HYDRODYNAMIC SIMULATION WITH MIKE 21 OF ABAIANG ATOLL, KIRIBATI

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The French Embassy for the funds that enabled me to have a placement at SOPAC.

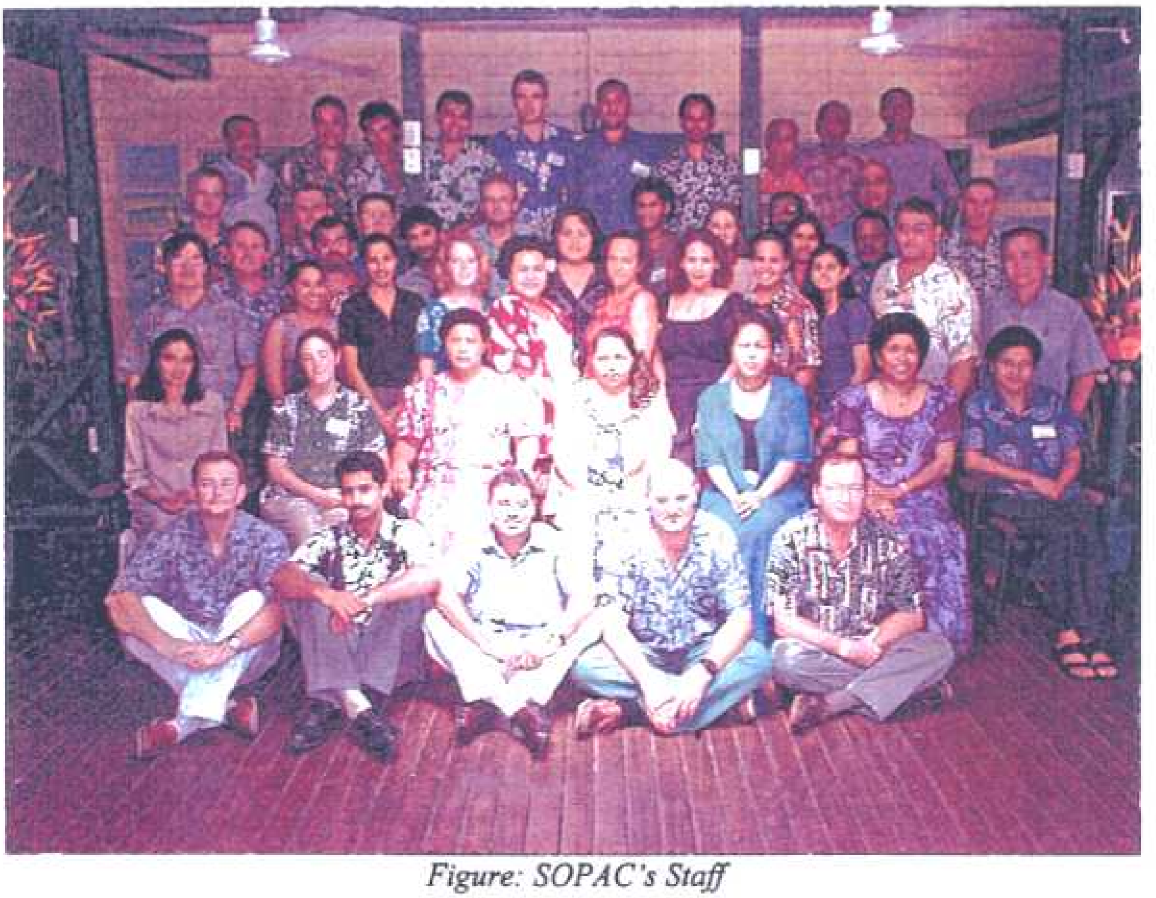

Figure: SOPAC's Staff

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ABSTRACT

Particularly warmly welcomed to the South Pacific Applied Geoscience Commission, I have been quickly involved in a project which aim is to assist the Ministry of Natural Resources Development and Fisheries Department of the Republic of Kiribati to develop marine resource management plans for Abaiang Atoll.

My own mission was assessing the hydrodynamic impact of the establishment of a mariculture project in this atoll thanks to a numerical modelling under MIKE 21, a professional modelling software for 2-D free surface flows.

Harbours and lagoons are all subject to some, or all, pollution, wave action, storm surge, seiching, tsunami, erosion and sedimentation, and sea-level rise studies linked to coastal management are often limited by data sets available, seasonal variations and cost. Numerical modelling provides an opportunity to view and analyze coastal problems and risks with minimal penalties for error as we are able to change the input parameters in the model and observe the response, a valuable symbiosis between development and application.

After having tried to avoid all the traps of the data processing, I made run two hydrodynamic models. The first one described the water circulation in the lagoon, and the second the circulation of biological parameters (temperature, salinity, B.O.D., dissolved oxygen…).

INTRODUCTION

SOPAC (South Pacific Applied Geoscience Commission), based in Suva (Fiji Islands), is in the early stages of a project of marine resources management plans which is aimed at extending seaweed cultivation in Abaiang Atoll, Republic of Kiribati.

The work carried out at the Coastal Unit and presented in this report has been mainly focused on the development of a hydrodynamic model for Abaiang Atoll, Kiribati.

Using the software MIKE 21 developed by the DHI (Danish Hydraulic Institute), a hydrodynamic model has been set up.

Compilation of the bathymetry model was based on a survey realized by Robert Smith in August 1999.

Following a brief presentation of SOPAC, a summary of the area studied here and of the objectives of this project, the assumptions used by MIKE 21 and basic equations that form the basis of numerical modelling are described. In all hydrodynamic situations, geographical configuration and bathymetry are the principal controlling factors that determine the hydraulics.

The parameters specified in MIKE 21 to run the simulations are described as well as for the parameters for calibrations. The numerical results obtained and the measurements are compared for the validation of the model.

I. Presentations

A. Presentation of SOPAC

1. Background

The South Pacific Geoscience Commission (SOPAC) is an independent, intergovernmental, regional organization established by a few South Pacific nations in 1972, originally as CCOP/SOPAC. Its secretariat is located in Suva, Fiji Islands, and has about 50 professional and support staff who are coming from all over the world.

Members countries are currently Australia, Cook Islands, Federated States of Micronesia, Fiji Islands, Guam, Kiribati, Marshall Islands, New Zealand, Niue, Papua New Guinea, Samoa, Solomon Islands, Kingdom of Tonga, Tuvalu and Vanuatu. French Polynesia and New Caledonia are Associates Members. Twelve members are developing Pacific Islands Countries. Australia and New Zealand do not receive Work Program assistance but are major donors.

2. Mission statement

To improve the well being of peoples of Pacific island member countries through the application of Geoscience to the management and sustainable development of their nonliving resources.

3. Work program

"It is difficult to think of any development of any country which hasn't benefited in some way from basic geoscientific knowledge."

Through its Secretariat, SOPAC carries out a wide range of Geoscience activities in the region. The secretariat's primary roles are to gather new data to assist member countries to assess their natural resources, and to build national capacities in the Geoscience towards self-sufficiency in the long term. Not all of the activities listed below are carried out at any one time, the balance of the Work Program depending on member country priorities and on the level of funding available to SOPAC at the time.

