GCP/RAF/271/FIN-TD/29 (En) March 1995

# HYDROLOGICAL MODELLING

by

V. Podsetchine and T. Huttula

FINNISH INTERNATIONAL DEVELOPMENT AGENCY

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Bujumbura, March 1995

# PREFACE

The Research for the Management of the Fisheries on Lake Tanganyika Project (Lake Tanganyika Research) became fully operational in January 1992. It is executed by the Food and Agriculture organization of the United Nations (FAO) and funded by the Finnish International Development Agency (FINNIDA) and the Arab Gulf Programme for United Nations Development Organizations (AGFUND).

This project aims at the determination of the biological basis for fish production on Lake Tanganyika, in order to permit the formulation of a coherent lake–wide fisheries management policy for the four riparian States (Burundi, Tanzania, Zaïre and Zambia).

Particular attention will be also given to the reinforcement of the skills and physical facilities of the fisheries research units in all four beneficiary countries as well as to the build–up of effective coordination mechanisms to ensure full collaboration between the Governments concerned.

**Prof. O.V. Lindqvist**
**Project Scientific Coordinator**

**Dr. George Hanek**
**Project Coordinator**

**LAKE TANGANYIKA RESEARCH**
**FAO**
**B.P. 1250**
**BUJUMBURA**
**BURUNDI**

**Telex: FOODAGRI BDI 5092**

**Tel.: (257) 22 9760**

**Fax.: (257) 22 9761**

# GCP/RAF/271/FIN PUBLICATIONS

Publications of LTR are issued in two series:

* A series of **technical documents (GCP/RAF/271/FIN–TD)** related to meetings, missions and research organized by the project; and

* A series of **manuals and field guides (GCP/RAF/271/FIN–FM)** related to training and field work activities conducted in the framework of the project.

For both series, reference is further made to the document number **(01)**, and the language in which the document is issued: English **(En)** and/or French **(Fr)**.

For bibliographic purposes this document should be cited as follows:

**Podsetchine, V. and T. Huttula,** Hydrological modelling.
**1995** FAO-FINNIDA Research for the Management of the Fisheries on Lake Tanganyika.
**GCP/RAF/271/FIN–TD/29 (En): 20p.**

**Dr. Victor Podsetchine** and **Dr. Timo Huttula** are members of LTR scientific team. Both are with the National Board of Waters and Environment, Tampere Water and Environment District, P.O. Box 297, FIN-33101 Tampere, Finland.

# ABSTRACT

A three–dimensional numerical circulation model of Lake Tanganyika is extended by including baroclinic term in momentum equations, representing the vertically integrated horizontal density gradients. The relative importance of different terms in governing equations is considered. Momentum equations are coupled via equation of state with energy equation, describing water temperature dynamics, and thus, forming closed system. Results of flow calculations for some typical water temperature distribution, known from observations (diagnostic computations), are presented. Difficulties in numerical modelling of thermocline dynamics are discussed. Possible steps in improvement of numerical model are suggested.

## ACKNOWLEDGEMENTS

The authors express their gratitude to Prof. Ossi V. Lindqvist, (University of Kuopio) the Scientific Coordinator of the LTR project and Dr. Hannu Mölsä (University of Kuopio) for their help. Dr. George Hanek, the Project Coordinator, and his field staff in Bujumbura, Kigoma and Mpulungu have made it possible to deploy our instruments and obtain the necessary data. Mr. Pekka Kotilainen, APO-Fisheries Biologist, has been responsible for organizing the cruises and the controlling the instruments.

## TABLE OF CONTENTS



**LIST OF FIGURES**

# 1. INTRODUCTION

Baroclinic effects or pressure changes due to water density variations within a water column play an essential role in the total hydrodynamical regime of the oceans and big lakes (Gill, 1982). It can be presumed that they are also important in the dynamical regime of Lake Tanganyika, despite the small seasonal temperature variations, as compared to lakes in moderate zones. Together with wind forcing and topographical effects, they create a very complicated permanently varying structure of currents within a lake, which, in turn, affect its biological productivity. As it is known from previous studies (Coulter et *al.,* 1991), Lake Tanganyika belongs to the class of meromictic tropical rift lakes with stable thermocline at depths from 50 to 100 m. Hypolimnetic waters are anoxic and have a constant temperature, around 23.5°C (Huttula et al., 1994). Strong southerly winds, blowing during the dry season from the end of May to mid-September, cause tilting of thermocline and upwelling of deep anoxic waters at the south end of the lake. Previous experiments with a three–dimensional circulation model (Podsetchine and Huttula, 1994) included only wind forcing (barotropic component of the pressure gradient) over the lake. They showed the model's sensitivity to the spatial distribution of the near–surface wind shear stresses.

This report gives an estimation of different terms in momentum equations, describes the water temperature regime in different parts of the lake on the basis of measurements, conducted by LTR, Hydrodynamical sub–program and previous studies. Results of baroclinic calculations using the prescribed water temperature and density distributions (diagnostic calculations) are discussed. Numerical experiments revealed some difficulties in computations of the thermocline dynamics. Possible solutions to overcome these problems are also discussed.

# 2. RESULTS

## 2.1 ESTIMATIONS OF THE SIGNIFICANCE OF DIFFERENT TERMS IN MOMENTUM EQUATIONS

The brief verbal description of the three-dimensional numerical circulation model of Lake Tanganyika was given in the previous report (Podsetchine and Huttula, 1994). Here our discussion will be restricted to the estimation of the relative role of different terms in momentum equations. The governing hydrodynamical equations, assuming that hydrostatic and Boussinesq approximations are valid, may be written in vector form as follows:

momentum

$$\frac{\partial \nu}{\partial \tau} + (\quad \nu)\nu + f \times \nu + w \frac{P}{\rho} + \quad (\nu_H \quad \nu) + \frac{\partial}{\partial z}\left(\nu_z \frac{\partial \nu}{\partial z}\right), \qquad \mathbf{(1)}$$

hydrostatic equation

$$\frac{\partial P}{\partial z} = -\rho g, \qquad \mathbf{(2)}$$

continuity equation

$$\frac{\partial w}{\partial z} + \quad \nu = 0, \qquad \mathbf{(3)}$$

free-surface evolution

$$\frac{\partial \zeta}{\partial t} + \int_{-h}^{\zeta} (\quad \nu) dz = 0, \qquad \mathbf{(4)}$$

equation of state

$$\rho = \rho(T), \qquad \mathbf{(5)}$$

energy equation

$$\frac{\partial T}{\partial t} + v \quad T + w \frac{\partial T}{\partial z} = \quad \cdot (K_H \quad T) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right). \qquad \mathbf{(6)}$$

Here **V(u,v)** is the horizontal velocity vector**, w** is the vertical velocity component, **f** is the Coriolis parameter**, P** is pressure, ρ is water density, **g** is gravity acceleration, $\mathbf{V_H}$, $\mathbf{V_Z}$ are horizontal and vertical turbulent exchange coefficients respectively, **T** is water temperature, $\mathbf{K_H}$, $\mathbf{K_Z}$ are horizontal and vertical diffusion coefficients respectively, ζ is water surface elevation, **h** is the depth from reference level, **v** is the horizontal gradient operator, **t** is time and **z** is the vertical coordinate positive upward.

