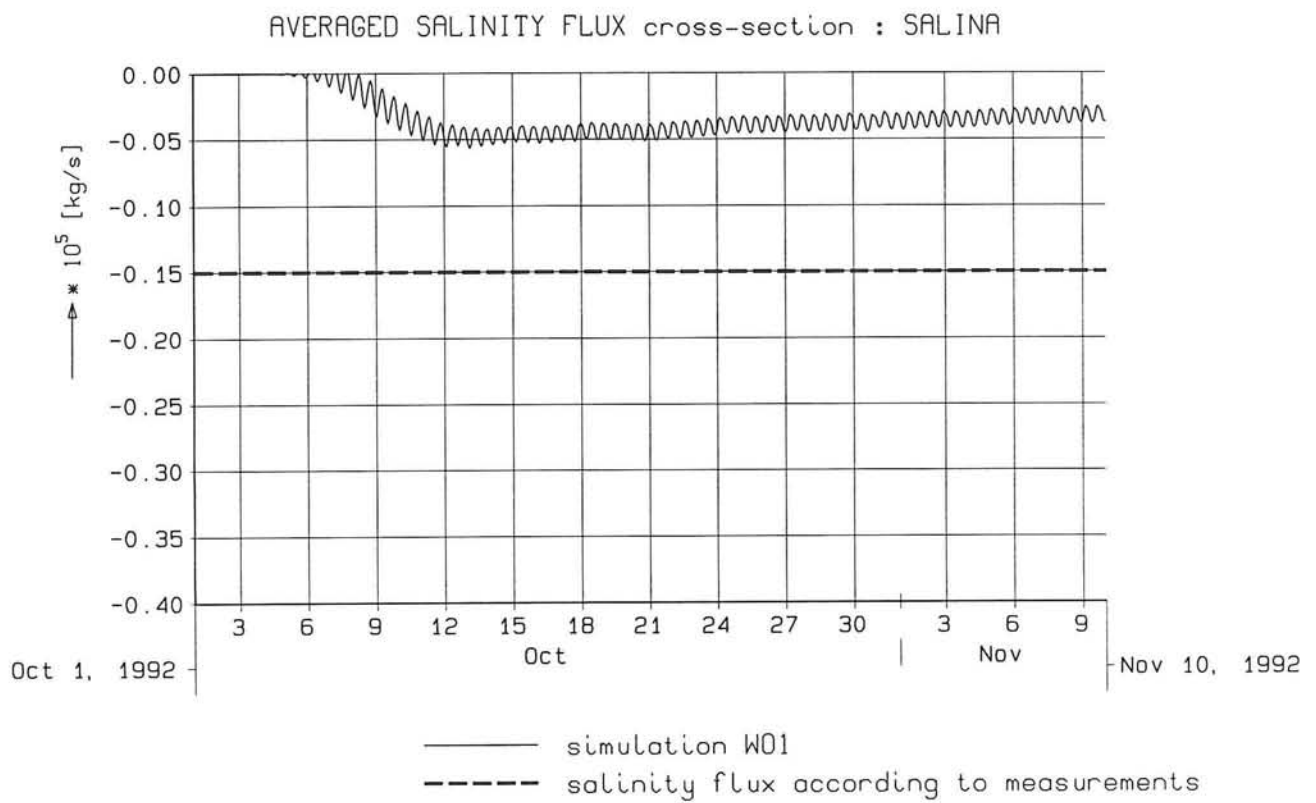
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-01-03

Fig 3.2



Simulated salinity flux and measurements  
 Model according to [Bijlsma, 1993]  
 algebraic turbulence model,  $D_h = 0.01 \text{ m}^2/\text{s}$

TRISULA

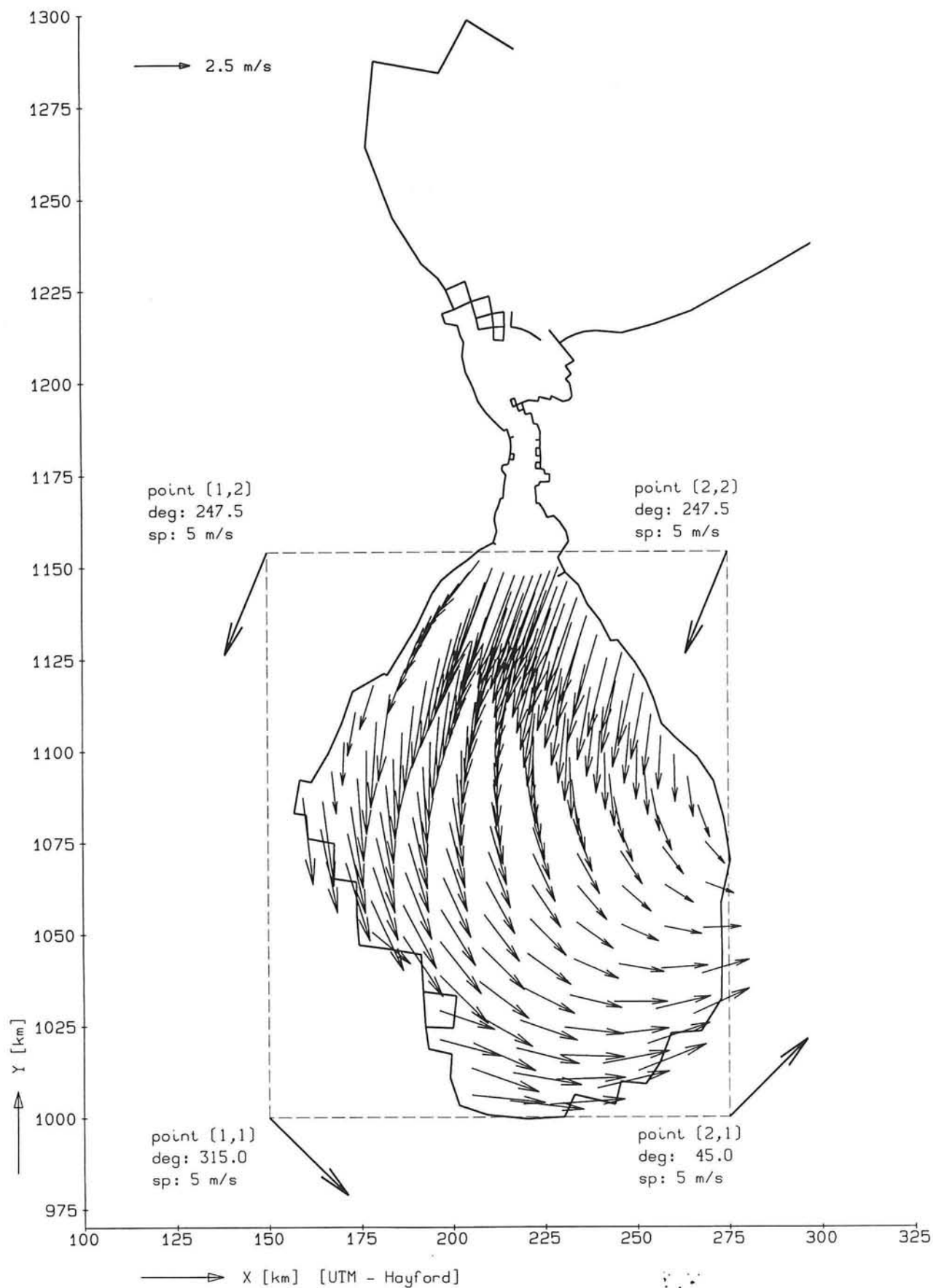
W01

Lago de Maracaibo

DELFT HYDRAULICS

1995-01-03

Fig **3.3**



Windfield over Lake Maracaibo  
- windfield in zeta-points  
- for [M,N] = [1,16;1,23]