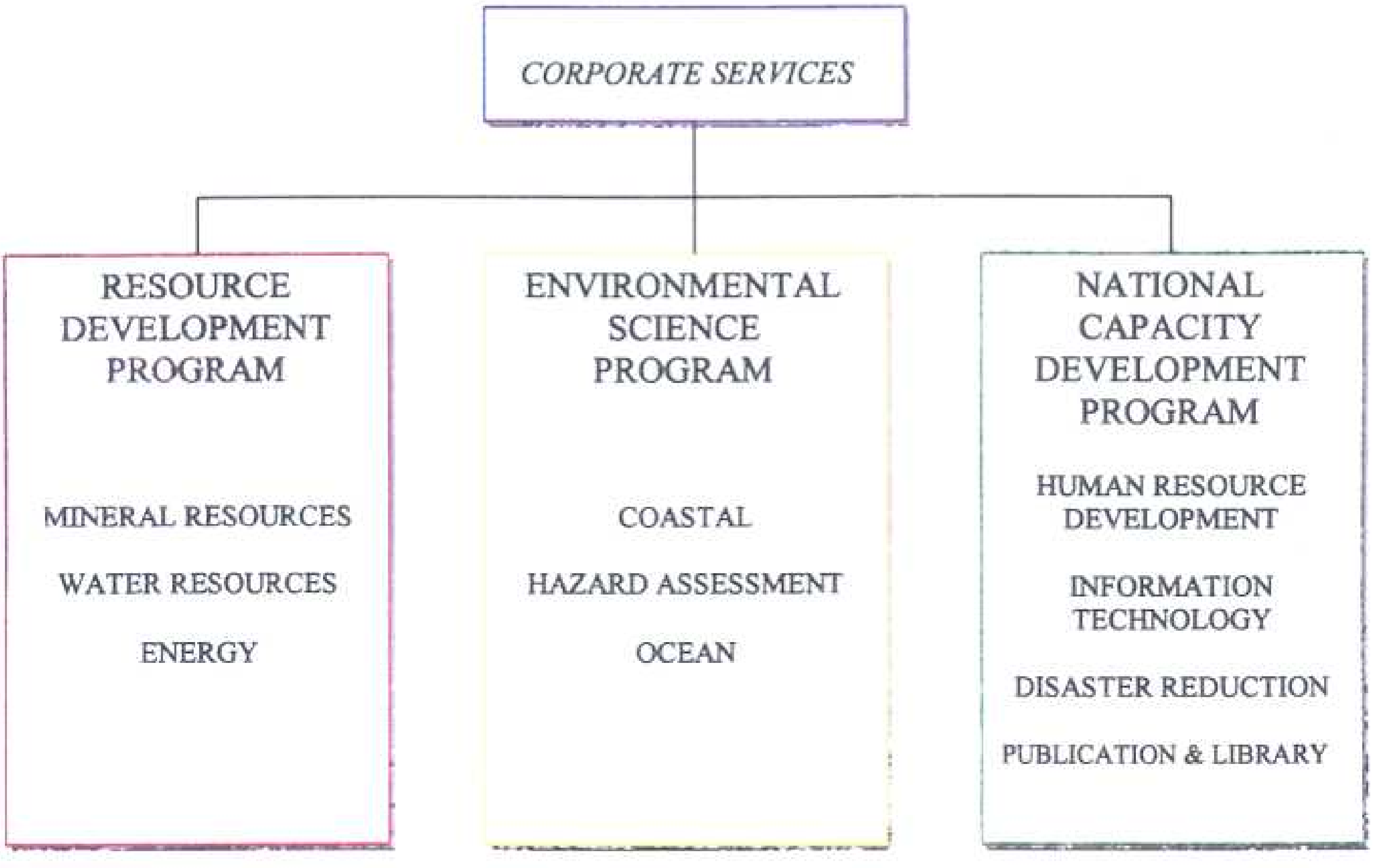
4. Areas of expertise

SOPAC's work for its member countries focuses on three key areas.

- resource development ;
- environmental Geoscience ;
- national capacity development in the geosciences.

To effectively deliver these services SOPAC maintains a regional data centre, provides information services, and offers technical and field services for specific project work.

5. Organizational Structure



6. Resource development program

Coastal Unit	Physical environment monitoring, physical processes studies. Coastal and shallow water seabed mapping, field equipment operation and maintenance *Ex: offshore bathymetry south Tarawa, Kiribati.*
Disaster Reduction Unit	Regional coordination, research information *Ex.: Taveuni Volcano Project, Fiji.*
Energy Unit	Policy and planning, small energy projects, renewable energy projects, monitoring alternative energy developments (OTEC, Wave & Geothermal) *Ex: petroleum price monitoring, Guam.*
Hazard Assessment Unit	Geohazard studies, vulnerability assessment, protection and engineering advice, lagoon/shallow water circulation studies *Ex: GIS physical database assembly, Papua New Guinea.*
Human Resource Development Unit	ESMG Certificate, fellowships, workshops and seminars, HRD advisory assistance, distance education development *Ex: basic geology and hydrology/hydrogeology; water resource management, Samoa*
Information Technology Unit	Computing services, communications, PEACESAT and data transfer, remote sensing and resource monitoring, database and GIS development *Ex: Support to member countries in intranet/internet development, Tuvalu.*
Mineral Resources Unit	Mineral and aggregate assessment/surveys, deep sea mineral assessments/surveys, promotion of mineral potential, minerals legislation and policy development, hydrocarbons promotion *Ex: manganese nodule strategic plan, Cook Islands.*
Ocean Unit	Ocean environment monitoring, deep water and seabed mapping, cruise coordination, physical oceanography, LOS/EEZ issues (MSR, ISBA, Continental Shelf) *Ex: ocean energy program.*
Publications and Library Unit	Editing, publications and reporting, library, public awareness *Ex: library assistance to organize mineral exploration reports, Solomon Islands*
Water Resources Unit	Sector strategy and action planning, technological and equipment support, surface and groundwater resource assessment, water supply and waste disposal advice, sanitation (with SPC), solid waste management (with SPREP) *Ex: rural water supply assistance, Federated States of Micronesia.*

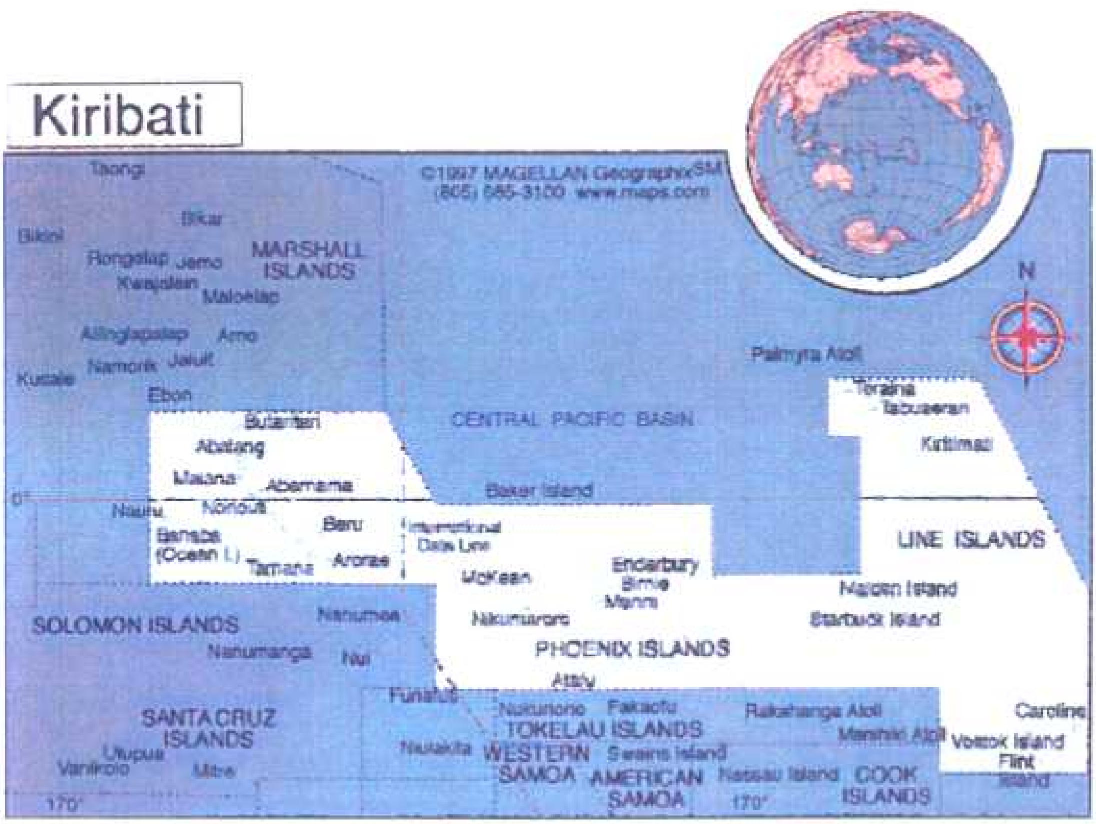
B. Abaiang Atoll, Republic of Kiribati

Some words about Kiribati:

The Republic of Kiribati is a state in the SW Pacific with a land area of about 726 km² and 75000 inhabitants. It comprises the Gilbert and the Phoenix Islands, Ocean Island, Christmas Island, Malden Island, Starbruck Island, Wostok Island, Caroline Island and Flint Island. All islands in the group are low lying coral islands many of them forming atoll. Kiribati became prominent during the World War II because of the battle between the US and Japan To day Kiribati is a Republic having left the Commonwealth in 1979. South Tarawa is really overcrowded; about 35000 people live there. The capital is Tarawa, in Tarawa Atoll with more than 30% of the national population residing in South Tarawa. This is the most densely populated area in the group. It can take some getting used to (*cf. Annexe 1*).