Integrating hydrostatic equation (2) and substituting expression for **P** in momentum equation, (1) can be rewritten as

$$\frac{\partial \nu}{\partial t} + ( \quad v)V + f \times V + w\frac{\partial v}{\partial z} = -g \quad \zeta - \frac{g}{\rho}\int_z^\zeta \rho dz' + \quad (v_H \quad V) + \frac{\partial}{\partial z}\left(v_z\frac{\partial V}{\partial z}\right) \qquad \textbf{(7)}$$

**(1) (2) (3) (4) (5) (6) (7) (8)**

Introducing non-dimensional variables by expressions: $\mathbf{V^*=V/V_0}$. $\mathbf{W^*=w/V_0}$ $\mathbf{X^*=x/L}$, $\mathbf{Z^*=z/H}$, **T=ft** and so on, where $\mathbf{V_0}$, **L**, **H** are characteristic scales of velocity, horizontal and vertical length, the non–dimensional combinations of parameters appear in equation (7). Calculated values of these parameters with the characteristic scales of Lake Tanganyika are combined in Table 1 : **L** = 600,000 m, **H** = 500 m, $\mathbf{V}_0 = 0.5\ ms^{-1}$, $\mathbf{W_0} = 1.x\ 10^{-3} ms^{-1}$, **f**= $1.52 \times 10^{-5}\ s^{-1}$ , $\mathbf{V_{H0}} = 100\ m^2s^{-1}$, $\mathbf{v_{z0}} = 10^{-2}\ m^2s^{-1}$

Table 1.
Characteristic values of different terms in momentum equations.

| Term of equation | Non–dimensional parameter | Numerical value |
|---|---|---|
| (1) | 1 | 1 |
| (2) | Rossby = $U_0/(fL)$ | 0.05 |
| (3) | 1 | 1 |
| (4) | $W_0/(fH)$ | 0.13 |
| (5) | $gH/(fLU_2)$ | 1000 |
| (6) | $gH/(fLU_0)$ | 1000 |
| (7) | $vHo/(fL^2)$ | $1.82 \times 10^{-5}$ |
| (8) | $v_{z0}/(fH^2)$ | $2.60 \times l0^{-3}$ |

Of course, these are rough average estimates, but they clearly demonstrate the dominating role of both the barotropic pressure gradient (term 5 ) and the baroclinic pressure gradient (term 6). Relative ratios of different terms vary in time and space, for example, convective terms are important in shallow coastal zones where high horizontal velocity gradients are observed. Similar estimates of the significance of different terms in momentum equations for lakes in temperate zones were presented by Demin *et al*. (1990).

## 2.2 WATER TEMPERATURE REGIME - OVERVIEW OF PREVIOUS STUDIES AND LATEST MEASUREMENTS

The temperature regime of Lake Tanganyika is characterized by small variations in time and depth if compared with lakes of temperate zones (Coulter *et al*., 1991). Due to high temperatures, density gradients are enough to ensure the stratification. There are two main periods in the year with distinctive weather characteristics, which determine the peculiarities of the water temperature regime. After the cessation of the southerly winds in September, heating of the surface layers begins. Reestablishment of thermocline takes place. At the end of May, it is located at the depth of 40 m in the southern part of the lake and is slightly tilted northward. In the north, it is located at the depth of 60m (Fig. 2.). Figure 1 shows the locations of the stations where profiles were measured. Below thermocline, in hypolimnion, water temperature is practically constant, though it gradually decreases with depth. The minimum temperature, measured in the deepest part of the lake, was 23.25°C (Coulter *et al.,* 1991). Horizontal temperature gradients during the wet season are small, around l.5°C.

From May to September, during the dry season, when strong regular southerly winds blow all over the lake, horizontal gradients in surface layers increase to 2-2.5°C. Thermocline is moved downwards and becomes more sharpened in the north, where it can be found at the depth of 80-100 m. It breaks at the south end of the lake, where vertical mixing is most intensive during this period (Fig. 3). The amplitude of diurnal fluctuations of water temperature rapidly decreases with depth from 2°C at the depth of 1 m to 0.5°C at the depth of 5 m. At greater depths, long-term oscillations are observed, probably connected with long—period internal waves (Fig. 4).

## 2.3 PURE BAROCLINIC FLOW PATTERNS UNDER THE TYPICAL WATER TEMPERATURE DISTRIBUTION

The barocline model was tested for a rectangular basin, in order to check the correctness of the numerical approximations of the baroclinic term in momentum equations. The dimensions of the model rectangular sea were 400 km x 800 km with a constant depth 65 m. This model roughly approximates the North Sea (Davies and Owen, 1979). Temperature distribution over the surface, shown in Figure 5, was constant over the vertical coordinate and did not change in time. The horizontal temperature gradient was equal 10°C/800 km. The model was run for a 5-day period with a time step of 6 minutes. The computational grid consisted of 45 nodes and 36 triangular elements. Calculated water level elevations, and depth— averaged flow field, induced by horizontal density gradients are shown in Figures 4 and 5. The total level difference was about 2.5 cm, which was in accordance with preliminary estimates. The flow field turned to the right from the direction of density gradient due to the influence of the Coriolis force.

In order to get a first impression about the sensitivity of the Lake Tanganyika model to baroclinic effects, temperature distribution typical for August, according to Coulter *et al.*, 1991 (Fig. 6) was used to derive the density distribution over the lake. In the calculations, no wind forcing was applied. These types of calculations, when water temperature is not calculated are called diagnostic computations. In this way, it is possible to study the effect of pressure variations on the flow field. In this particular case, the pressure variations were caused by density gradients (barocline effect).

A series of numerical tests showed that the model, with a time step order of several minutes, gives unrealistic high values of velocities. Thus the model was run with shorter time steps. Results of calculations, presented in Figures 7–13 were performed with a time step of 30 seconds, horizontal eddy diffusivity was 50 $m^2s^{-1}$. Calculations were ended after twelve hours, when the calculated fields were more or less consistent with each other. First of all, they reveal a zone of numerical instability -eastern coast of the northern trench, where the highest bottom slope gradients are observed.

A probable reason for this could lie in the low vertical resolution of the model (10 layers). It was shown by Haney (1991) that a 10-layer primitive model with sigma-coordinate transformation, applied to the topographic slopes typical for the California Current region, may produce a false geostrophic current of the order 10–12 cm $s^{-1}$. In our case, the bottom slopes are also very high: within one grid element a depth varies from 30-50 m to 1000 m, in some areas of Lake Tanganyika.

For the deep zones, the present vertical resolution gives a vertical grid cell size more than one hundred meters, while in the coastal zone it decreases to 4–5 meters. The straightforward solution is to increase vertical resolution two or three times. However, this will increase computational time drastically. This means that updating of the grid system is required.

## 3. CONCLUSIONS

Estimations of the weights of different terms in momentum equations clearly showed the dominant role of barotropic and baroclinic pressure gradients. An accurate approximation of these terms is required in the model, since small errors in calculations of water temperature distribution will cause considerable errors in calculations of velocities and vice versa.