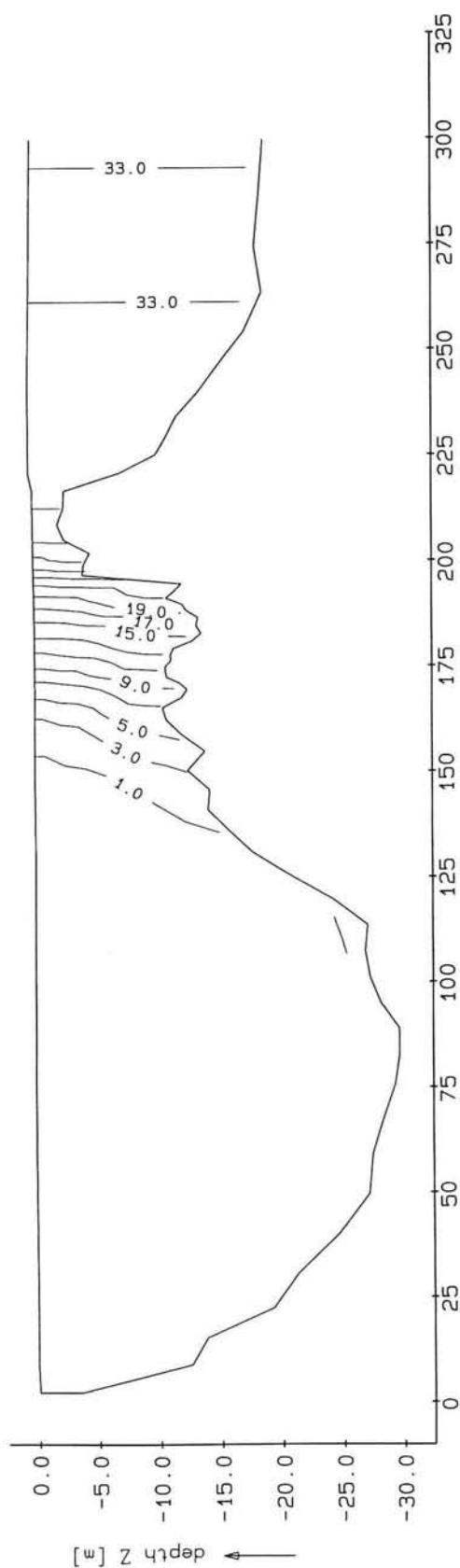
TRISULA

Logo de Maracaibo

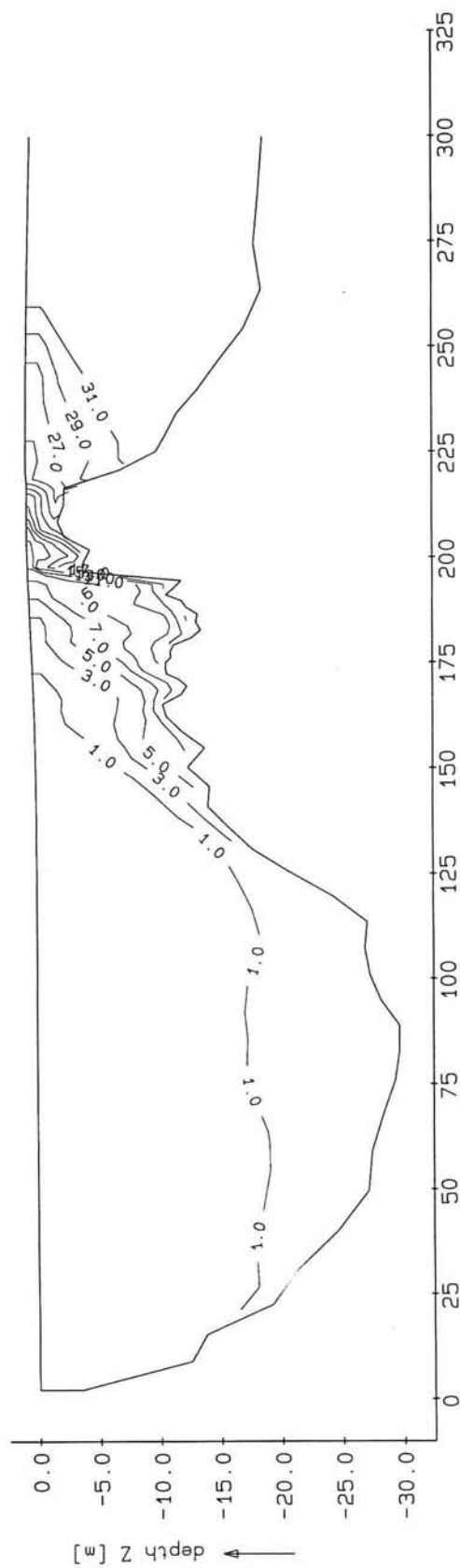
DELFT HYDRAULICS

1995-03-08

Fig **3.4**



A) algebraic model, isolines of salinity, time = 45 days [6480]



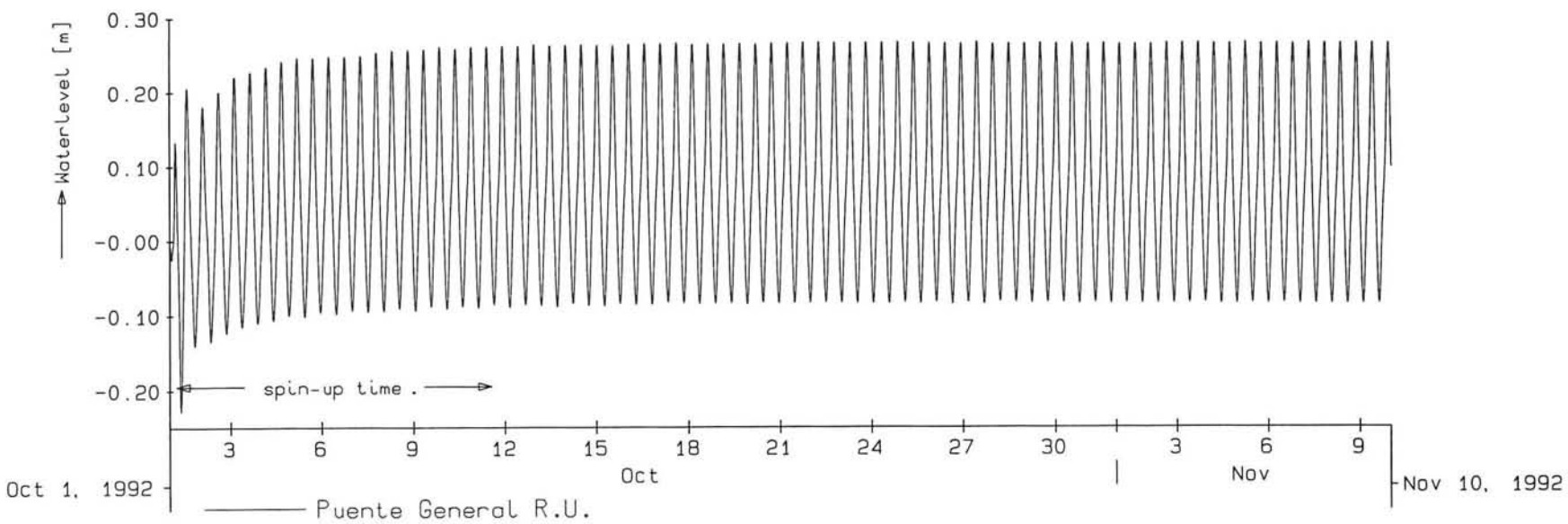
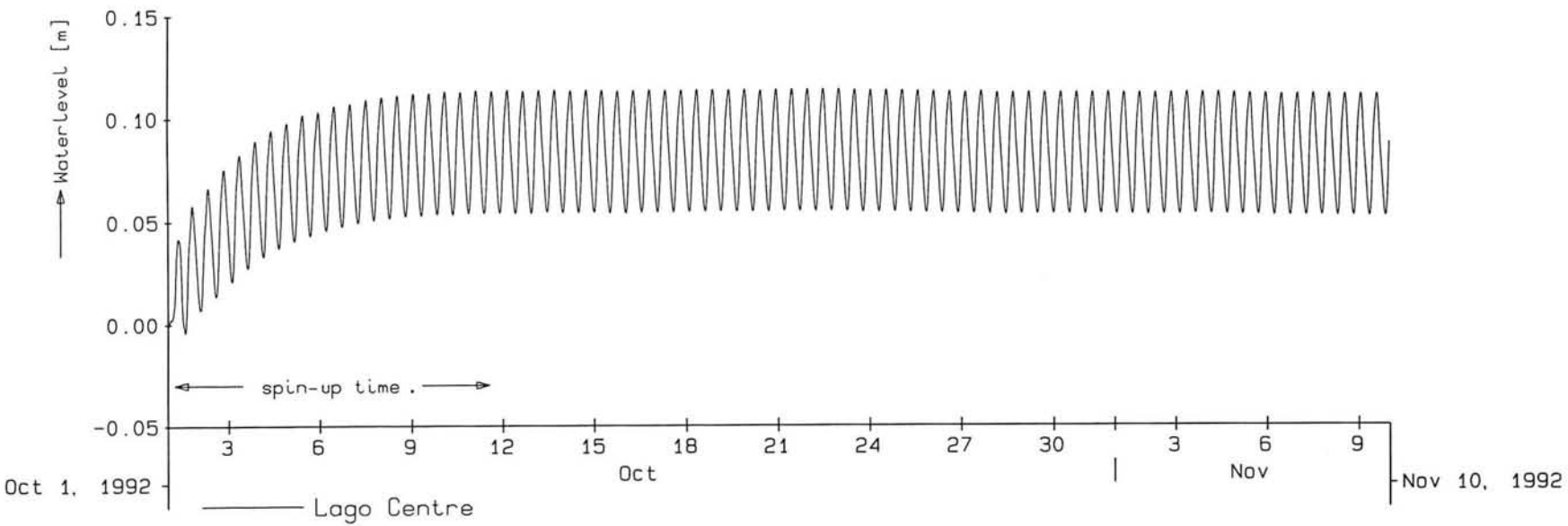
B) k-epsilon model, isolines of salinity, time = 45 days [6480]

Isolines of salinity after 45 days of computation  
 A) W01: algebraic turbulence model,  $D_h = 0.01 \text{ m}^2/\text{s}$   
 B) W02: k-epsilon turbulence model,  $D_h = 0.01 \text{ m}^2/\text{s}$

TRISULA

W01, W02

Lago de Maracaibo



Waterlevel in stations:

- Lago Centre [M,N]=[9,10]  
- Puente General R.U. [M,N]=[6,30]