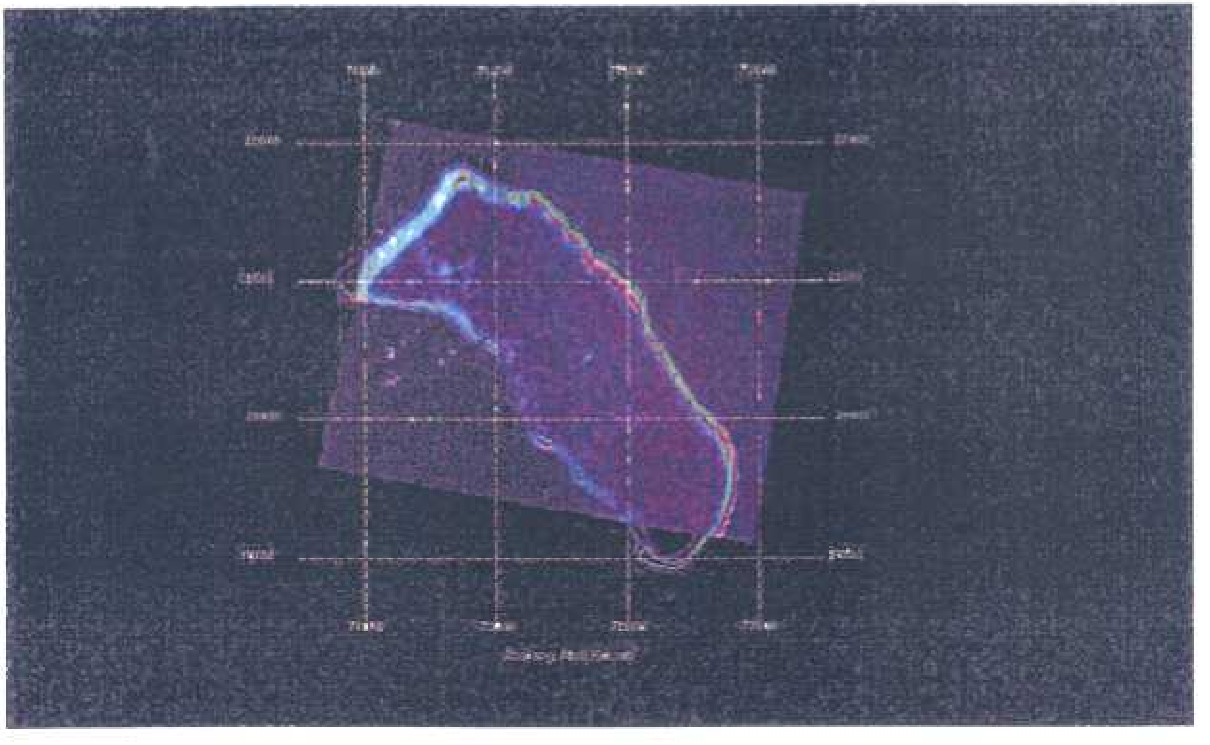
1. Localization

Abaiang Atoll is the fourth island to the north of the Gilbert Islands Group in the Pacific Ocean, lying one degree north of the equator and is some ten nautical miles northeast of Tarawa Atoll. The atoll is easily accessible by both sea and local airlines.



2. Description

By atoll standards Abaiang is of medium size almost rectangular in shape with a central axis of the atoll orientated NW – SE, some 27 kilometres long and 12.5 kilometres wide. This represents some 240 km^2 plus of lagoon alone The reef barrier at its widest in the north is some 1.6 km wide. A number of small islets exists in the northeast and northwest of the atoll. One long continuous island some 36 km in length separates the lagoon from the ocean along the eastern and southern flanks of the lagoon, where the island population of some 6000 people is mainly distributed.
Access to the lagoon is via a number of passes and channels of various sizes breaking the barrier reefs and connecting the lagoon to the ocean.
With the winds predominantly from the east, the eastern side of the atoll is often rough. The lagoons and the western reefs are therefore more sheltered



3. Physical Environment

3.1. Tidal Range

The tides of Abaiang are mainly *semi-diurnal* with two high and two low tides each day. Mean Sea Level is reported as 1.25m (Admiralty tide tables 1999). The tidal range reported for Abaiang ranges from 1.1 to 1.3m. Two water-level recorders were located within the lagoon.

3.2. Wave climate

Local winds and distant southeasterly swells create waves along the southwestern and northern (by diffraction) reefs of Abaiang Atoll. Generally, wave energy is dissipated along the fringing reef, some distance away from the shore except during more extreme events where surge and set-up allows a greater portion of wave energy to impact on the shoreline.

3.3. Currents

Kiribati (included Abaiang) is affected by several currents; some directed east to west and others to opposite direction. Abaiang is located inside the Pacific Equatorial/Tropical current system.
There is current data for Abaiang lagoon. Currents in the lagoon are largely driven by tides and are known to reach speeds of 0.8 $m.s^{-1}$ during spring tides in passes.

3.4. Winds

Seasonal movements of the Intertropical Convergence Zone (ITCZ) and the Equatorial Doldrum Belt (EDB) govern according to Burgess (cf. Annex 5), Kiribati weather. June to November is drier and southeasterly tradewinds dominate; December to May is wetter and winds from the north and the east quadrants are prevalent. Winds are usually light; strong winds are associated with westerly squalls. Wind roses from Tarawa (south of Abaiang) indicate that the westerly winds are more common during the months of June to November.
Easterly and southeasterly winds are generally around 4-10 knots (7.4-18.5 $km.h^{-1}$) and the strongest wind recorded between 1979 and 1986 was 52 knots (96 $km.h^{-1}$) from northwest west.
A study of Carter (*cf. Annex 5*) presented wind data from before and during the severe El Niño event of 1982-1983 which illustrate the dramatic increase in strong westerly winds which accompanied it. Winds of 17-33 knots (32-61 $km.h^{-1}$) were relatively common during that event.

Cyclones are very rare this close to the Equator, but they have been known to occur.

3.5. Wave climate

Wave information is very limited in this region. Deep water detected from satellites show a mean significant height H_s<1.8 m. for the years 1986-1989. This agrees well with the satellite data for the first three months of 1997, during which the mean H_s was 1.8 m. in a region from 0-3 degrees North and 172-174 degrees East.

Carter (*cf. Annex 5*) hindcast ocean waves of H_s<2 m. with peak period T_p<6 s. The westerly winds which accompanied the 1982 El Niño produced hindcast waves of H_s>5 m. and T_p=10 s.

4. Aquaculture Development

4.1. The seaweed industry of Kiribati

The seaweed cultivation industry in Kiribati presents a set of slightly different problems and issues from those observed in other marine resource sectors such as fisheries. The species of seaweed grown in Kiribati is *Kappaphycus alvarezii* var. **tambalang** (its local name), otherwise described as *Eucheuma cottonii*, a red seaweed or Rhodophyceae. The seaweed is grown for the purpose of export to the global carrageenan market, carrageenan being the name given to the hydrocolloid extract from the cell wall, which forms water-soluble gels for use in the food and pharmaceutical industry.
According to Mr. Simon L. Wood (1996), problems fall into three categories: commercial, cultural and scientific.

4.1.1. Commercial problem

The commercial problems include cash flow, internal and external shipping costs, and infrastructure building to improve information flow between outer islands and Tarawa.

4.1.2. Cultural problem

Culturally, the problems for the company lie in the degree to which individuals wish to apply themselves to seaweed farming. The lifestyle on the outer islands is still very much one of subsistence and most people are not willing to view seaweed farming as a full-time occupation. From a company's point of view, its future is very much reliant on the outer island farmers and their level of motivation.

4.1.3. Scientific problem

The scientific challenge that faces the company is how to stabilize production. At the root of the problem observed is the non-indigenous nature of the resource. Stephen Why introduced the seaweed to the Line Islands in 1980, then working as a VSO in Fisheries Division, and it was subsequently moved to Tarawa lagoon in 1982.

The seaweed in Kiribati is thought to be sterile, thus no matter how long the plant is left in the water it will not produce spores or gametes. Propagation of seaweed is achieved by cloning – by breaking off sections of the plant and trying to culture lines supported in a farm structure.

With cloning as the only method of propagation the cultured seaweed has the same genetic make-ups as the number of genetic individuals introduced by Why. This lack of genetic variation in the current system means that large quantities of cultured seaweed in Kiribati are very susceptible to disease. Should a disease arise, what we would expect to see is large quantities of cultured plants wiped out over a very short space of time.

The inherent problems of lack of genetic diversity in the population are compounded by the lack of specific knowledge of the environmental parameters required for good, sustainable growth. All plants require sunlight, oxygen, carbon dioxide, a specific temperature, salinity and nutrients (such as nitrate, nitrite and phosphate, as well as many trace nutrients) in order to grow. Each of these specific factors, physical or biological must fall within a certain range for plant growth to be at its optimum. The more of these factors there are outside the ideal range for the plant, the more stressed the plant will be, and slower growth will occur. If too many of these factors or any single factor is too far beyond the seaweed's acceptable range, the plant will die.
The plants in the lagoons of the Gilbert Islands (like Abaiang) are thought to exist very close to their limit of temperature tolerance. Thus a small rise in water temperature may cause a collapse in production.

At present there is a distinct lack of knowledge of which these factors, physical and/or biological, are the limiting factors to growth.

4.2. The Abaiang seaweed production

The tables below show the production of seaweed in Abaiang Atoll and Nuotea from 1985 to 1999. Some data were not available.