Calculations of pure baroclinic currents in Lake Tanganyika were done using prescribed water temperature distribution. They revealed some numerical problems. The reason for this lies in the “hydrostatic inconsistency” (Haney, 1991) of the present version of the model, i.e. poor vertical resolution, associated with the sigma–coordinate system.

Improvement of the model performance requires the updating of the model, since an increase in the number of vertical grid system of the layers, will considerably increase a computational time. Parallelization of the code, full exploitation of the architecture of the modern High Performance Computers will give considerable savings in CPU time. This refinement of the grid will be done in the next phase of the model development work. The lake wide CTD measurements in a certain tilting situation of thermocline, together with flow measurements, will help considerably in the development of the baroclinic model.

## 4. REFERENCES


**Coulter G.W. , Spigel R.H.** Hydrodynamics. In: Lake Tanganyika
**1991** and its life (Chapter 3). British Museum (Natural History) and Oxford University Press.

**Davies A.M. and Owen A**. Three dimensional numerical sea model
**1979** using the Galerkin method with a polynomial basis set. Appl. Math. Modelling, 3, 421.

**Demin Yu. L., Akhverdiev 1.0., Beletsky D.V., Filatov N.N.**
**1990** Hydrodynamical diagnosis of currents in big lakes and reservoirs. Department of Computational Mathematics of Academy of Sciences, Moscow. Preprint N 267. 38 pp. /in Russian/.

**Gill, A.E.** Atmosphere—Ocean Dynamics. Academic Press. New York.
**1982**

**Haney R.L.** On the pressure gradient force over steep topography
**1991** in sigma coordinate ocean models. J. of Physical Oceanography, V. 21. P.610 - 619.

**Hughes T.J.R., Ferencs R.M. and Hallquist J.O.** Large-scale
**1986** vectorized implicit calculations in solid mechanics on a Cray XMP/48 utilizing EBE preconditioned conjugate gradients. Computer Methods in Applied Mechanics and Engineering. 61. p.215—248.

**Huttula, T., Podsetchine, V.** Hydrological Modelling on Lake
**1994** Tanganyika. FAO/FINNIDA Resarch for the Management of the Fisheries on Lake Tanganyika. **GCP/RAF/271/FIN-TD/20 (En): 19 p.**

**Huttula, T., Podsetchine, V., Peltonen, A., Kotilainen, P.,**
**1994 Mölsä, H.** Hydrology of Lake Tanganyika. Nordic Hydrological Conference, Torshavn, Faroe Islands. 2—4 August 1994. NHP-report no.34. P.43-52.

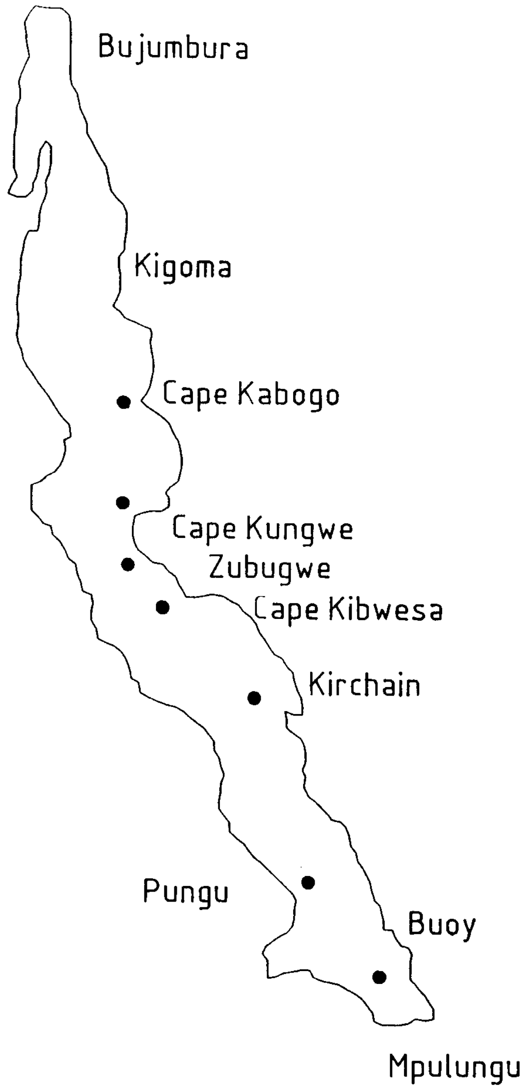

Bujumbura
Kigoma
Cape Kabogo
Cape Kungwe
Zubugwe
Cape Kibwesa
Kirchain
Pungu
Buoy
Mpulungu