TRISULA

X01

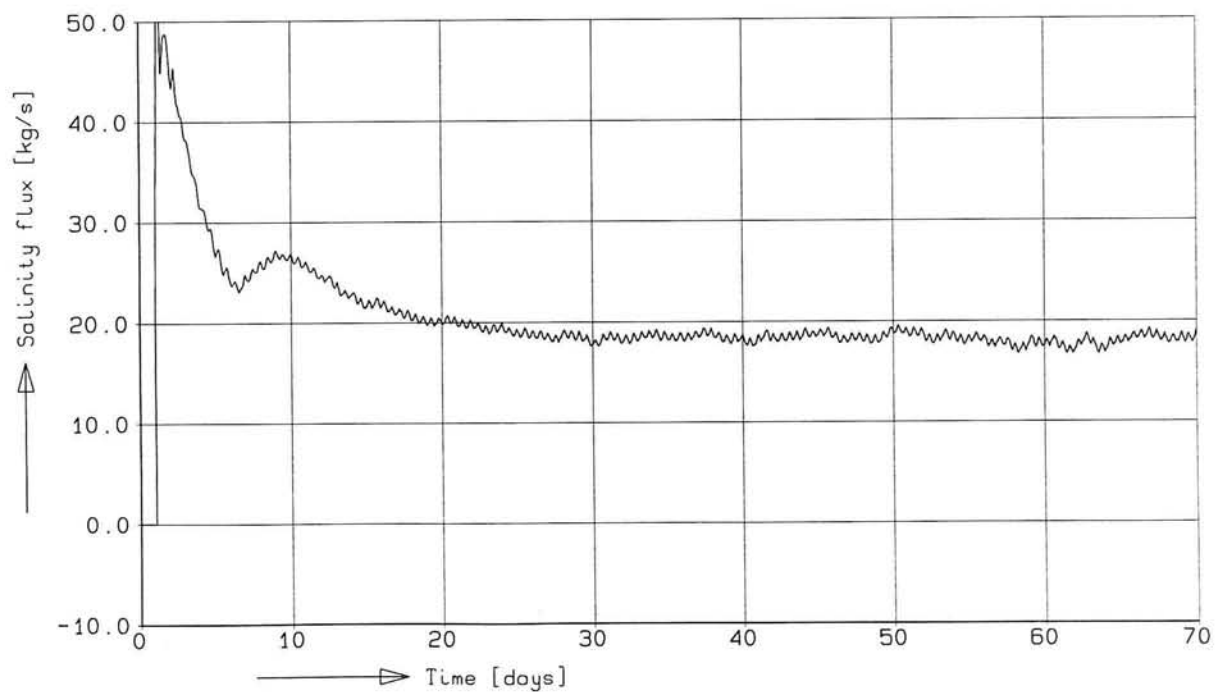
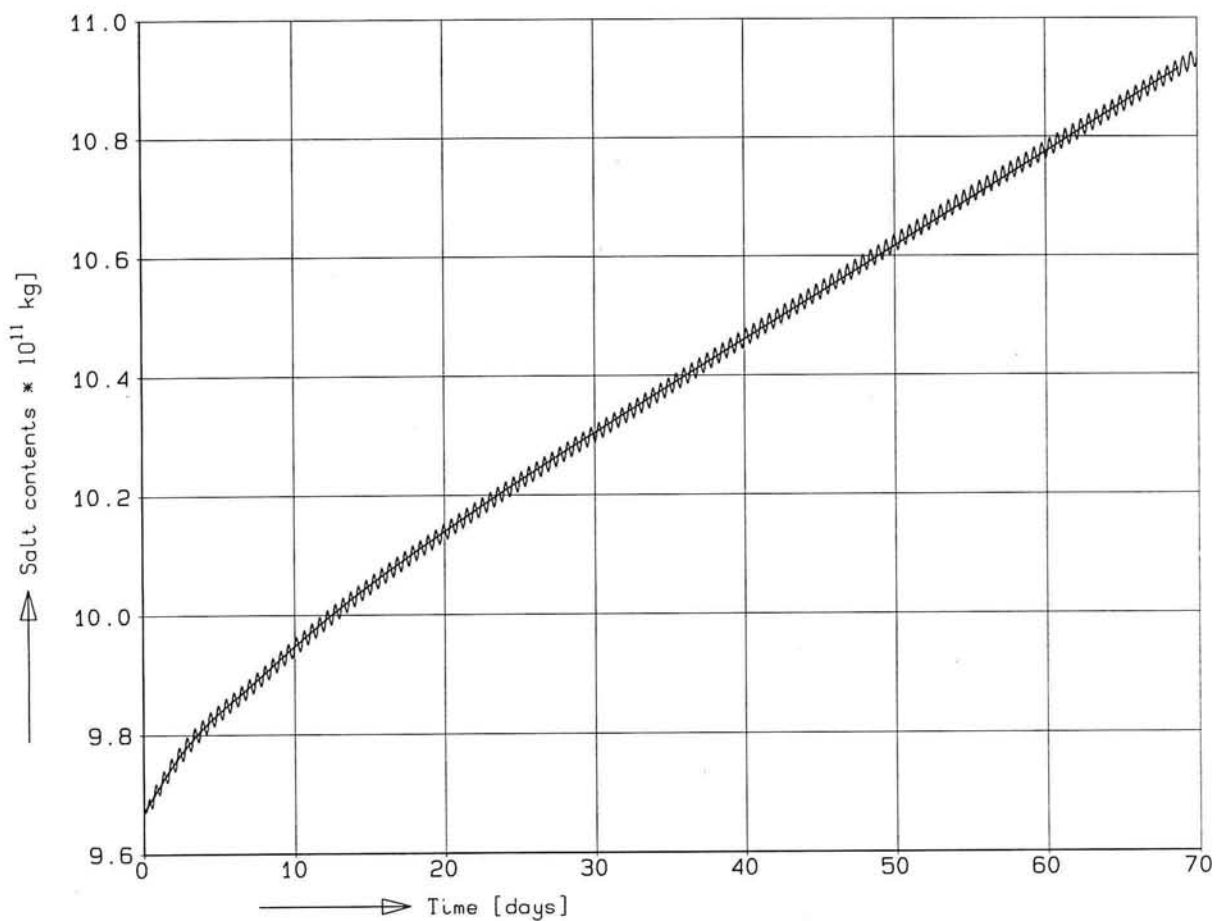
Lago de Moracaiabo

DELFT HYDRAULICS

1995-03-12

Fig. 3.6





Total salt contents [kg] and salinity flux [kg/s]  
 Lake defined as [M,N,K] = [1,16;1,23;1,8]  
 For simulation X01 - dry season

TRISULA

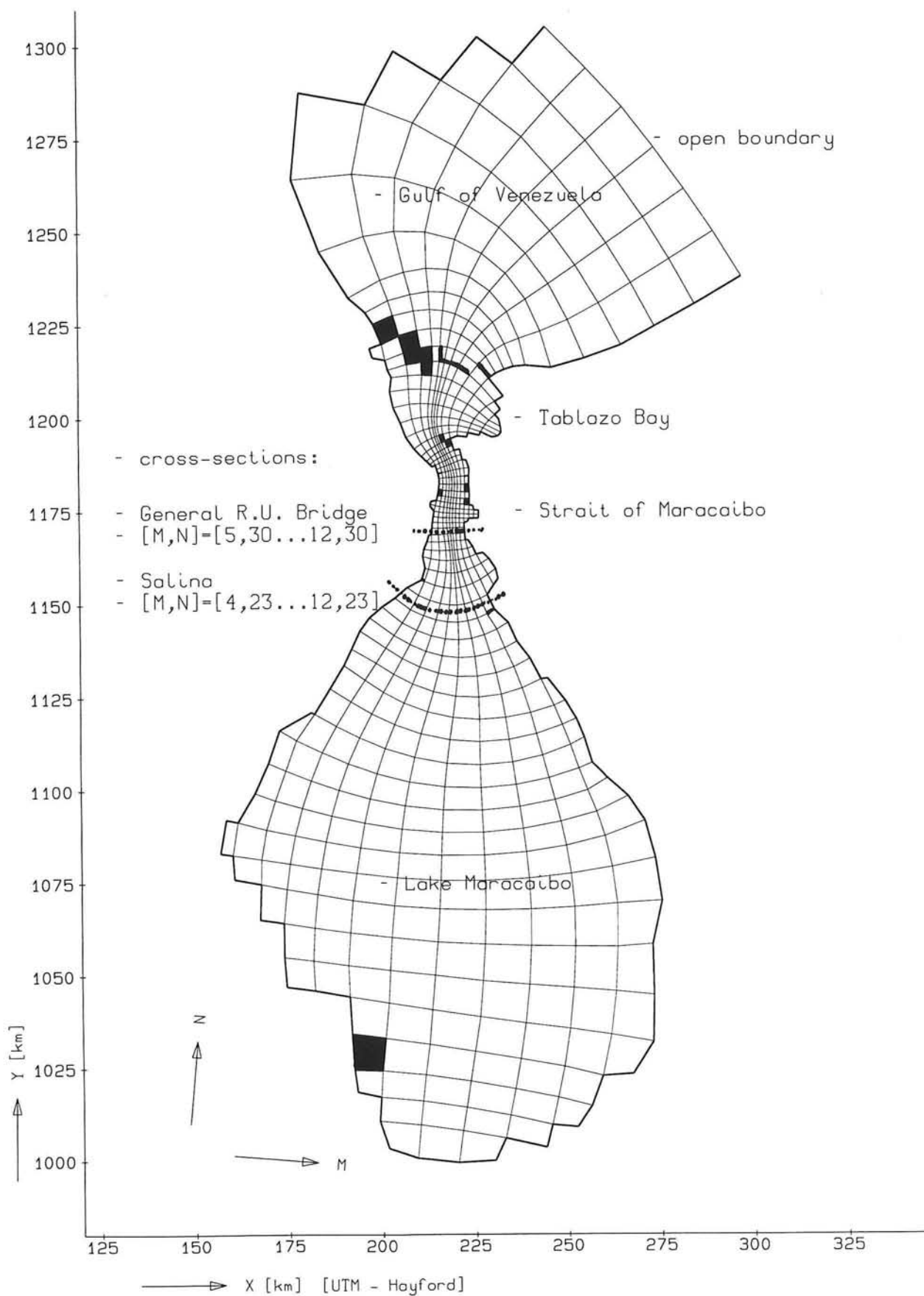
ZOUVOL

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-07

Fig. 4.1



Computational grid, - evaporation [M,N]=[1,16;1,30]  
 - windfield [M,N]=[1,16;1,23]  
 - total salt contents [M,N,K]=[1,16;1,23;1,8]

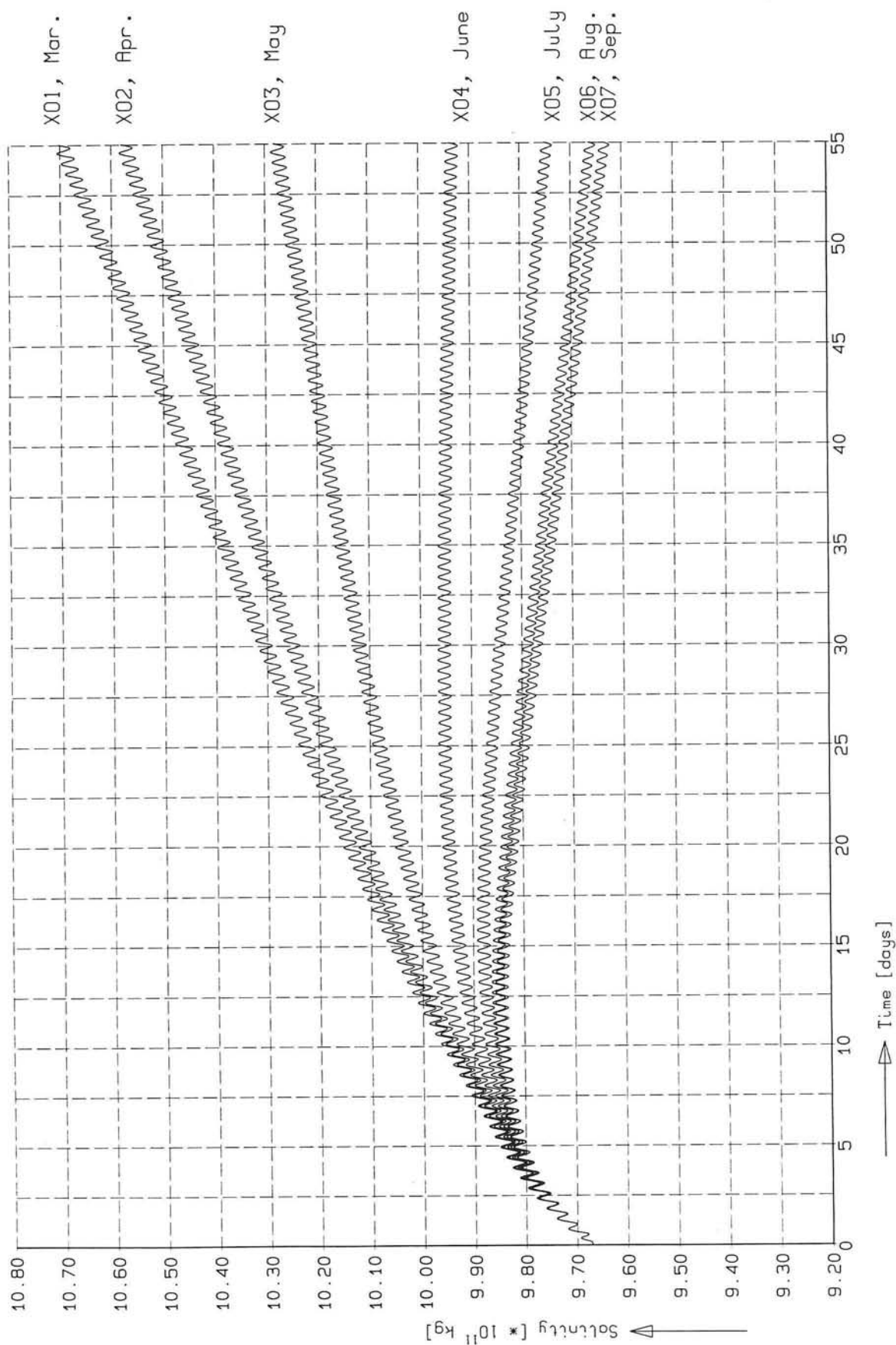
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-02-21