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Abaiang	0	2	5	20	82	581	684	290	157	242	32

Table: Abaiang Yearly Production (Tons) 1985-1995 (includes Nuotea)

	1993	1994	1995	1996	1997	1998	1999
Jan	7.843	23.308	4.989	0.057	0.184	0.000	0.061
Feb	12.686	35.539	3.270	0.240	0.000	0.000	0.000
March	11.634	20.944	3.578	0.051	0.000	0.000	0.000
April	23.868	15.158	2.510	0.000	0.000	0.000	0.000
May	7.022	39.194	4.093	0.311	0.000	0.000	0.000
June	5.740	23.298	0.000	0.733	0.000	0.000	0.015
July	11.338	18.277	4.485	1.371	0.000	0.045	0.065
Aug	13.229	30.940	3.425	0.614	0.000	0.222	0.076
Sept	12.742	16.894	2.012	0.038	0.000	0.033	0.014
Oct	15.033	14.453	1.786	0.000	0.000	0.198	0.000
Nov	19.746	3.192	0.679	0.000	0.000	0.000	0.000
Dec	16.479	0.946	0.641	0.000	0.000	0.040	0.095

Table: Abaiang Monthly Production (Tons) 1993-1999

	1996	1997	1998	1999
Jan	1.588	1.574	0.000	0.000
Feb	2.251	2.033	0.000	0.000
March	1.755	0.850	0.000	0.000
April	3.346	0.400	0.000	0.000
May	4.049	0.594	0.000	0.000
June	7.124	0.000	0.000	0.000
July	3.061	0.000	0.000	0.000
Aug	4.061	0.000	0.000	0.000
Sept	3.616	0.000	0.000	0.000
Oct	1.385	0.000	0.000	0.000
Nov	1.181	0.000	0.000	0.000
Dec	2.076	0.000	0.000	0.000

Table: Nuotea Monthly Production (Tons) 1993-1999

4.3. The Seaweed cultivation criteria

Data supplied by the Atoll Seaweed Company in Kiribati for the environmental farm-site selection are as follows:

- Subtidal littoral flats of depths: < 2 m.
- Temperature optimal: 26-30 °C
- Salinity optimal: 35-38 ppt
- Water movement from: -tidal currents, -advection, -waves
- Current optimally of: > 20 $cm.s^{-1}$
- Currents 10-20 $cm.s^{-1}$ satisfactory in areas experiencing waves

5. Own mission

The field of investigations and numerical modeling which was required to determine potential impacts and opportunities to avoid, remedy or mitigate adverse impacts includes the following:

- Determine the actual bathymetry of the reef and the lagoon.
- Measure hydrodynamic conditions to improve the understanding of the existing situation, especially in relation to water levels, currents, sediments transport, temperature, dissolved oxygen…
- Model existing situation and propose modifications to assess effects and allow design optimization using 2-dimensional numerical models calibrated with field measurements.

II. Data

This part of the work represents the basis of the carried out work. As a consequence it is the most important one too.
The engineer work consists in choosing the relevant spot where the relevant data of GPS or of bathymetry must be collected, considering what is eventually required for the simulation under MIKE 21. Unfortunately I did not have the opportunity to do the survey and also to see the measurements step.
The purpose of the different surveys are establishing the bathymetry inside the lagoon, measuring the water level and the currents to compare them with the model values.
The CTD allowed to measure Dissolved O_2, turbidity, temperature, and salinity as well.

A. Warning

The physical environment of the coastlines and near-shore areas is complex and dynamic. The seabed, foreshore and water characteristics respond to the ever-changing effects of the tides, waves, ocean currents and winds. These natural changes occur on time scales varying from only a few seconds (wave by wave), to a few months (seasonally), to several years (long term erosion or accretion).

Apart the typical problems of fouling, corrosion, waterproof electronics, the main problem to face is the inability to isolate phenomenon. Each water rising is due to the wind, the current, the tide. It means that it is impossible to simulate an extreme case with a tsunami, a very high tide and strong currents at the same time whereas it can happen.

The measurements are limited because only acoustic waves can travel in the water…when it is possible because of sediments in suspension or over problems.

It is furthermore impossible to reproduce a phenomenon.

B. Measurements

To assist the Ministry of Natural Resources Development and Fisheries Department of the Republic of Kiribati to develop marine resource management plans and development of aquaculture projects in Abaiang Atoll, there was a need for baseline knowledge of lagoon bathymetry, the circulation regime water level and temperature, conductivity-temperature-depth profiles, and dissolved oxygen levels.

Some 800 kilometers of high-resolution bathymetric data was collected for Abaiang Atoll lagoon. Five sites were occupied to measure current flow. Two water-level recorders were also deployed to monitor tides. Twenty-seven stations in the lagoon were monitored for salinity, temperature, and dissolved oxygen, measured with and turbidity determined with the aid of a secchi disk. Bottom sediments were also taken at each of these locations. For longer-term monitoring, six long-term temperature loggers were deployed for a period of up to twelve months.

1. Objectives

The objectives of this survey (SOPAC survey number KI9401) were to:

1. Map the bathymetry of Abaiang lagoon
2. Monitor circulation
3. Collect physical baseline data for Abaiang lagoon.

The field survey study was done over the period 3rd to 19th August 1999.

Photo: "Yautalai" the boat of SOPAC

2. Measurements

2.1. GPS measurements

2.1.1. Principle of the GPS

Developed by the US department of Defense, the Global Positioning System or GPS is a worldwide navigation system. GPS receivers use fours of the 24 satellites orbiting high above the Earth to avoid the problems encountered by land based systems as reference points to calculate positions of accuracy to a matter of meters. The system uses triangulation: it measures the time taken by radio signal to reach four satellites, and knowing that radio signals travel at the speed of the light, finds out the distance to each. At the intersection of the three circles, the expected point

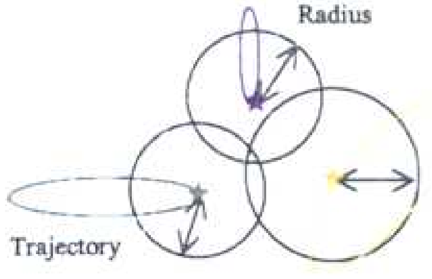


Figure: System of global positioning

The measurements have been taken thanks to a Differential GPS; these more advanced measurements require one stationary receiver to correct the errors with the already known position. The differences are then used to correct the roving receiver measurements. A fourth satellite is needed because of the time.

System	Accuracy
GPS	10 m.
DGPS	1 m.
DGPS + atmosphere composition	1 cm.

Table: Accuracy of the different GPS

2.2. Bathymetry

In all hydrodynamics situations, geographical configuration and bathymetry are the principal controlling factors that determine the hydraulics

2.2.1. Equipment

Special equipment had to be taken because of the very shallow water in this area. Although SOPAC has got a multi-beam echo sounder, it was not possible to use it even at high tide. That is why a simple transducer called Odom echotrack has been used for profiling the seabed, and the digital output logged with Del Norte 1009. Echo depth sounding is a method of measuring water depth by computing the time interval required for sound waves to travel.

2.2.2. *Measurements*

With the above equipment, the boat has been steered in the entire lagoon. Every approximately twenty seconds, GPS measurements were taken. All the bathymetric data collected are reduced to chart datum based on predicted tides for Abaiang Lagoon.

2.3. Water level recorders

As said above, the tides of Abaiang are mainly semi-diurnal with two high and two low tides each day. Mean Sea Level is reported as 1.25 m. (Admiralty tide tables 1999). The tidal range reported for Abaiang ranges from 1.1 to 1.3 m.
Two water level recorders have been installed in two locations in the lagoon 25 kilometers apart.

2.4. Currents

During the sixteen-day survey three Aanderaa currentmeters were laid out in five locations within the lagoon and channels to monitor currents.

2.4.1. *Aanderaa current meters*

The current meters used are eulerian. Three current meters were deployed in five locations within the lagoon and channels to monitor currents. All the sensor are mechanic.
Recording Current Meter Model 7 is a self-recording current meter intended to be moored for obtaining and recording vector average speed, direction and temperature of the ocean currents. "I-anchoring" has been used as described on the picture.