Fig. 1

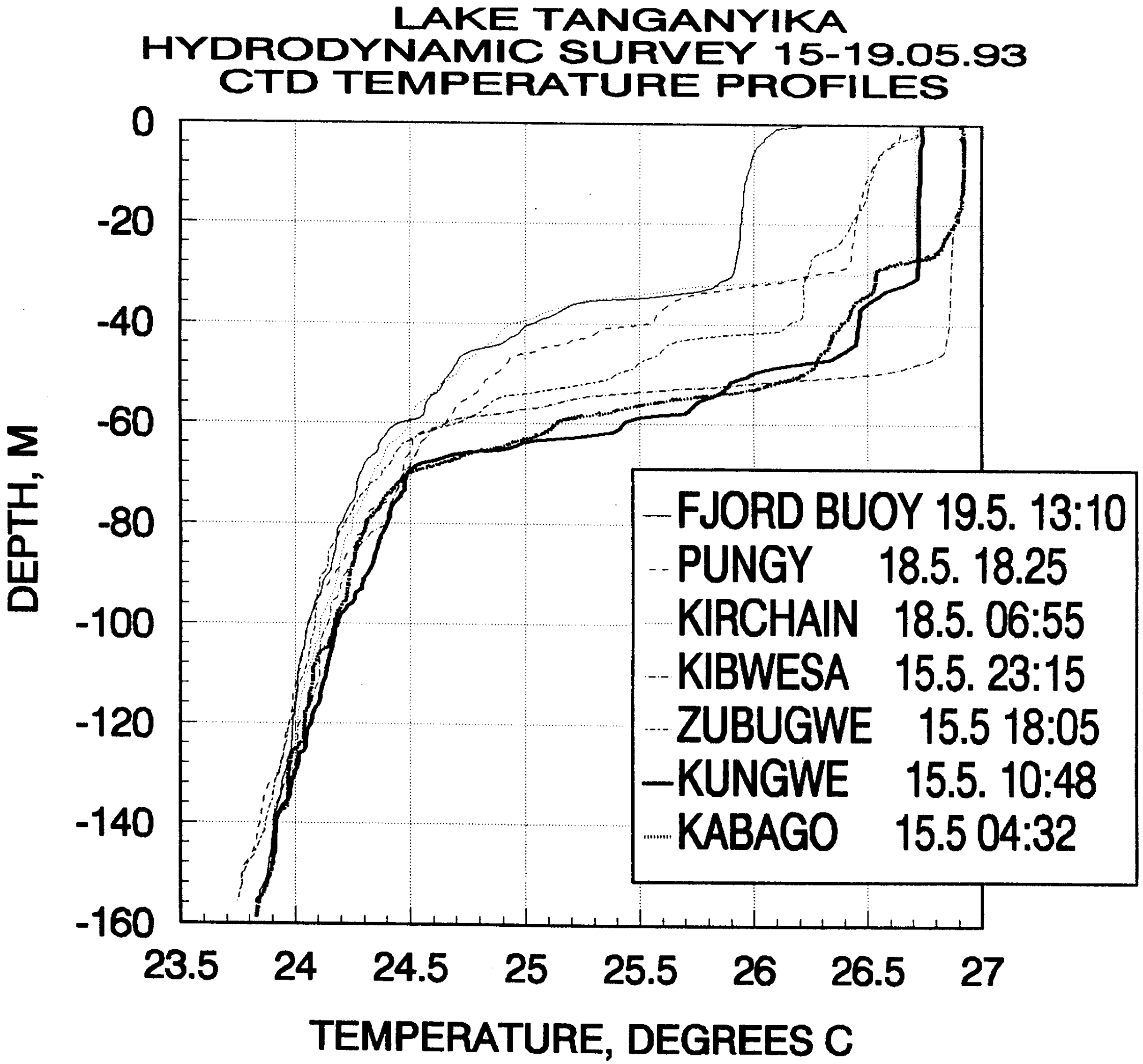

LAKE TANGANYIKA
HYDRODYNAMIC SURVEY 15-19.05.93
CTD TEMPERATURE PROFILES
0
-20
-40
-60
-80
-100
-120
-140
-160
DEPTH, M
23.5
24
24.5
25
25.5
26
26.5
27
TEMPERATURE, DEGREES C
FJORD BUOY 19.5. 13:10
PUNGY 18.5. 18.25
KIRCHAIN 18.5. 06:55
KIBWESA 15.5. 23:15
ZUBUGWE 15.5 18:05
KUNGWE 15.5. 10:48
KABAGO 15.5 04:32