Fig. 4.2



Total salinity in [kg] in Lake Maracaibo  
 Lake defined as [M,N,K] = [1,16;1,23;1,8]  
 For simulations X01 ...X07

TRISULA

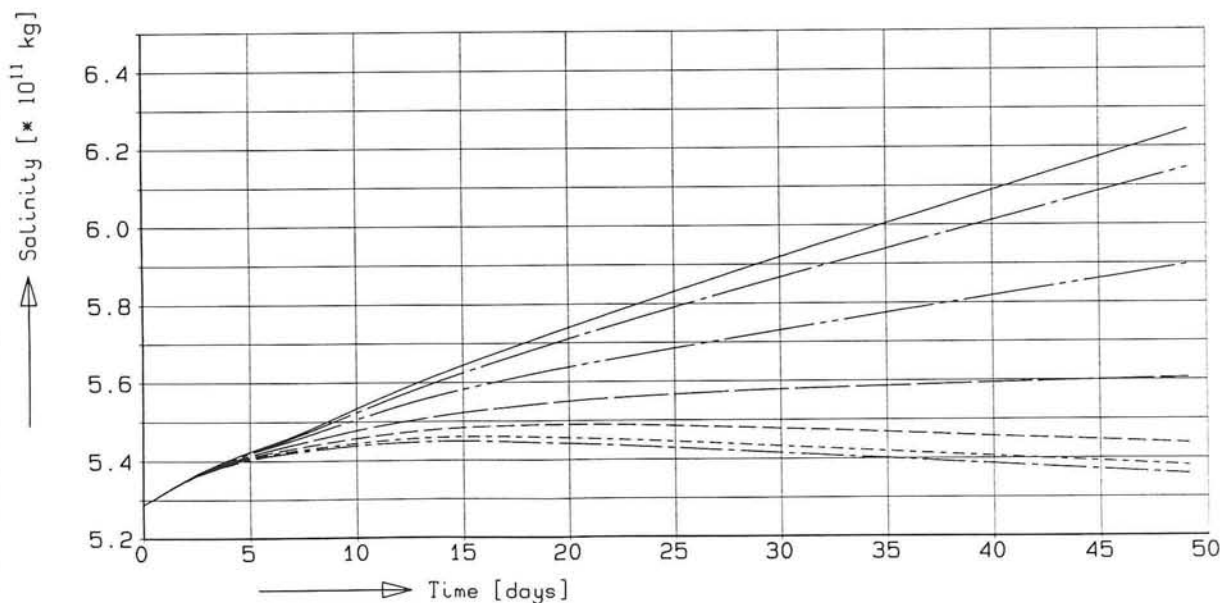
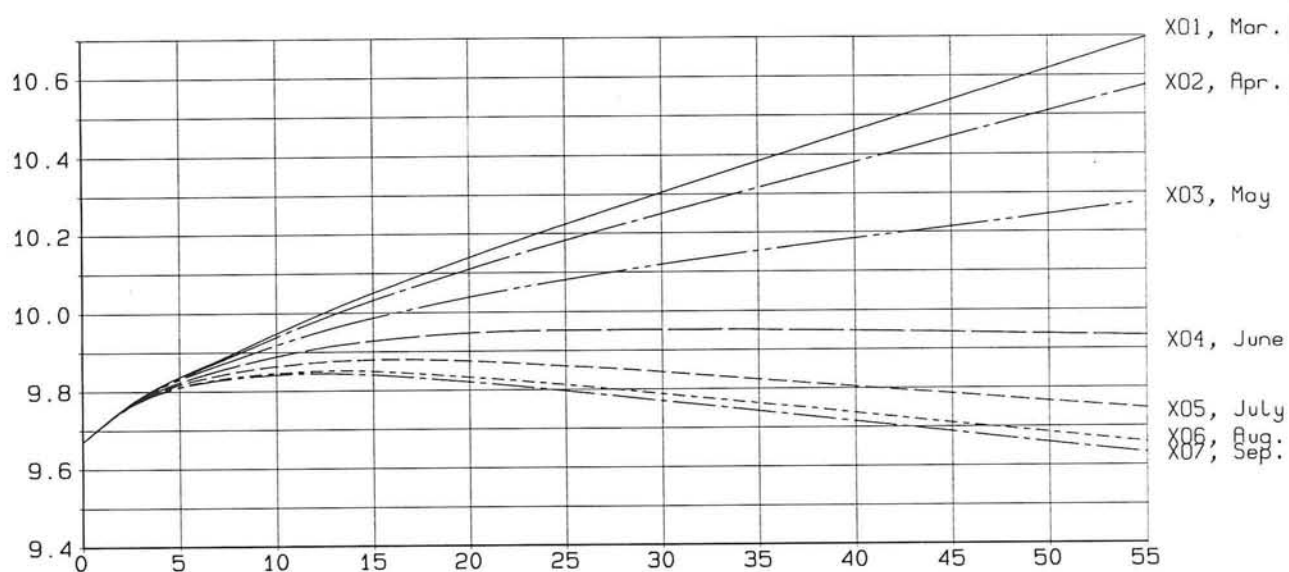
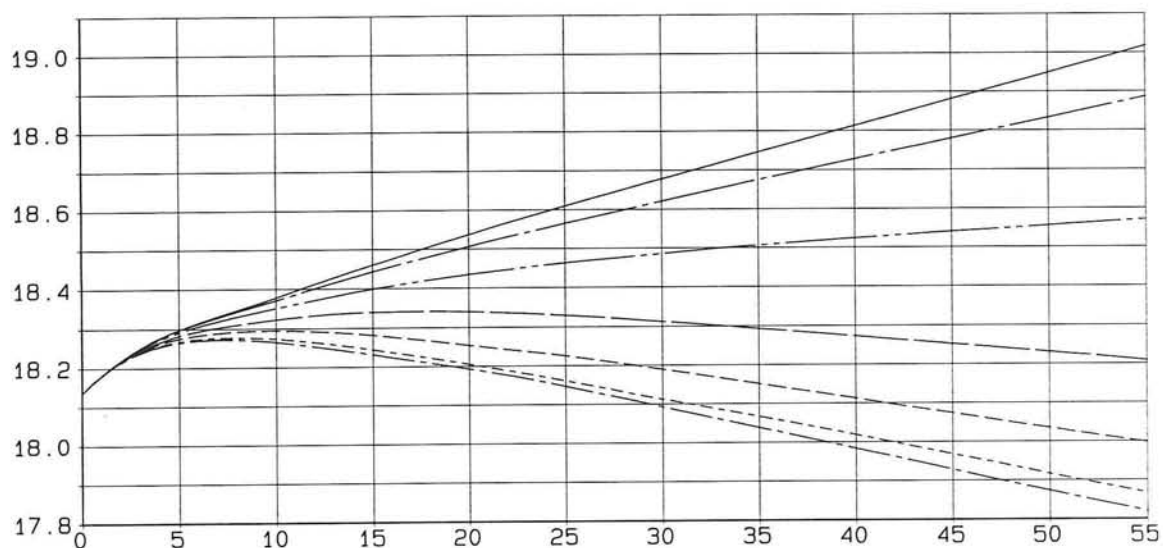
X

Lago de Maracaibo

DELFT HYDRAULICS

1995-03-14

Fig. 4.3



Total salinity in [kg] in Lake Maracaibo  
Lake defined as [M,N,K] = [1,16;1,23;1,8]  
For simulations X01 ... X21