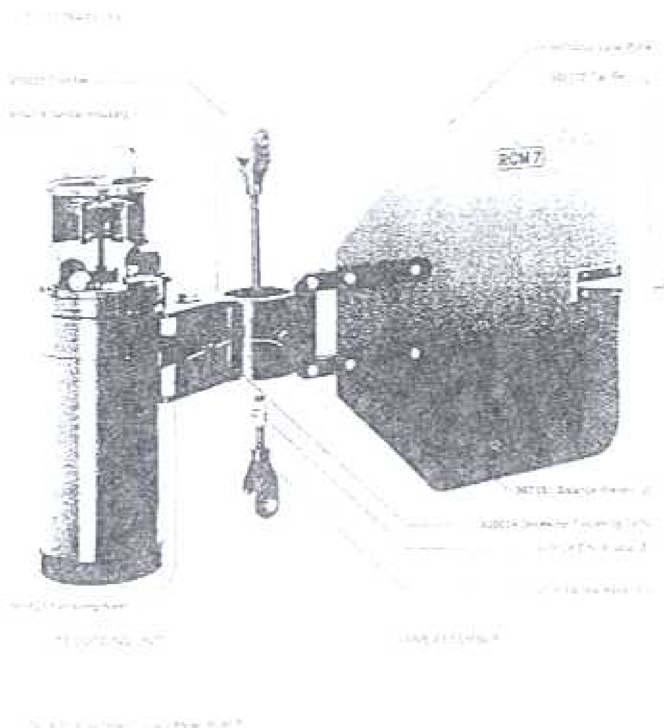


Figure: Recording Current Meter Model 7

The measuring consists of six channels in sequence: reference, temperature, conductivity, pressure, current direction and current speed.
The complete instrument is free to swing around the spindle thanks to the *coefficient de trainee*. RCM7 depth capability is 2000 meters. As the current meter aligns itself in the current, the direction is measured by the orientation of the instrument. The direction sensor is a compass located at the bottom of the recording unit. At the top of it, a rotor senses the current speed. The revolutions of this rotor are magnetically coupled to an electronic counter placed inside the unit. Every half revolution is counted. Speed and direction are sampled 50 times per recording interval. A vector averaging method is used for recording the speed and the direction of the current.

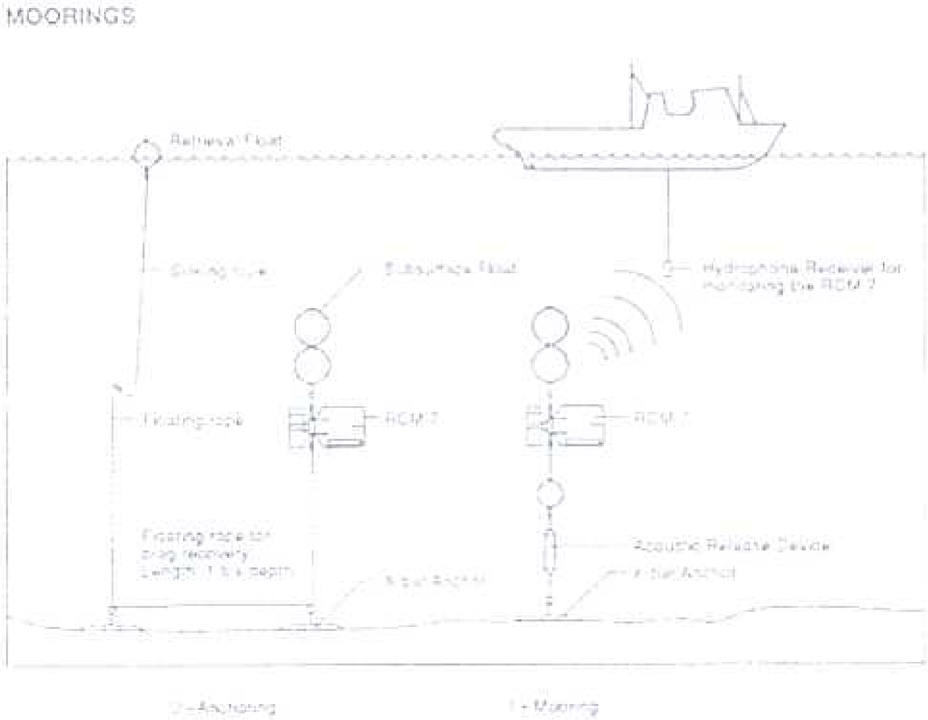


Figure: Description of the moorings

The majority of the current meters are robust, quite simple but very precise. In our case, the purpose of the current meters is only checking the values of the model.

Specifications	Direction (degrees)	Speed ($cm.s^{-1}$)
Sensor type	Magnetic compass with needle clamped onto potentiometer ring	Rotor with magnetic coupling
Range	0 to 360 degrees	2 to 250 $cm.s^{-1}$
Accuracy	5 degrees	Max (1 $cm.s^{-1}$; 2%)

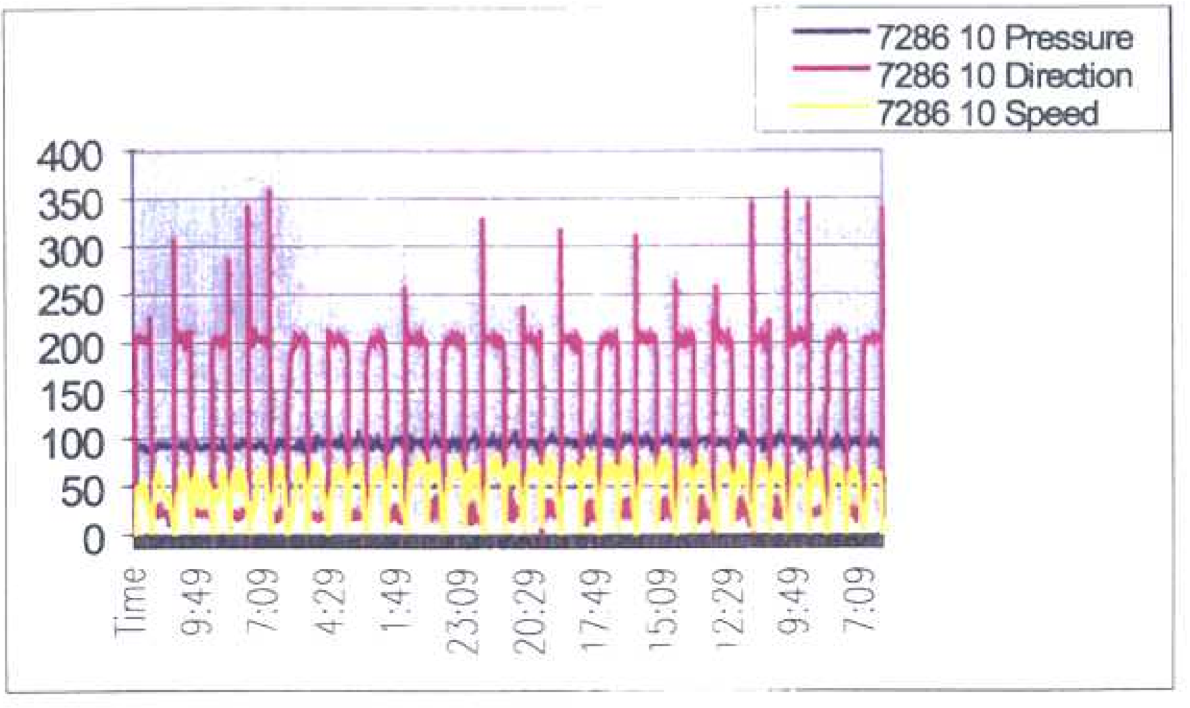
Tab.: Accuracy of the current meter

2.4.2. *Choice of the spot*

Three current meters were available for the sixteen-day survey At least two had to be at the main entries of the atoll in order to have measurements at the boundary to compare with the model. The others had to be in the areas where the mariculture project will be established.

2.4.3. *Plots*

The most significant measurements are the current speed and direction in the channel. It is also where the current seems to be the strongest



Indeed the plots of speed and direction have almost periodic looks:

1. The trend line of the speed is a sine except a relative small peak at the minimum of the sine.
2. The trend lines of the direction are two constants equal to 25 and 205 degrees, which are the main directions of the flow in- and out-coming with the tide.

C. Bibliography

1. Elevation of the sea level

There is much debate and uncertainty about the increasing levels of CO_2 and other gases in the atmosphere and their effects on the climate (the Greenhouse Effect). The potential effects are variation in rainfall patterns and regime due to increased temperature, evaporation and shifts in regional wind system, and increase in the frequency of tropical cyclones, due to increased air and sea surface temperature. Many scientists also propose that a rise in sea level due to thermal expansion of seawater as a result of temperature increase and also due to some polar and glacial melting could be expected to occur gradually over the next 50-60 years. Estimates of sea level rise vary widely but the International Panel on Climate Change have indicated that as result of the enhanced greenhouse effect, sea level will rise (relative to its 1990 level) 0.18 m. by the year 2030 and 0.44 m. by the year 2070. This means that the future rate of sea level rise will probably increase to between 4.5 mm/year and 5.5 mm/year.

2. Tides

Seeing that measurements have periodic plots, the tide had to be taken into account. Thanks to the Admiralty Tide Tables, we can calculate the water elevation and compare it with the measurements.