Fig. 2

LAKE TANGANYIKA WATER TEMPERATURE VS. TIME AND DEPTH
STATION AT MPULUNGU. TIME: 10.06 - 14.07.93

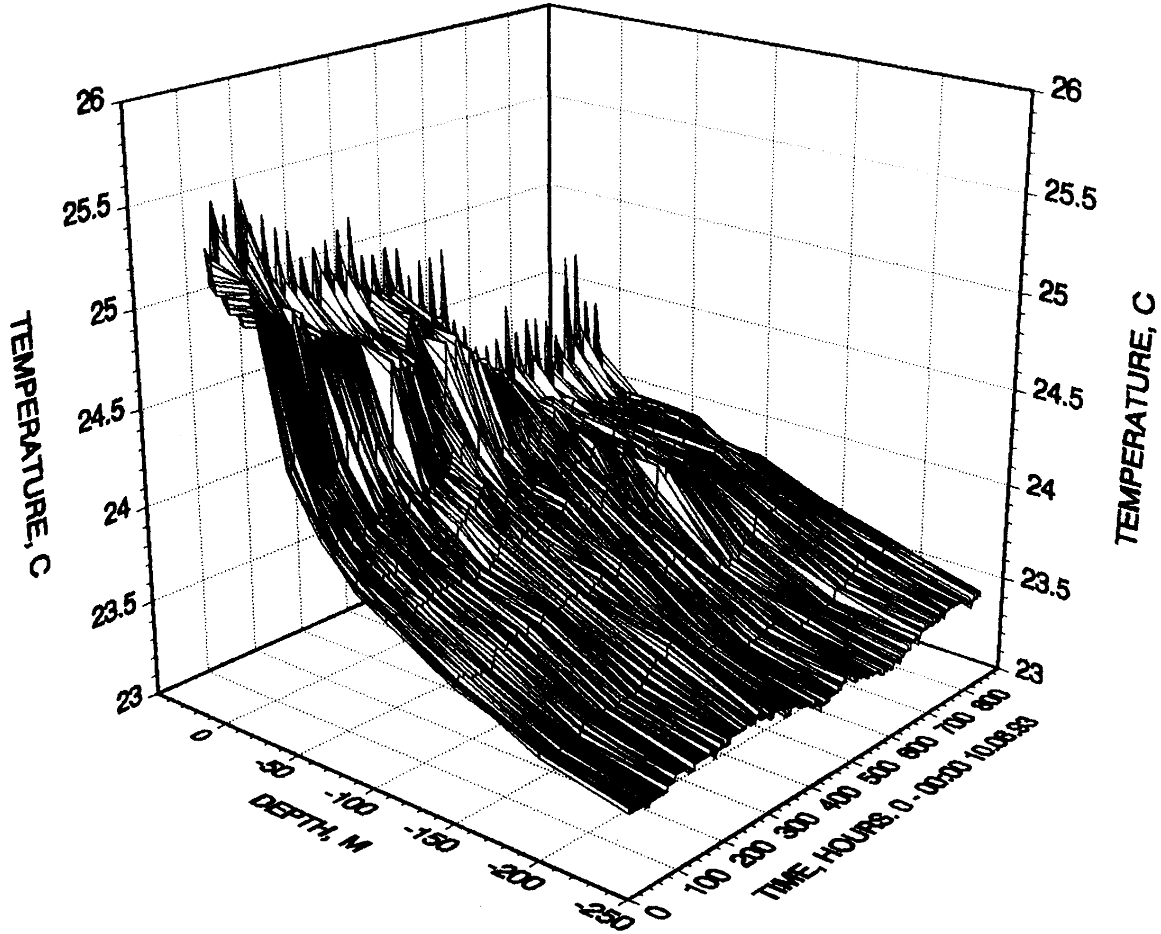



Fig. 3

# WATER SURFACE ELEVATION

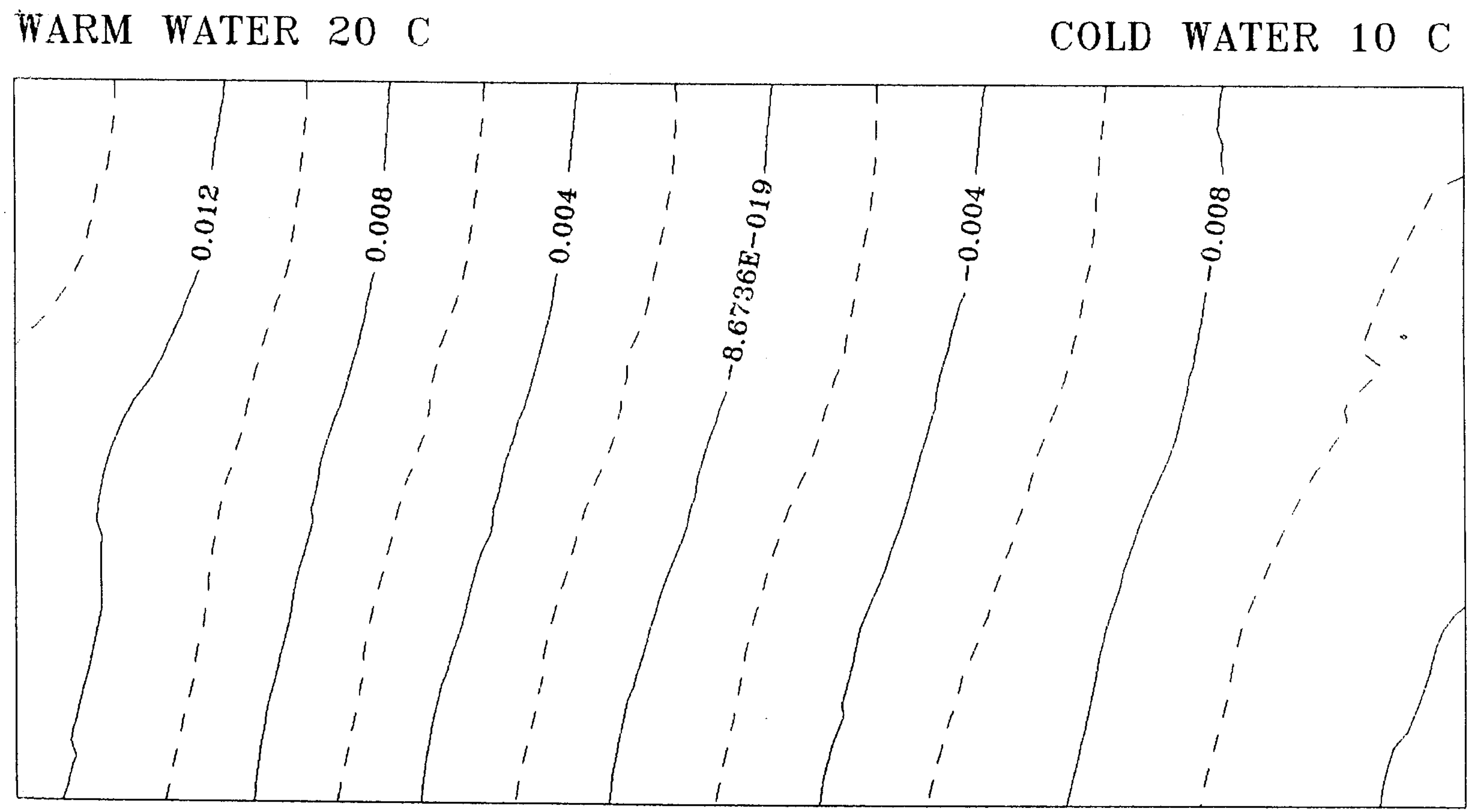
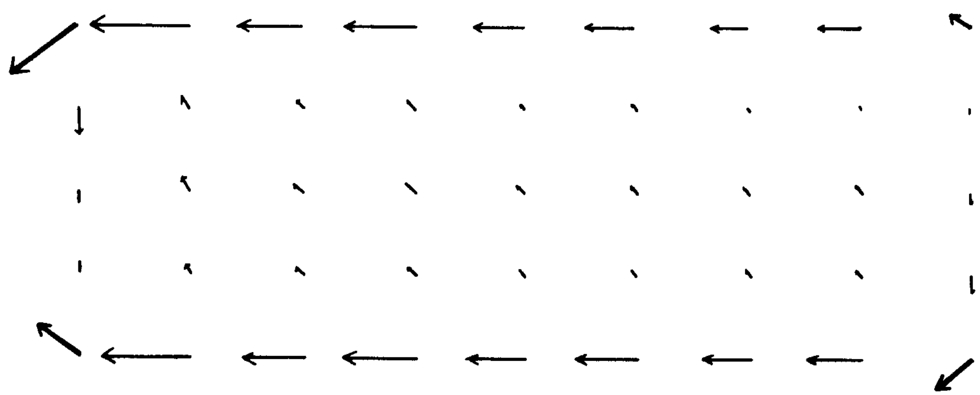



Fig. 4