TRISULA

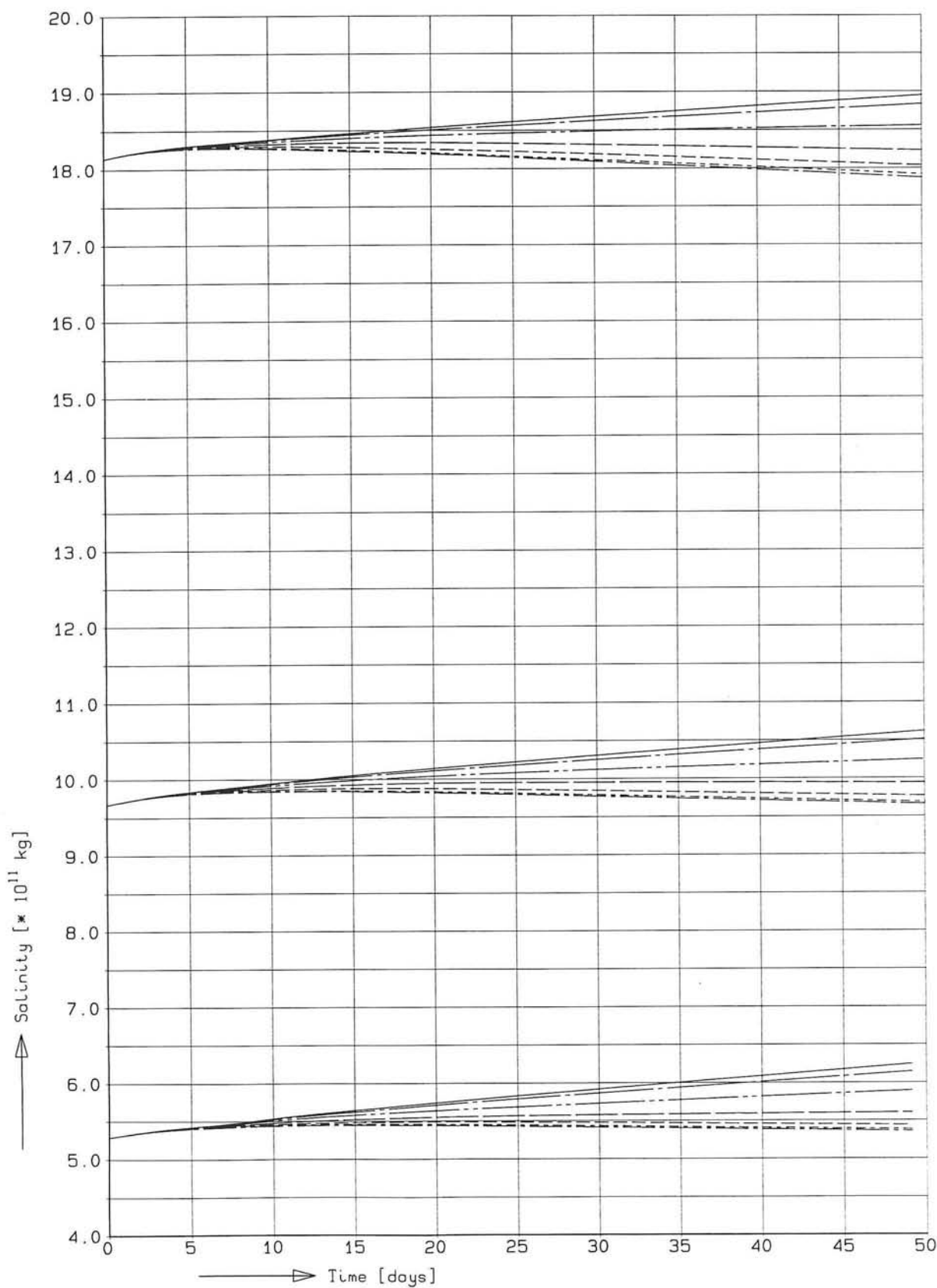
ZOUVOL

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-07

Fig. 4.4



Total salinity in [kg] in Lake Maracaibo  
 Lake defined as [M,N,K] = [1,16;1,23;1,8]  
 For simulations X01 ... X21

TRISULA

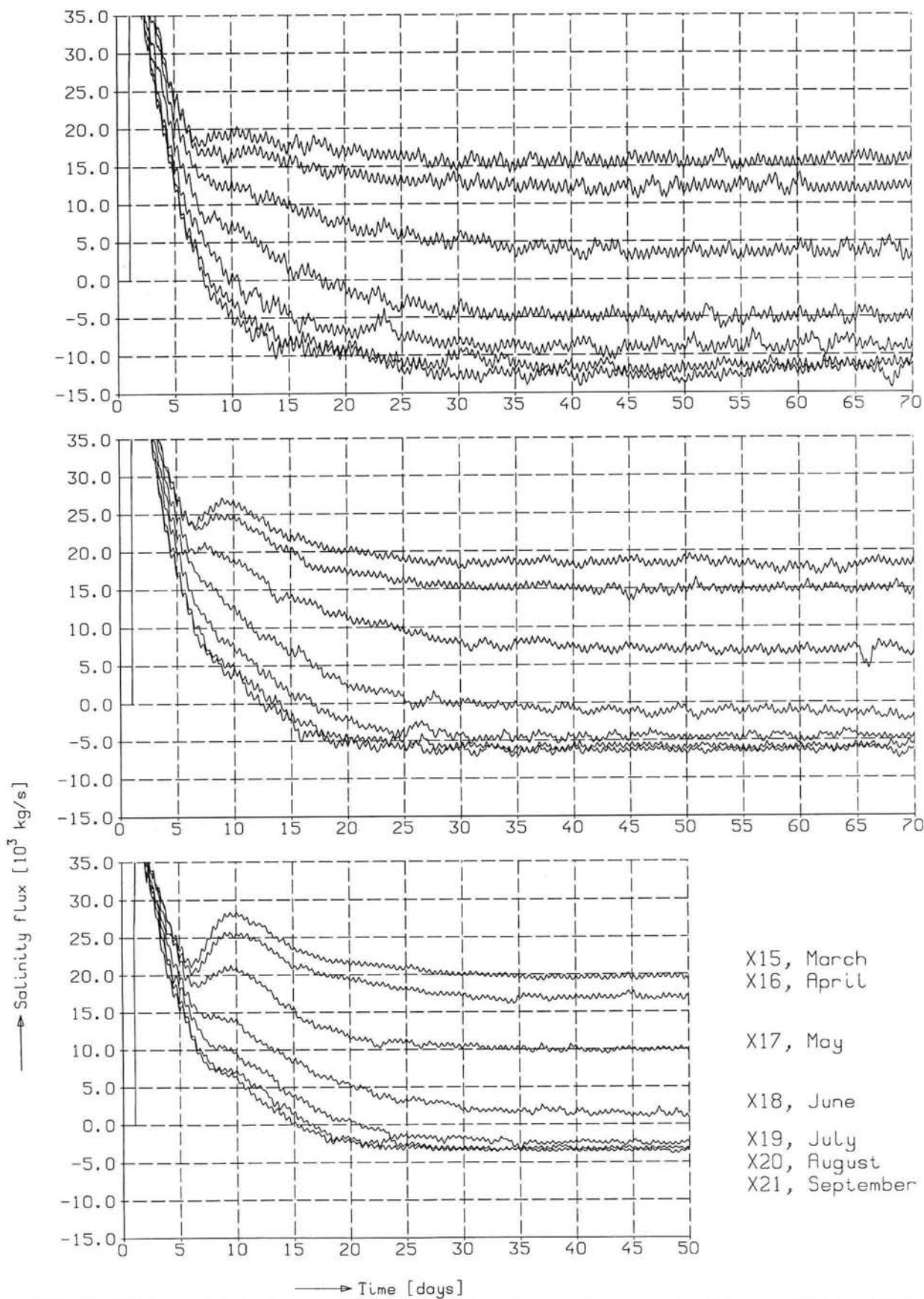
ZOUVOL

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-07

Fig. 4.5



Simulated salinity flux for cross-section Salina  
Computation of 70 days, simulations X01 .. X21  
Flux averaged over 24h50'

TRISULA

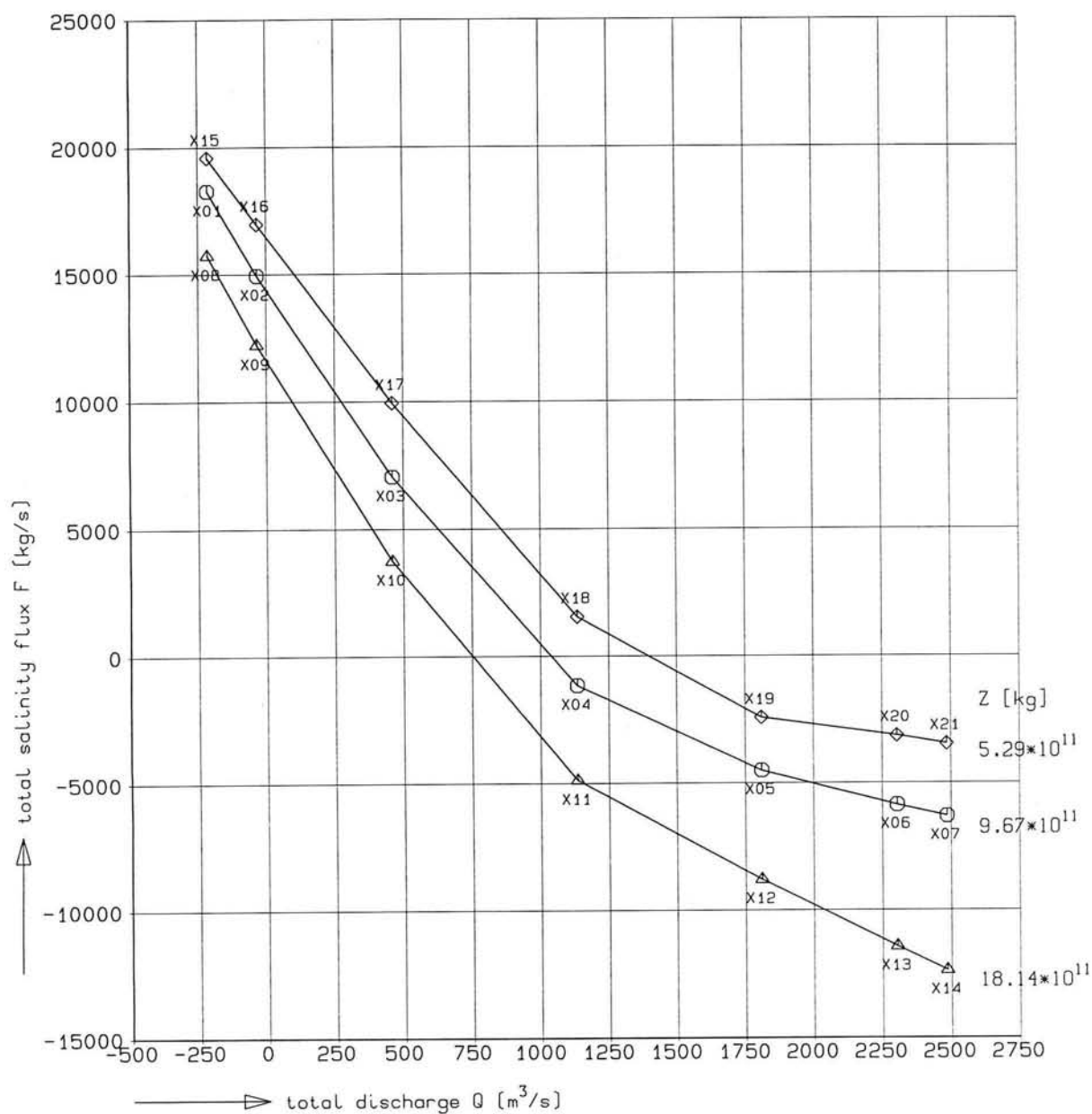
ZOUVOL

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-05

Fig. 4.6



Averaged salinity flux  $F$  as function of the river discharges  $Q$  and initial salt contents  $Z$ , for X01 .. X21 [incl.: k-epsilon turbulence model, wind, precipitation]