Place	M.L.	Harmonic constants				Zone +1100				S.W. corrections			
	Z_0	M_2		S_2		K_1		O_1		1/4 diurnal		1/6 diurnal	
Abaiang Atoll	m.	g°	H.m.	g°	H.m.	g°	H.m.	g°	H.m.	f_4	F_4	f_6	F_6
	1.25	137	0.56	164	0.28	255	0.08	212	0.05	(-)	(-)	(-)	(-)

Figure: Tidal constituents of Abaiang Atoll from the Admiralty Tide Tables

(-) No data available

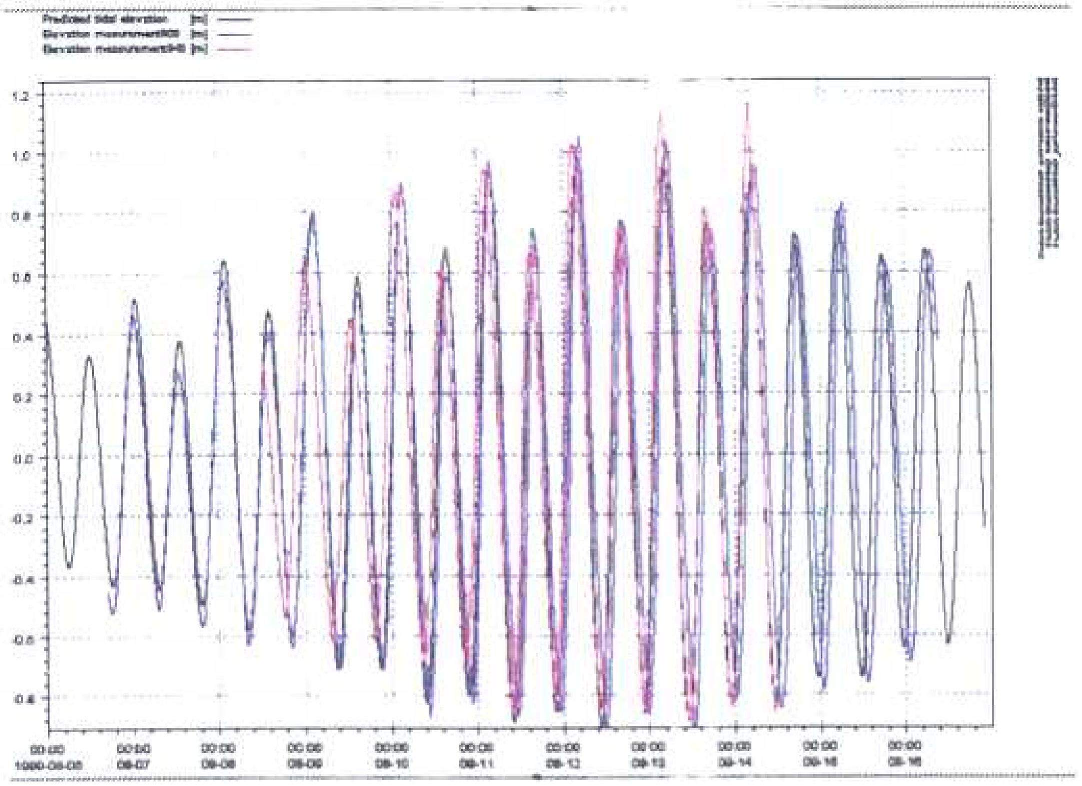


Figure: Graph comparing the measured water elevation and the water elevation calculated from the Admiralty Tide Table constituents

Seeing that the delay is due to the different times when the water level recorders and current meter were switched on, the admiralty values are quite good for the simulation.

III. Simulation

A. MIKE 21 package

1. Application area

Developed by the DHI (Danish Institute of Technology), MIKE 21 is two-dimensional depth averaged hydrodynamic software. To perform all the different models like a water quality, a sedimentary transport or a tsunami model for instance, it is essential to first set up the basic hydrodynamic model where all the others will be based on.

Mike 21 can be applied to a wide range of hydraulic and related phenomena. These can be divided into four main application areas:

1- *Coastal hydraulics and Oceanography.* This includes modelling of tidal hydraulics, wind and wave generated currents, storm surges and flood waves.

2- *Environmental Hydraulics.* This encompasses everything from normal advection-dispersion simulation of conservative pollutants to complex water quality simulations including chemical reactions. This means that we can investigate the impact on the marine environment from various sources such as sewage, storm water and cooling water outfalls. The environment parameters which could be studied are bacterial concentrations, eutrophication, algae blooms, BOD-OD (bacteriological oxygen demand – dissolved oxygen) and others. Heavy metal dispersion and its influence on marine flora and fauna can also be investigated.

3- *Waves.* This covers wave agitation in harbours, harbour seiching, hindcast and forecast design wave parameters, non-linear transformation and ship motions. We can therefore use Mike 21 as a tool in the design of harbours and offshore structures. It can be used to test the effects of new breakwater alignments, navigation channels, wharf areas etc., and to produce design wave parameters for offshore installations.

4- *Sediment Processes* on coast, in estuaries and rivers. These include sediment transport investigations of navigation channels, harbour entrances, coasts, river ports, etc.

The 13 computational modules of which Mike 21 consists have the following properties:

The computational Modules	
Hydrodynamic Module	• Full non-linear equations of continuity and conservation of momentum • ADI finite difference solution of second-order accuracy • Smagorinsky eddy formulation
Advection-dispersion Module	• Conservation of mass equation • Transport of conservative, heat dissipating and non-linear decaying matter • Third-order explicit finite difference solution
Water quality Module	• BOD-DO, oxygen depletion and bacterial decay balances • Organic nitrogen, ammonia and nitrate balances
Eutrophication Module	• Phytoplancton, benthic algae, zooplankton, benthic algae, zooplankton, oxygen balances and mineralisation estimates • Dependence on nutrient availability, light and temperature
Heavy Metals Module	• Combined physical, chemical and biological processes • Uptake in organism
Mud Transport Module	• Cohesive sediment erosion, transport and deposition
Sand Transport	• Non-cohesive sediment transport using Engelund-Fredoe's formulation under the action of currents and waves, both breaking and non-breaking
Particle Module	• Transport and fate of solutes or suspended matter • Pollutants are considered as particles • Lagrangian approach
Boussinesq Wave Module	• Boussinesq equations with improved linear dispersion characteristics • Irregular, directional waves from deep to shallow water • Non-linear wave – wave interactions • Diffraction, partial reflection
Elliptic Mild-Slope Wave Module	• Linear refraction-diffraction in sheltered areas • Harbour resonance and seiching • Radiation stress include diffraction and reflection • Monochromatic waves, wave breaking, reflection
Parabolic Mild-Slope Wave Module	• Linear refraction-diffraction in larger coastal areas • No diffraction behind obstacles and no reflection • Superposition over frequency and direction
Nearshore Spectral Wind-Wave Module	• Discrete directions, parametric in frequency • Stationary wind fields • Wave breaking, wave-current interaction, radiation stresses • No diffraction, no reflection
Offshore Spectral Wind-Wave Module	• Discrete directions and frequency • Time varying wind fields • Second generation wind-wave model • Parametric wave – wave interaction

Tab.: Computational modules of MIKE 21

All these modules require at least the Hydrodynamic Module to be run. For this reason the set up of the hydrodynamic model is by far the most important task for any study. Therefore, the results of an advection-dispersion model or a sediment transport model, for instant, are reliant on the quality of the hydrodynamic model.

2. Numerical Modelling – Equations

Unlike other related disciplines, such as Sedimentology and water quality, the basic equations are well known in hydrodynamics. The only and difficult problem is to solve them. All equations in hydrodynamics stem from the three-dimensional Navier-Stokes equations that read:

2.1. Continuity

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

2.2. Momentum

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \qquad (2)$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial vw}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \qquad (3)$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial w^2}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-g \qquad (4)$$

2.3. Boundary conditions

Free surface condition:

$$w=\frac{\partial \tau}{\partial t}+u\frac{\partial \xi}{\partial x}+\frac{\partial \xi}{\partial y}\ \text{for } z=\xi(x,y,z) \qquad (5)$$

Bottom condition:

$$u=v=w=0 \ pour\ z=-h \qquad (6)$$

Where x, y, z denote the space coordinates, u, v, w represent the three components of the velocity, ρ is the density and p is the pressure.

The continuity equation expresses the mass conservation, while the momentum equation is actually the fundamental law of dynamics, written for fluids. The only assumption in these equations is that the fluid should be Newtonian and this is indeed an excellent approximation for water. The main difficulty of the Navier-Stokes equations stems in the non-linear terms that challenge the numerical algorithms and are also responsible for the flow turbulence. As a matter of fact, it is important to note here that turbulence, with all its complexity, is contained in the Navier-Stokes equations.

For the time being, no industrial tool for directly solving the 3D Navier-Stokes equations for free surface flows is available. One of the greater difficulties is the free surface itself, which causes the computational domain to vary in time. Many kinds of simplifications have been proposed, the most popular being the Shallow Water equations given by Barre de Saint-Venant one century ago, and MIKE 21 is based on it.