DEPTH-AVERAGED FLOW



VELOCITY SCALE: 1 CM/S
MAXIMUM VALUE: 1.3260 CM/S

Fig. 5

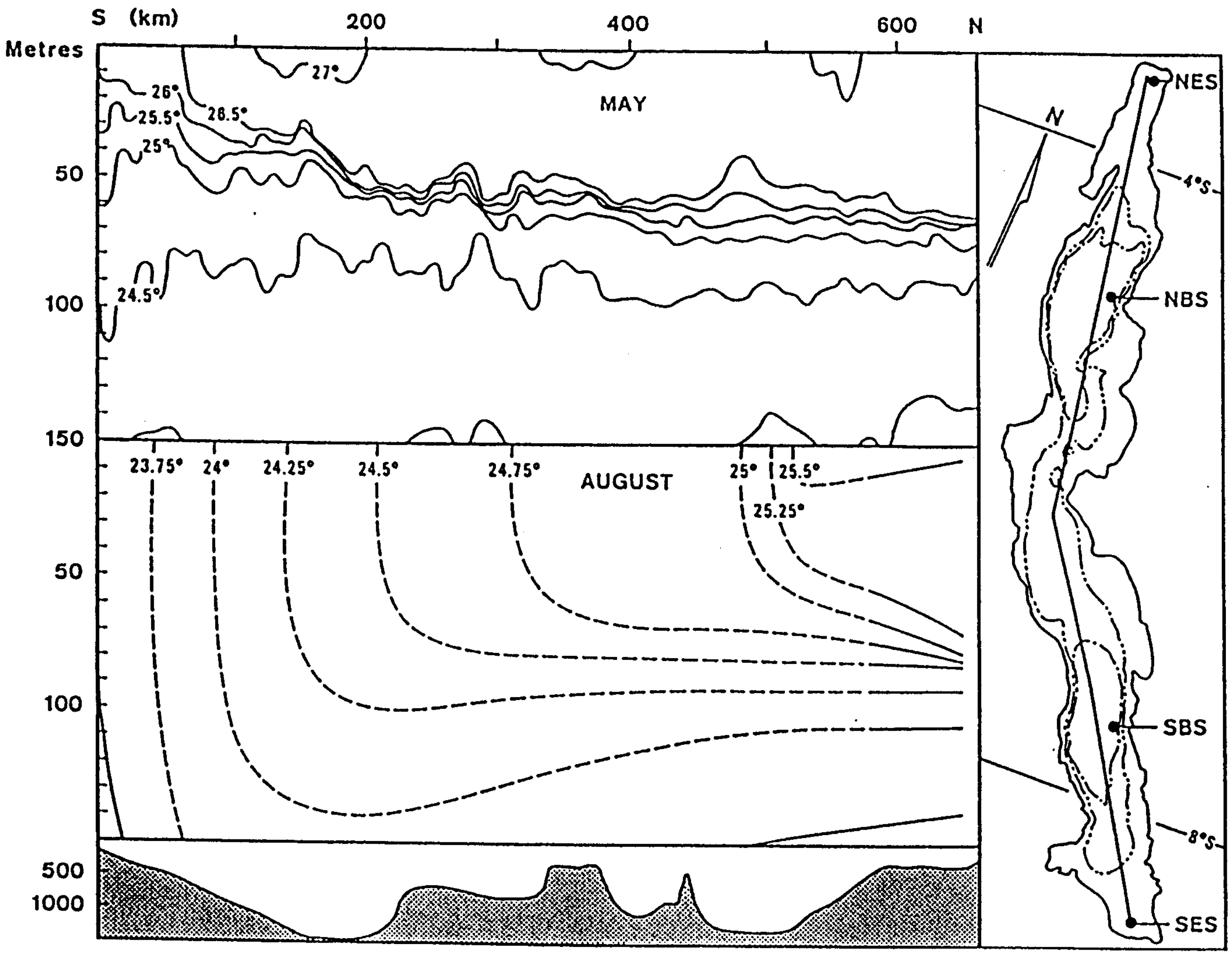

S (km)
200
400
600
N
Metres
MAY
27°
26°
26.5°
25.5°
25°
24.5°
50
100
150
AUGUST
23.75°
24°
24.25°
24.5°
24.75°
25°
25.5°
25.25°
50
100
500
1000
NES
NBS
SBS
SES
4°S
8°S
N