TRISULA

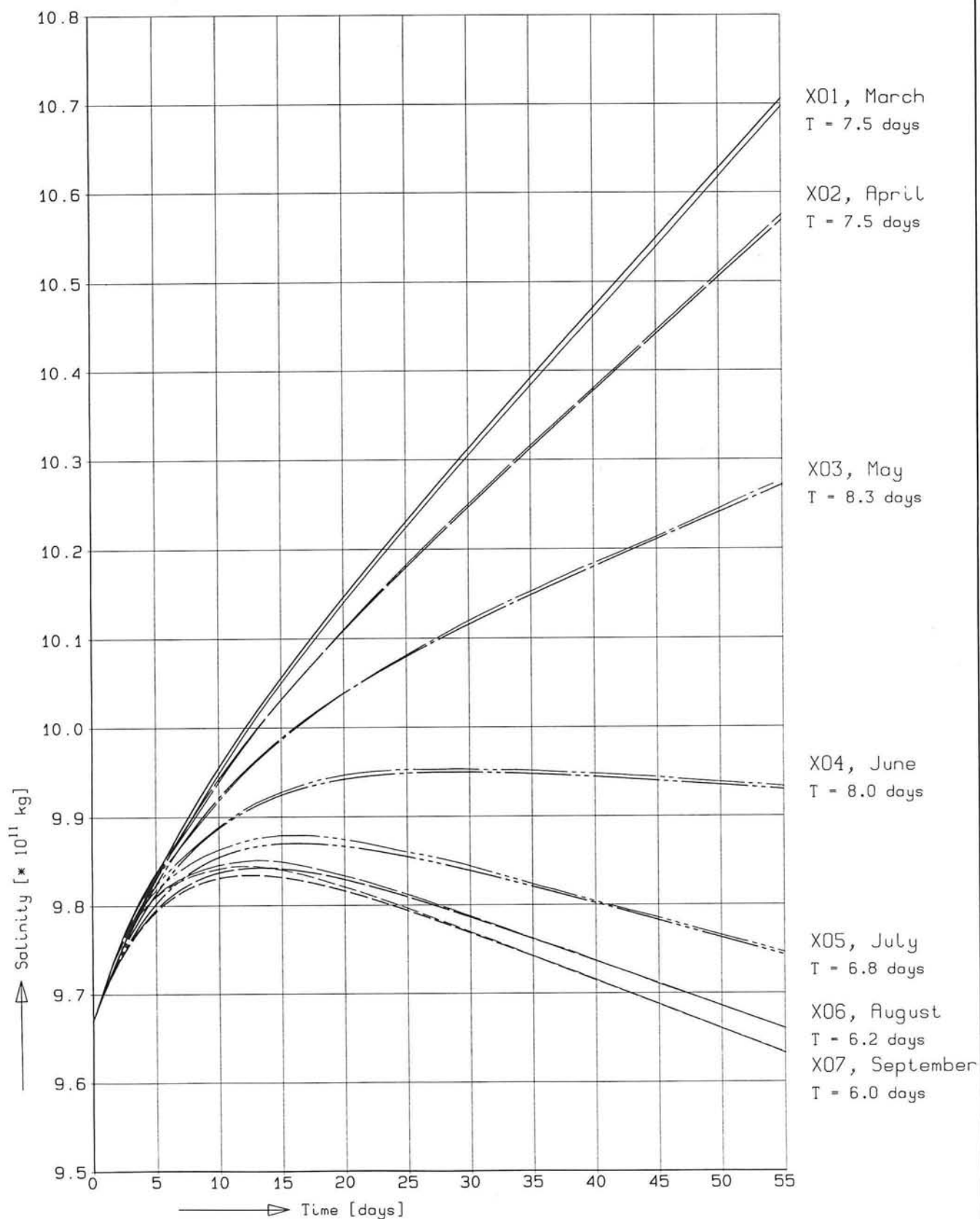
Lago de Maracaibo

DELFT HYDRAULICS

1995-04-05

Fig. 4.7

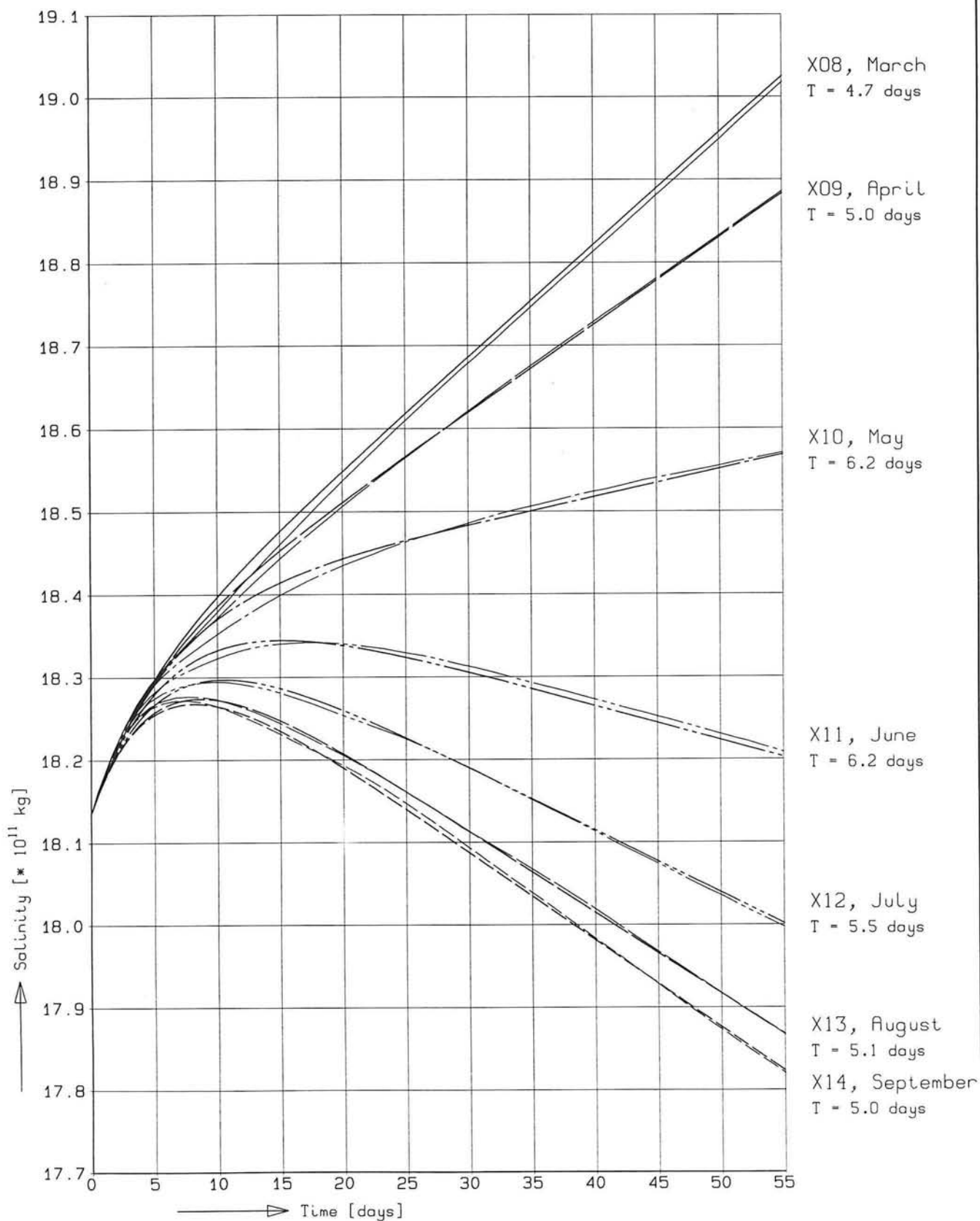




Calibration box-model, relaxation time T  
 - TRISULA simulations X01 ... X07, [thin lines]  
 - Simulations with BOX-model, [thick lines]

TRISULA

Lago de Maracaibo



Calibration box-model, relaxation time T  
 - TRISULA simulations X08 ... X14, [thin lines]  
 - Simulations with BOX-model, [thick lines]