2.4 Shallow Water Equations

The 2D Shallow Water equations are obtained by means averaging of the 3D Navier-[4] Stokes equations over the depth. The new variables obtained are mean values over the depth. Let's call:

$$U(x,y,z) = \int_{-h}^{\xi} u\,dz \text{ and } V(x,y,z) = \int_{-h}^{\xi} v\,dz \qquad (7)$$

Where ξ is the free surface and h is the bottom elevation. Solving the equations will consist of finding the values of U, V and h everywhere in a domain, during a given lapse of time, as functions of initial conditions and the boundary conditions.

Full derivation of the equations:
The derivation of the shallow water equations is mainly based on the Leibnitz rule:

$$\frac{\partial}{\partial x}\int_{z_1}^{z_2} u\,dz = \int_{z_1}^{z_2}\frac{\partial u}{\partial x}dz + u(z_2)\frac{\partial z_2}{\partial x} - u(z_1)\frac{\partial z_1}{\partial x} \qquad (8)$$

Any function can be divided with an average $\bar{\varphi}$ and a fluctuant $\tilde{\varphi}$:

$$\varphi(x,y,z,t) = \bar{\varphi}(x,y,z,t) + \tilde{\varphi}(x,y,z,t)$$

Integration of the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (9)$$

$$\int_{-h}^{\xi}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)dz + \int_{-h}^{\xi}\frac{\partial w}{\partial z}dz = 0 \qquad (10)$$

$$\frac{\partial}{\partial x}\int_{-h}^{\xi} u\,dz - u(\xi)\frac{\partial \xi}{\partial x} - u(-h)\frac{\partial h}{\partial x} + \frac{\partial}{\partial y}\int_{-h}^{\xi} v\,dz - v(\xi)\frac{\partial \xi}{\partial y} - v(-h)\frac{\partial h}{\partial y} + w(\xi) - w(-h) = 0 \qquad (11)$$

Following the bottom and the free surface conditions, it remains:

$$\frac{\partial \xi}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\xi} u\,dz + \frac{\partial}{\partial y}\int_{-h}^{\xi} v\,dz = 0 \qquad (12)$$

Taking the average we finally obtain:

$$\frac{\partial \xi}{\partial t}+\frac{\partial \overline{U}}{\partial x}+\frac{\partial \overline{V}}{\partial y}=0 \qquad (13)$$

Integration of the vertical movement equation

In order to obtain the pressure in z, the following is:

$$\int_z^{\xi}\left(\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial w^2}{\partial z}\right)dz=\int_z^{\xi}-\frac{1}{\rho}\frac{\partial p}{\partial z}dz+\nu\int_z^{\xi}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)dz-\int_z^{\xi}g\,dz \qquad (14)$$

From the Leibnitz rule, we obtain the expressions:

$$\int_z^{\xi}\frac{\partial w}{\partial t}dz=\frac{\partial}{\partial t}\int_z^{\xi}w\,dz \qquad (15)$$

$$\int_z^{\xi}\frac{\partial uw}{\partial x}dz=\frac{\partial}{\partial x}\int_z^{\xi}uw\,dz-u(\xi)w(\xi)\frac{\partial \xi}{\partial x} \qquad (16)$$

$$\int_z^{\xi}\frac{\partial vw}{\partial y}dz=\frac{\partial}{\partial y}\int_z^{\xi}vw\,dz-v(\xi)w(\xi)\frac{\partial \xi}{\partial y} \qquad (17)$$

$$\int_z^{\xi}\frac{\partial w^2}{\partial z}dz=w^2(\xi)-w^2(z) \qquad (18)$$

$$\int_z^{\xi}\frac{\partial p}{\partial z}dz=p(\xi)-p(z) \qquad (19)$$

$$\int_z^{\xi}g\,dz=g(\xi-z) \qquad (20)$$

The free surface condition shows that:

$$w^2(z=\xi)=\frac{\partial \xi}{\partial t}w(\xi)+\left(u(\xi)\frac{\partial \xi}{\partial x}+v(\xi)\frac{\partial \xi}{\partial y}\right)w(\xi) \qquad (21)$$

Moreover, the pressure at the free surface is taken to be equal to zero, ie. $p(z=\xi)=0$.
Summing up all the terms, we obtain:

$$\frac{\partial}{\partial t}\int_z^{\xi}w\,dz+\frac{\partial}{\partial x}\int_z^{\xi}uw\,dz+\frac{\partial}{\partial y}\int_z^{\xi}vw\,dz-w^2(z)=\frac{1}{\rho}p(z)-g(\xi+h)+\nu\int_z^{\xi}\Delta w\,dz \qquad (22)$$

Taking the mean of the above equation; then making the assumption that the vertical velocity remains small, then we assume that $w=0$; an often overlooked consequence is that step slopes should be avoided when they are facing the flow.

$$\overline{\frac{\partial}{\partial t}\int_{z}^{\xi} w\,dz} = \frac{\partial}{\partial t}\int_{z}^{\xi} \overline{w}\,dz = 0 \qquad (23)$$

$$\overline{\nu\int_{z}^{\xi} \Delta w\,dz} = \nu\int_{z}^{\xi} \Delta\overline{w}\,dz \qquad (24)$$

$$\overline{\frac{\partial}{\partial x}\int_{z}^{\xi} uw\,dz} = \frac{\partial}{\partial x}\int_{z}^{\xi} \overline{(\overline{u}+\tilde{u})\tilde{w}}\,dz = \frac{\partial}{\partial x}\int_{z}^{\xi} \overline{\tilde{u}\tilde{w}}\,dz \qquad (25)$$

$$\overline{\frac{\partial}{\partial y}\int_{z}^{\xi} vw\,dz} = \frac{\partial}{\partial y}\int_{z}^{\xi} \overline{(\overline{v}+\tilde{v})\tilde{w}}\,dz = \frac{\partial}{\partial y}\int_{z}^{\xi} \overline{\tilde{v}\tilde{w}}\,dz \qquad (26)$$

$$\overline{g(\xi - z)} = g(\overline{\xi} - z) \qquad (27)$$

$$\overline{\frac{p(z)}{\rho}} = \frac{P(z)}{\rho} \qquad (28)$$

This gives the following result:

$$\frac{P(z)}{\rho} = g(\overline{\xi} - z) + \frac{\partial}{\partial x}\int_{z}^{\xi} \overline{\tilde{u}\tilde{w}}\,dz - \frac{\partial}{\partial y}\int_{z}^{\xi} \overline{\tilde{v}\tilde{w}}\,dz - \overline{\tilde{w}^2}(z) \qquad (29)$$

Integration of the horizontal momentum equations:
The derivation is detailed term by term for the first momentum equation:

$$\int_{-h}^{\xi}\left(\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z}\right)dz = -\int_{-h}^{\xi}\frac{1}{\rho}\frac{\partial p}{\partial x}\,dz - \nu\int_{-h}^{\xi}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)dz \qquad (30)$$

$$\int_{-h}^{\xi}\frac{\partial u}{\partial t}\,dz = \frac{\partial}{\partial t}\int_{-h}^{\xi} u\,dz - u(\xi)\frac{\partial \xi}{\partial t} \qquad (31)$$

$$\int_{-h}^{\xi}\frac{\partial u^2}{\partial x}\,dz = \frac{\partial}{\partial x}\int_{-h}^{\xi} u^2\,dz - u^2(\xi)\frac{\partial \xi}{\partial x} - u^2(-h)\frac{\partial h}{\partial x} \qquad (32)$$

$$\int_{-h}^{\xi}\frac{\partial uv}{\partial y}\,dz = \frac{\partial}{\partial y}\int_{-h}^{\xi} uv\,dz - u(\xi)v(\xi)\frac{\partial \xi}{\partial y} - u(-h)v(-h)\frac{\partial h}{\partial y} \qquad (33)$$

$$\int_{-h}^{\xi}\frac{\partial uw}{\partial z}\,dz = u(\xi)w(\xi) \qquad (34)$$

$$\int_{-h}^{\xi}\frac{\partial p}{\partial x}\,dz = \frac{\partial}{\partial t}\int_{-h}^{\xi} p\,dz - p(-h)\frac{\partial h}{\partial t} + p(\xi)\frac{\partial \xi}{\partial x} \qquad (35)$$

hence summing all these terms, it results in the following term that is equal to zero because of the free surface condition:

$$u(\xi)\left(w(\xi) - u(\xi)\frac{\partial \xi}{\partial x} - v(\xi)\frac{\partial \xi}{\partial y} - \frac{\partial \xi}{\partial t}\right) = 0 \qquad (36)$$