Fig. 6

# D E P T H - A V E R A G E D   F L O W

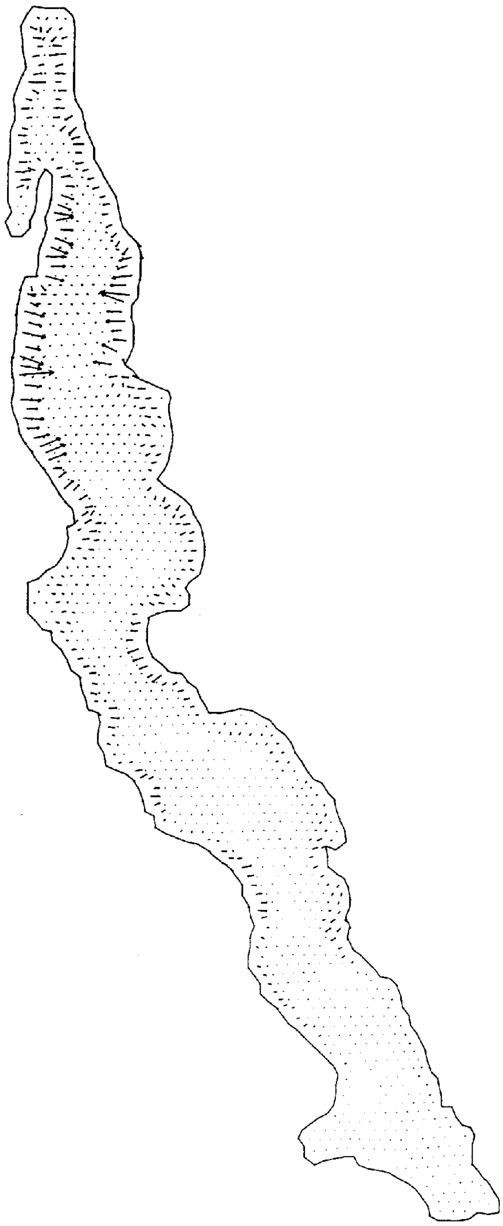



Fig. 7

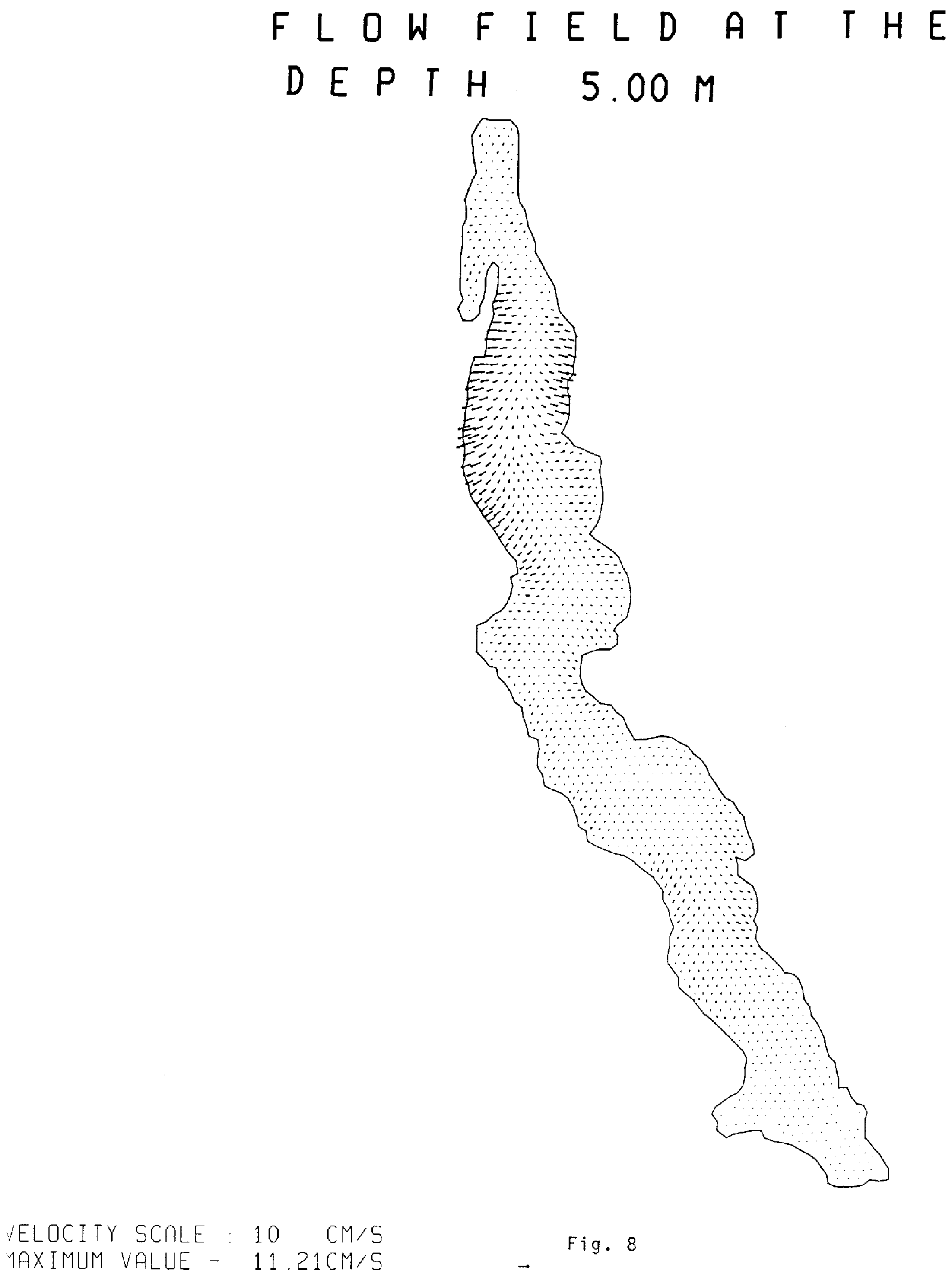
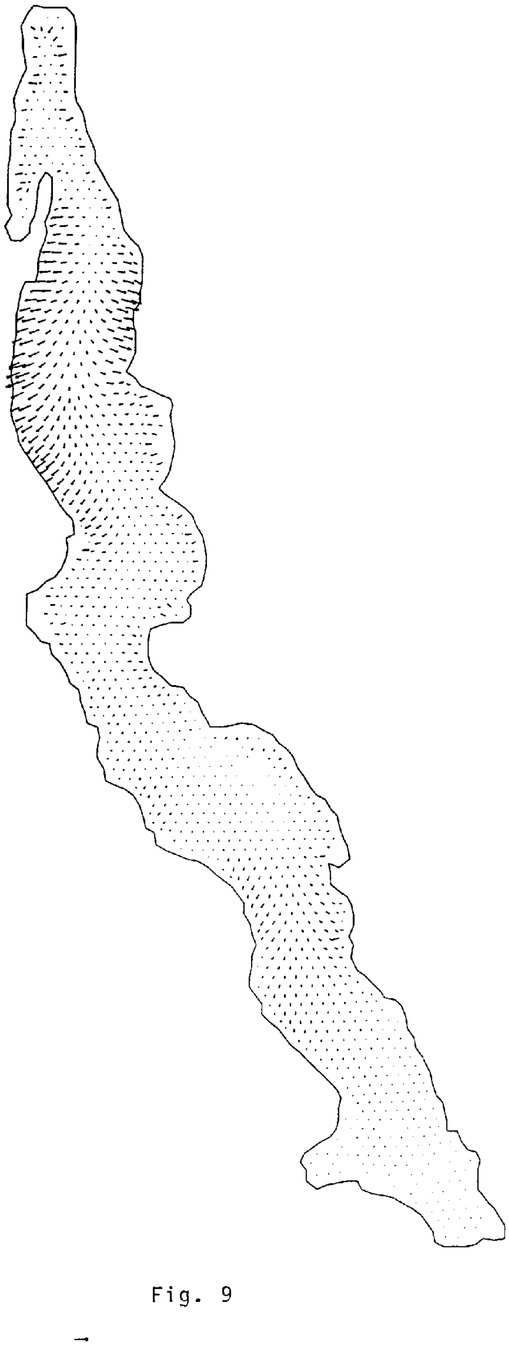