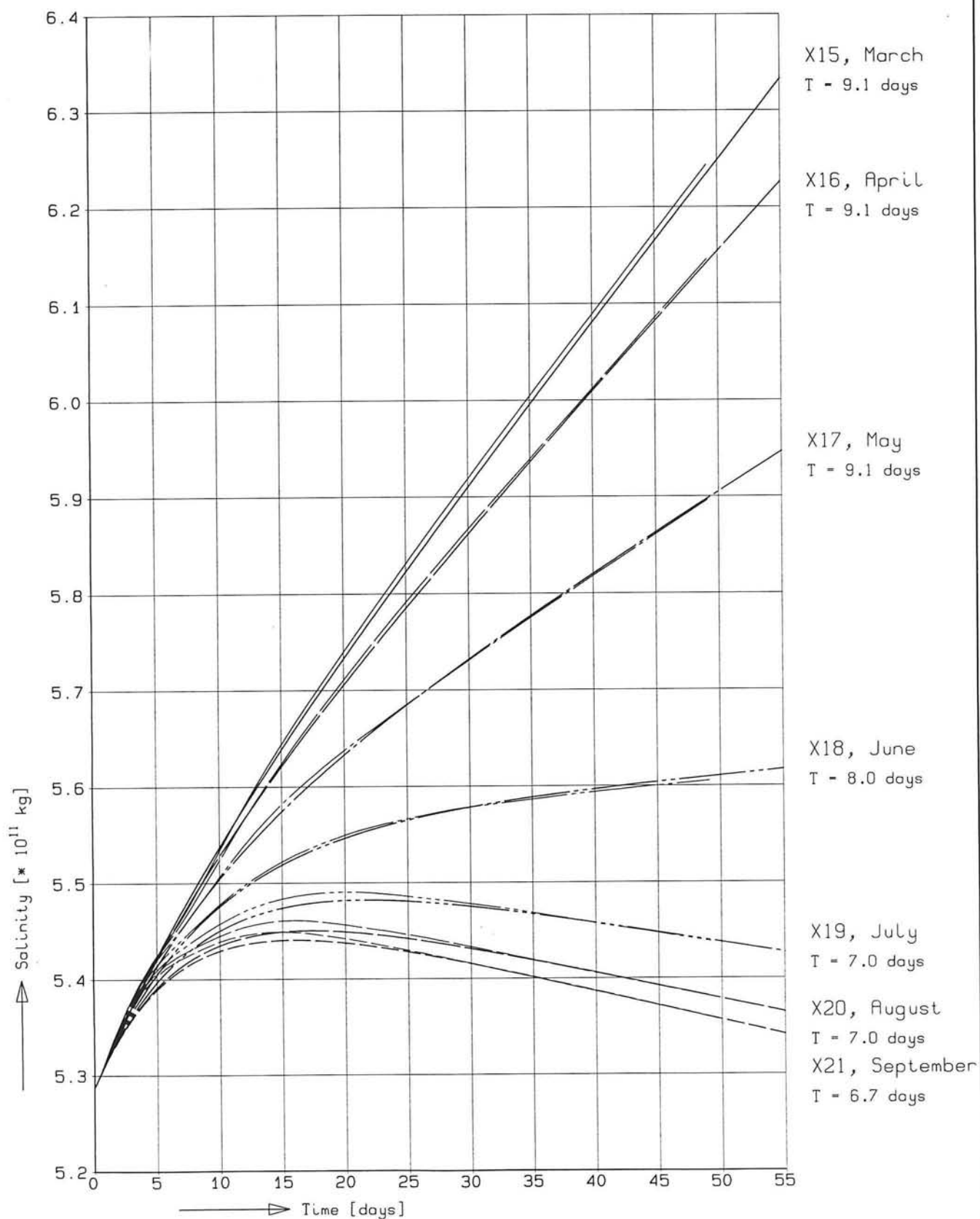
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-25

Fig. 5.2



Calibration box-model, relaxation time T  
 - TRISULA simulations X15 ... X21, [thin lines]  
 - Simulations with BOX-model, [thick lines]

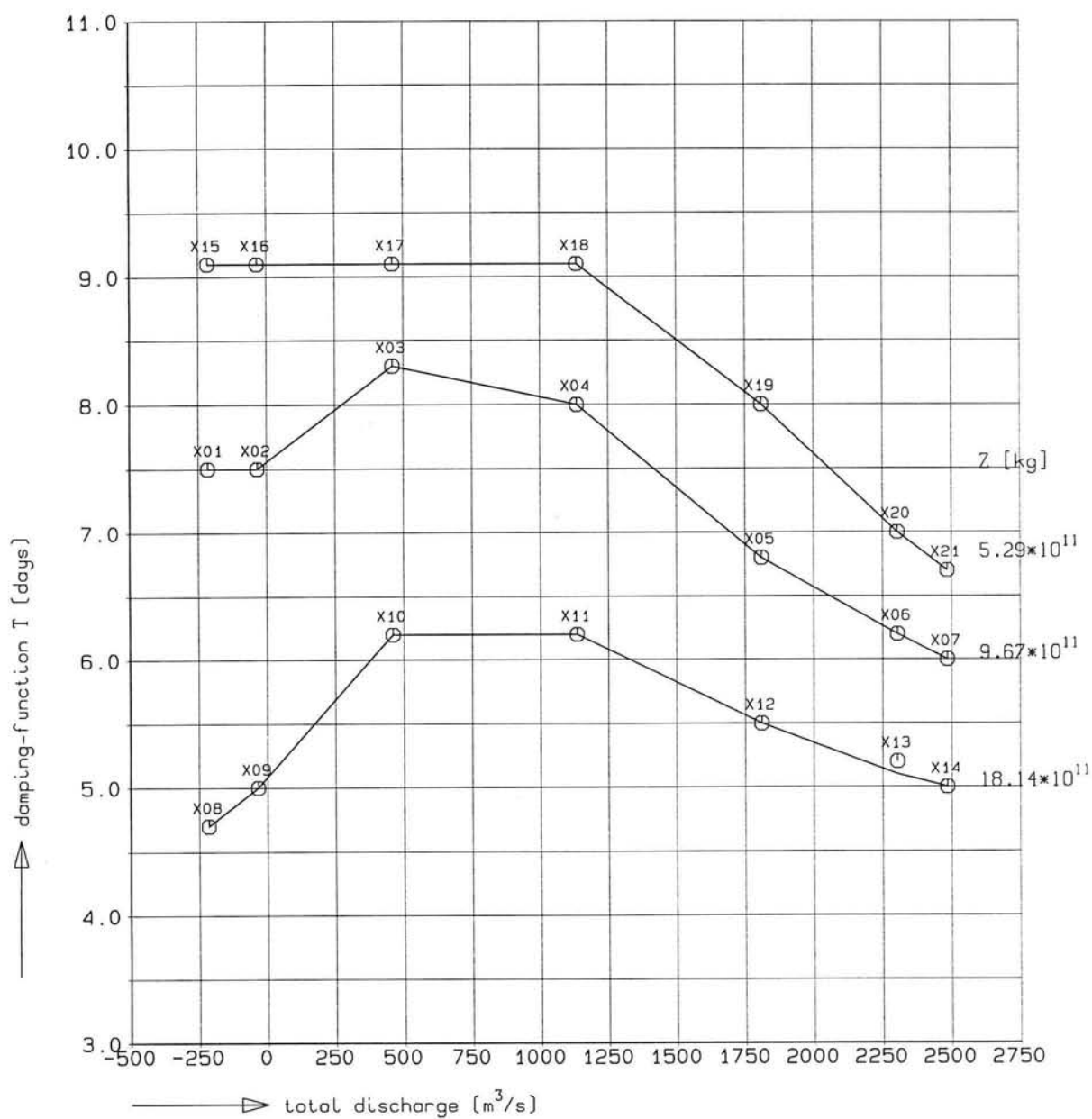
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-25

Fig. 5.3



Relaxation time  $T$  [days] as function of discharges  $Q$  [ $\text{m}^3/\text{s}$ ] and initial salt contents  $Z$  [kg] for simulations X01 ... X21

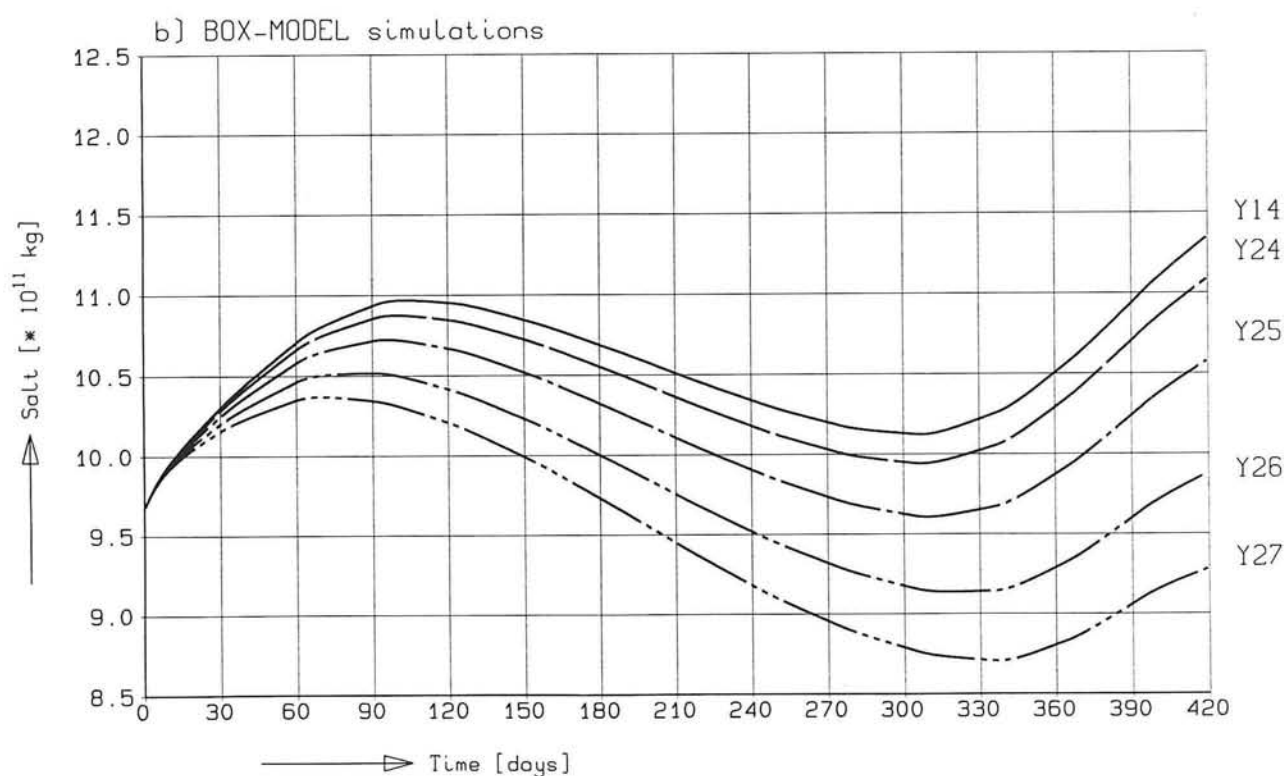
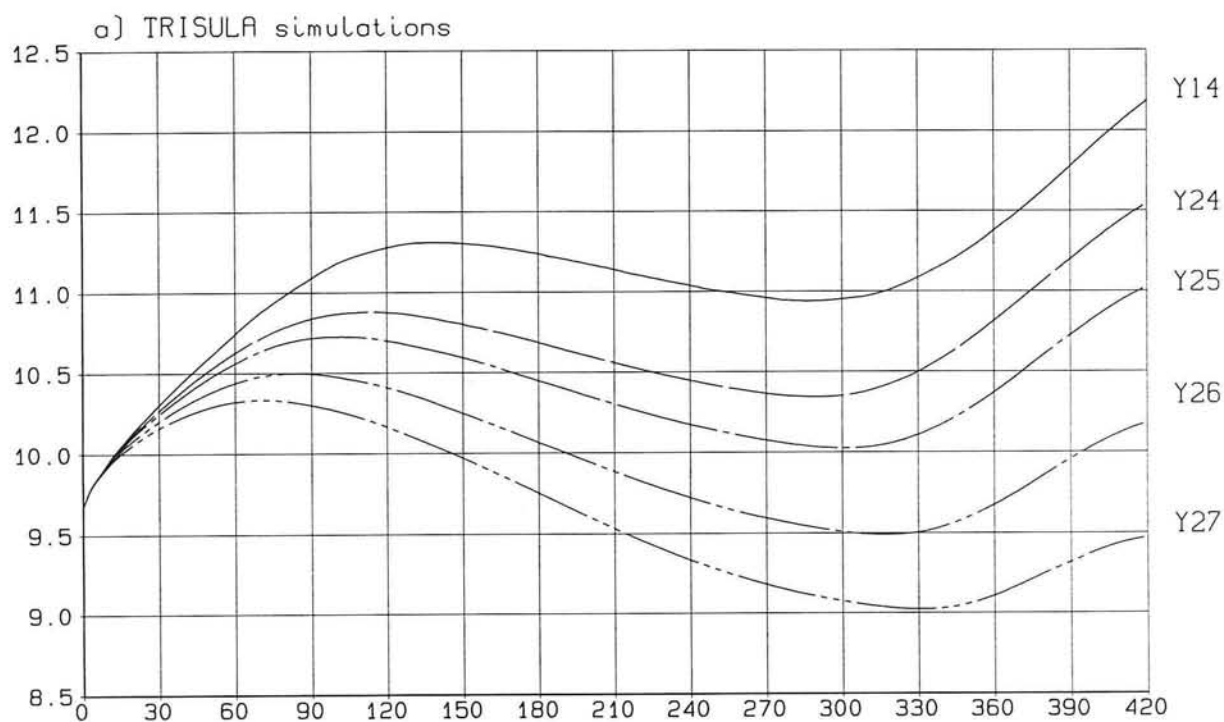
TRISULA

Logo de Maracaibo

DELFT HYDRAULICS

1995-04-25

Fig. 5.4



Total salt contents in Lake Maracaibo  
a) TRISULA simulations  
b) Simulations with BOX-model

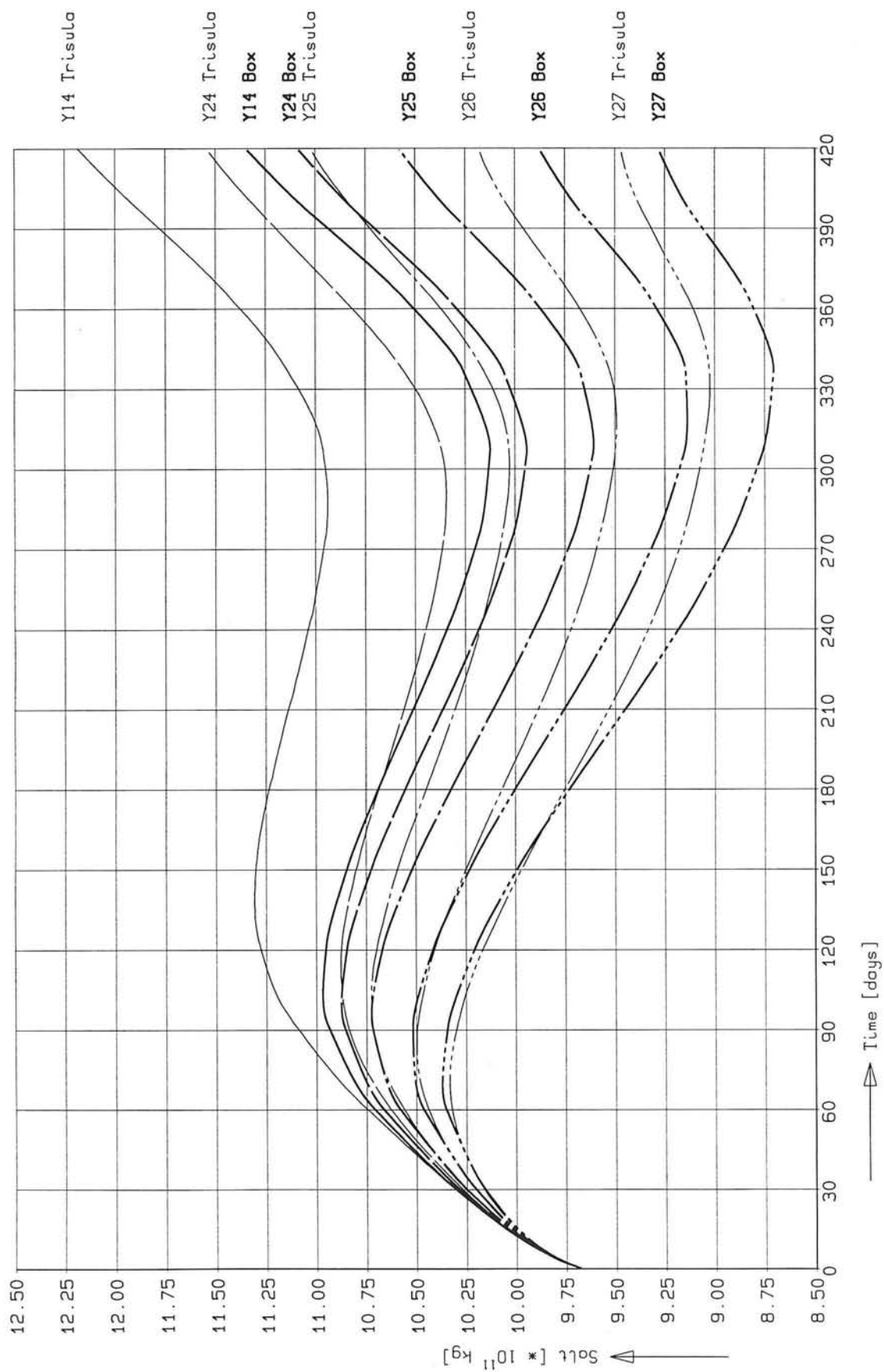
TRISULA

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-25

Fig. 5.5



Total salt contents in Lake Maracaibo  
 - TRISULA simulations (thin lines)  
 - BOX-model simulations (thick lines)

TRISULA

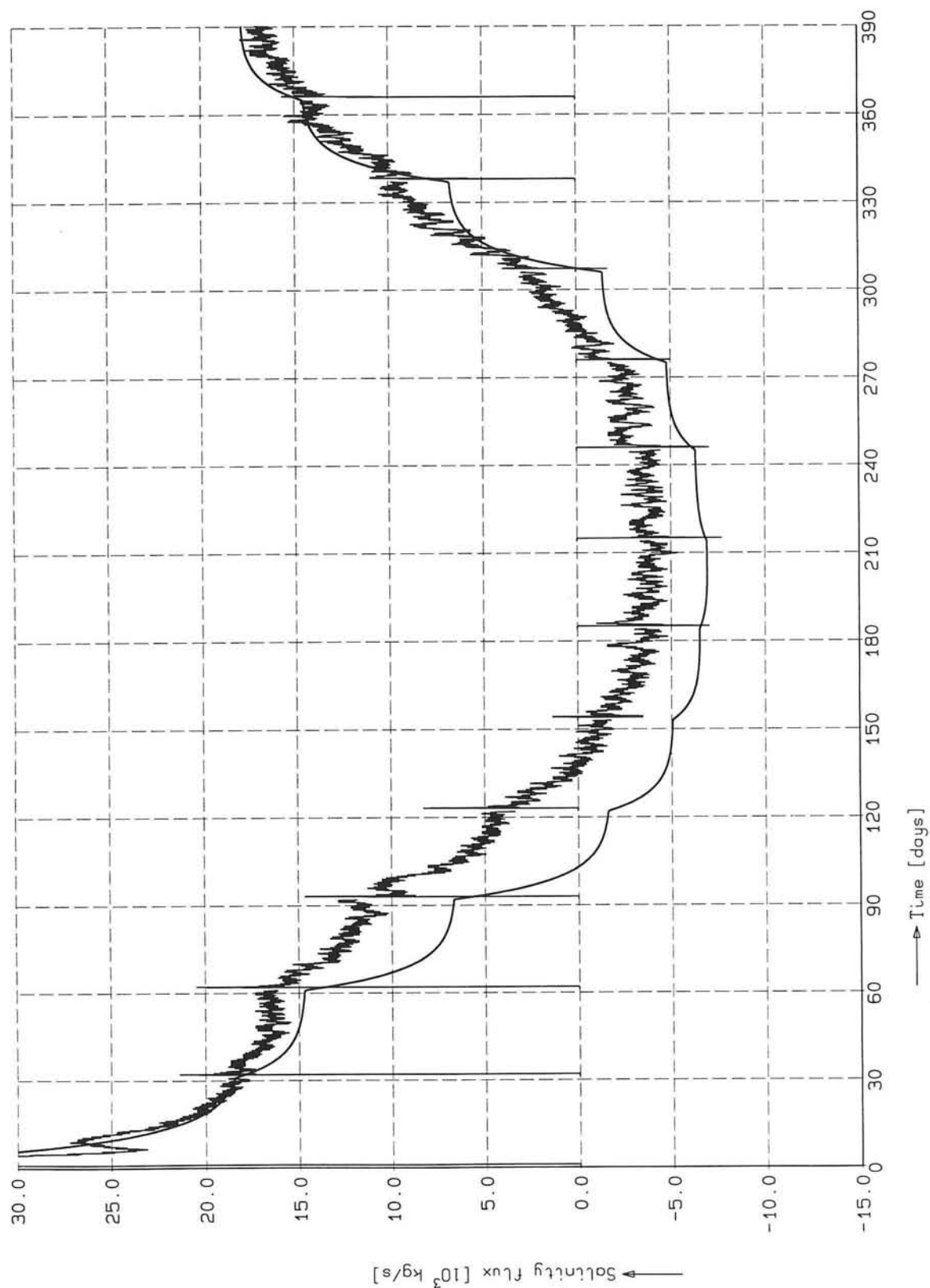
Lago de Maracaibo

DELFT HYDRAULICS

1995-04-25

Fig. 5.6

# AVERAGED SALINITY FLUX cross-section : SALINA



Salinity flux in Lake Maracaibo  
 - TRISULA simulation Y14  
 - BOX-model simulation Y14 (smooth line)

TRISULA

ZOUVOL

Lago de Maracaibo

DELFT HYDRAULICS

1995-04-27

Fig **5.7**