FLOW FIELD AT THE
DEPTH 5.00 M
VELOCITY SCALE : 10 CM/S
MAXIMUM VALUE - 11.21CM/S

Fig. 8

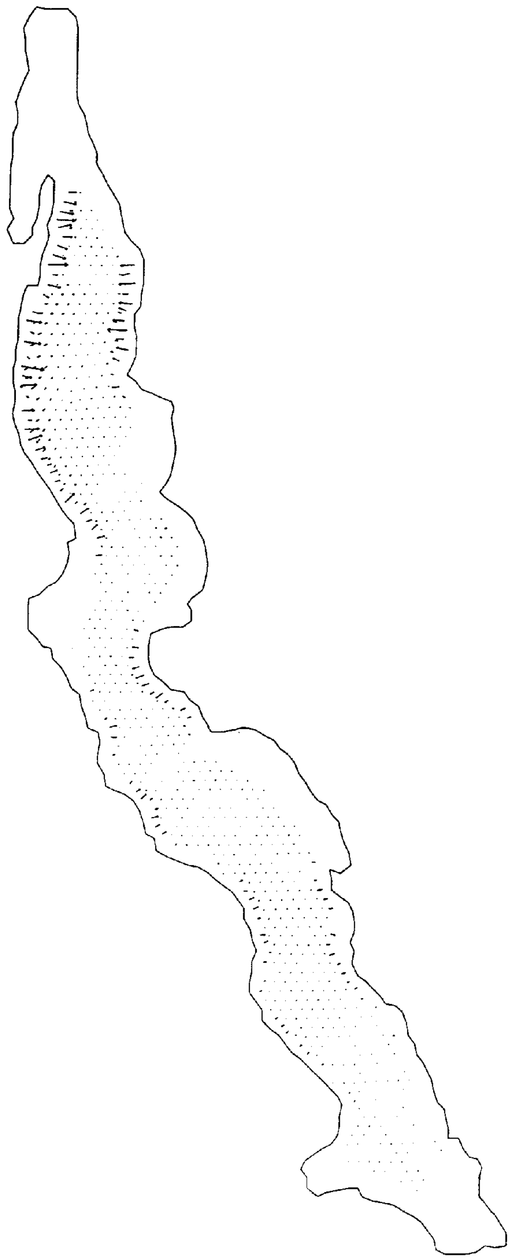
FLOW FIELD AT THE DEPTH 50.00 M



VELOCITY SCALE : 10 CM/S
MAXIMUM VALUE - 10.12CM/S

Fig. 9

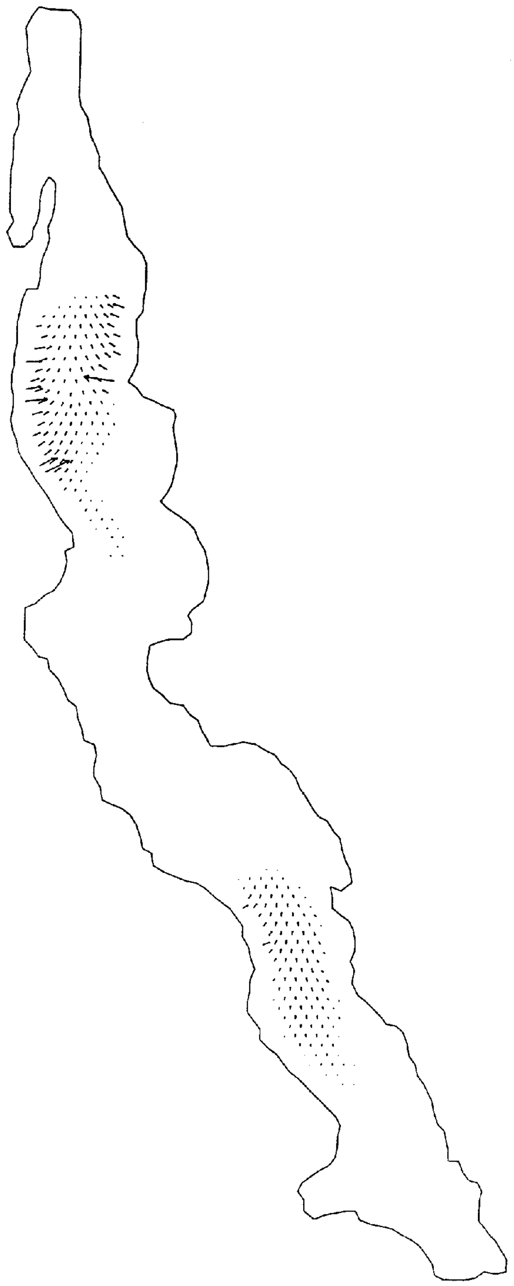
# FLOW FIELD AT THE DEPTH 300.00 M



VELOCITY SCALE : 10 CM/S
MAXIMUM VALUE - 11.95CM/S

Fig. 10

FLOW FIELD AT THE
DEPTH 1000.00 M



VELOCITY SCALE : 10 CM/S
MAXIMUM VALUE - 8.81CM/S

Fig. 11

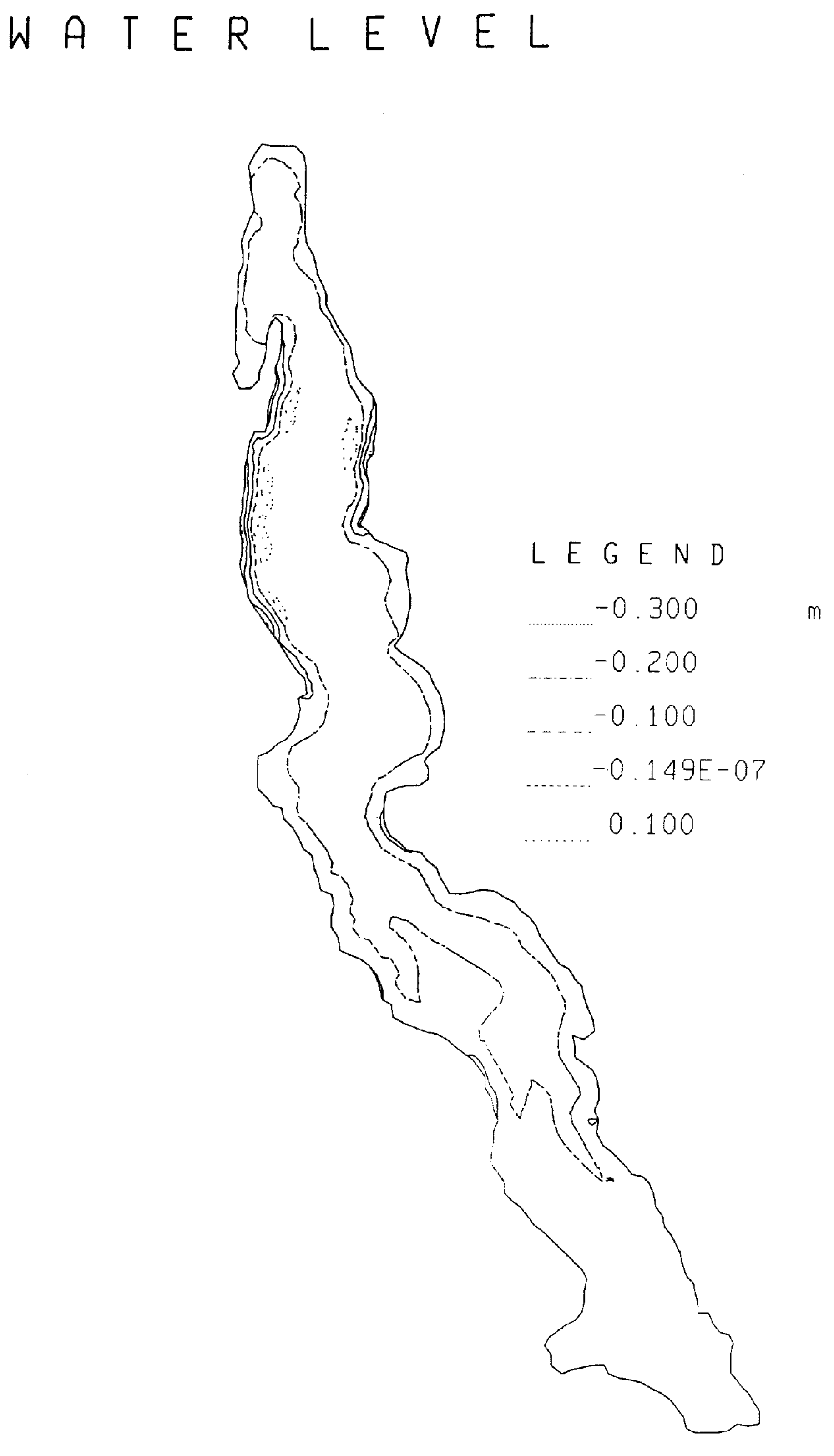



Fig. 12

# V E R T I C A L   V E L O C I T Y

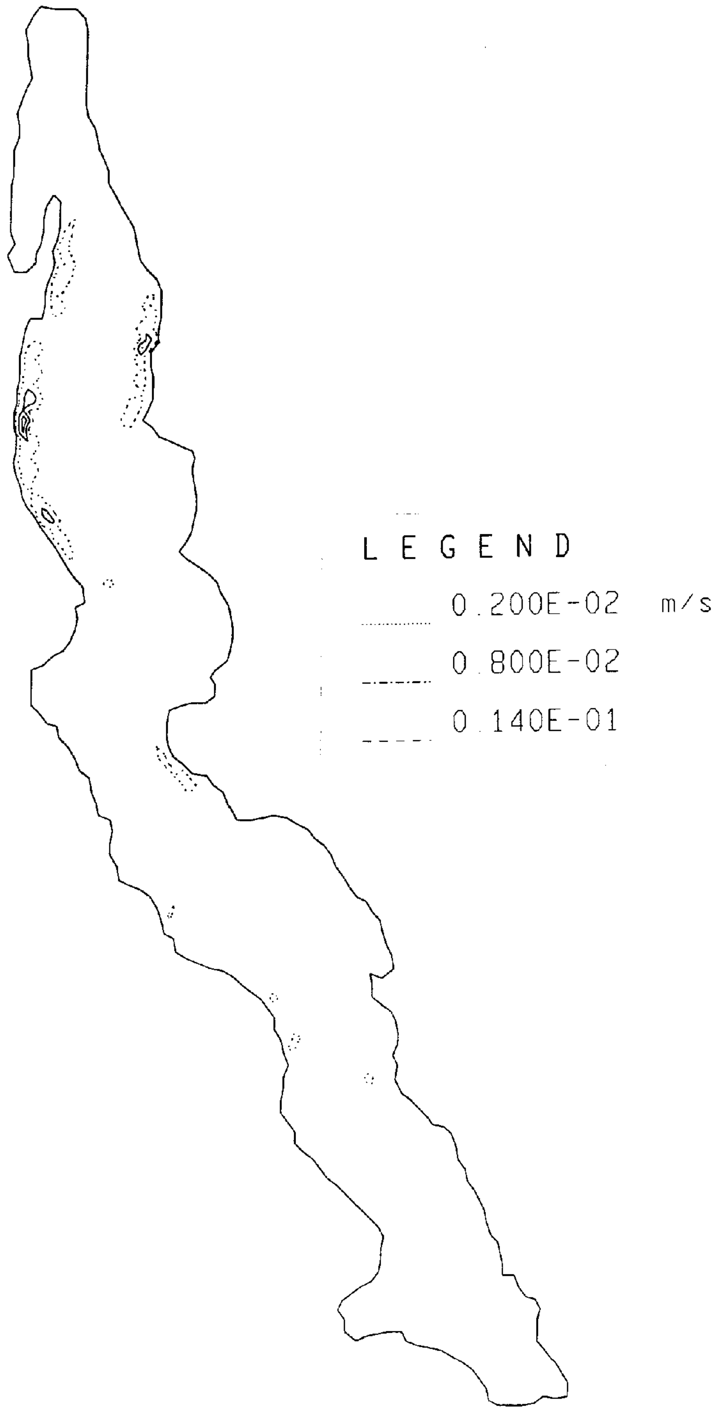



Fig. 13