The pressure at the free surface and the speed at the bottom are taken as zero. It remains:

$$\frac{\partial}{\partial t}\int_{-h}^{\xi} u\,dz + \frac{\partial}{\partial x}\int_{-h}^{\xi} u^2\,dz + \frac{\partial}{\partial y}\int_{-h}^{\xi} uv\,dz + \frac{\partial}{\partial x}\int_{-h}^{\xi}\frac{p}{\rho}\,dz - \frac{p(-h)}{\rho}\frac{\partial h}{\partial x} = \upsilon\int_{-h}^{\xi}\Delta u\,dz \qquad (37)$$

Taking the mean of each term:

$$\overline{\int_{-h}^{\xi}\frac{\partial u}{\partial t}\,dz} = \overline{\frac{\partial}{\partial t}\int_{-h}^{\xi}(\bar{u} + \tilde{u})\,dz} = \frac{\partial \bar{U}}{\partial t} \qquad (38)$$

$$\overline{\frac{\partial}{\partial x}\int_{-h}^{\xi}u^2\,dz} = \overline{\frac{\partial}{\partial x}\int_{-h}^{\xi}(\bar{u} + \tilde{u})^2\,dz} = \frac{\partial}{\partial x}\int_{-h}^{\xi}\bar{u}^2\,dz + \frac{\partial}{\partial x}\int_{-h}^{\xi}\overline{\tilde{u}^2}\,dz \qquad (39)$$

$$\overline{\int_{-h}^{\xi}\frac{\partial uv}{\partial y}\,dz} = \overline{\frac{\partial}{\partial y}\int_{-h}^{\xi}(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})\,dz} = \frac{\partial}{\partial y}\int_{-h}^{\xi}\bar{u}\bar{v}\,dz + \frac{\partial}{\partial y}\int_{-h}^{\xi}\overline{\tilde{u}\tilde{v}}\,dz \qquad (40)$$

$$\overline{\upsilon\int_{-h}^{\xi}\Delta u\,dz} = \upsilon\int_{-h}^{\xi}\Delta \bar{u}\,dz \qquad (41)$$

$\bar{p}$ is defined as the average dynamic pressure at the bottom.

$$\bar{p} = \overline{P(-h)} - \rho g(\bar{\xi} - h) \qquad (42)$$

Hence:

$$\overline{\frac{p(-h)}{\rho}\frac{\partial h}{\partial x}} = \bar{p}\frac{\partial h}{\partial x} - \frac{\partial}{\partial x}\left(\frac{1}{2}\rho g(\bar{\xi} + h)^2\right) - g(\bar{\xi} + h)\frac{\partial \bar{\xi}}{\partial x} \qquad (43)$$

$$\frac{\partial \bar{U}}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\xi}\frac{\partial \overline{u}^2}{\partial t}\,dz - \frac{\partial}{\partial y}\int_{-h}^{\xi}\frac{\partial \overline{uv}}{\partial t}\,dz = \frac{\partial}{\partial x}\left(\int_{-h}^{\xi}\overline{\left(\bar{u}^2 + \frac{\bar{p}}{\rho}\right)}\,dz - \frac{1}{2}g(h + \bar{\xi})^2\right)$$

$$- \frac{\partial}{\partial y}\int_{-h}^{\xi}\overline{\tilde{u}\tilde{v}}\,dz - g(\bar{\xi} - h)\frac{\partial \bar{\xi}}{\partial x} + \bar{p}\frac{\partial h}{\partial x} + \overline{\upsilon\int_{-h}^{\xi}\Delta u\,dz} \qquad (44)$$

We obtain the movement equation integrated on the vertical and averaged on a period. Two terms depend on the speed fluctuations:

$$S_{xx} = \int_{-h}^{\xi} \left(\overline{p + \rho u^2} \right) dz - \rho g (h + \overline{\xi})^2 \qquad (45)$$

$$S_{xy} = \int_{-h}^{\xi} \overline{\rho u v}\, dz \qquad (46)$$

Or for the second momentum equation:

$$S_{yy} = \int_{-h}^{\xi} \left(\overline{p + \rho v^2} \right) dz - \frac{\rho g}{2} (h + \overline{\xi})^2 \qquad (47)$$

$$S_{yx} = \int_{-h}^{\xi} \overline{\rho v u}\, dz \qquad (48)$$

The terms $\tau_{ij} = \frac{\partial S_{ij}}{\partial x_j}$ are the components of the effective shear stress.

A last assumption is made assuming that the mean horizontal velocities are constant along the vertical.

$$\int_{-h}^{\xi} \overline{u^2}\, dz = \overline{u}^2 (\overline{\xi} - h) = \overline{u U} \qquad (49)$$

$$\int_{-h}^{\xi} \overline{u v}\, dz = \overline{u v} (\overline{\xi} + h) = \overline{u V} = \overline{U v} \qquad (50)$$

Then we obtain the Shallow Water equations expressed in averaged velocity. Introducing the wind and bottom friction stress components, the system of equations becomes:

$$\frac{\partial \overline{\xi}}{\partial t} + \frac{\partial \overline{U}}{\partial x} + \frac{\partial \overline{V}}{\partial y} = 0 \qquad (51)$$

$$\frac{\partial \overline{U}}{\partial t} + U \frac{\partial \overline{U}}{\partial x} + V \frac{\partial \overline{U}}{\partial y} = -g(\overline{\xi} + h) \frac{\partial \overline{\xi}}{\partial x} + \frac{\tau_{sx}}{\rho} - \frac{\tau_{bx}}{\rho} - \frac{\tau_{xx}}{\rho} - \frac{\tau_{xy}}{\rho} + \frac{\partial}{\partial x}\left(\upsilon_t \frac{\partial \overline{U}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\upsilon_t \frac{\partial \overline{U}}{\partial y} \right) - f\overline{V} \qquad (52)$$

$$\frac{\partial \overline{V}}{\partial t} + U \frac{\partial \overline{V}}{\partial x} + V \frac{\partial \overline{V}}{\partial y} = -g(\overline{\xi} + h) \frac{\partial \overline{\xi}}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{\tau_{by}}{\rho} - \frac{\tau_{yx}}{\rho} - \frac{\tau_{yy}}{\rho} + \frac{\partial}{\partial x}\left(\upsilon_t \frac{\partial \overline{V}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\upsilon_t \frac{\partial \overline{V}}{\partial y} \right) - f\overline{U} \qquad (53)$$

With

τ_{ij} : component of effective shear stress
τ_b : bottom friction stress
τ_w : wind friction stress
ε_t : turbulent viscosity
f : Coriolis parameter

The values of the bottom friction stress and of the turbulent viscosity terms are very important in the stability of the numerical model. The bottom friction stress term is obtained introducing the Chézy coefficient written C.

$$\tau_b = \rho g \frac{U^2+V^2}{C^2} \qquad \tau_{bx} = \rho g \sqrt{\frac{U^2+V^2}{C^2}}\,U \qquad \tau_{by} = \rho g \sqrt{\frac{U^2+V^2}{C^2}}\,V$$

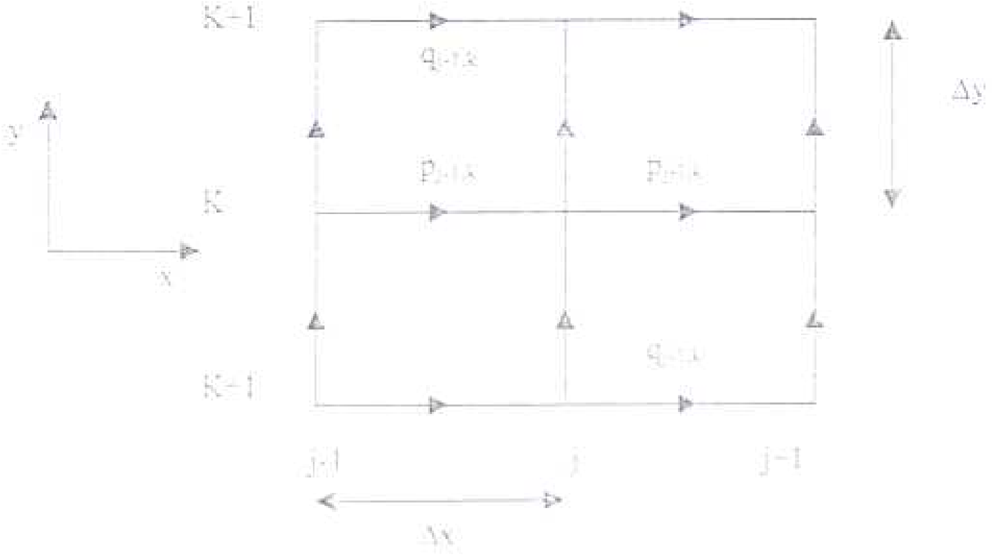
2.5. Numerical formulation

The numerical model is a finite-difference schema using an A.D.I. (Alternating Direction Implicit) technique to integrate the equation for mass and momentum conservation in the space-time domain. A Double Sweep (DS) algorithm resolves the equation matrices.

MIKE 21 HD has the following properties:

1. Zero numerical mass and momentum falsification and negligible numerical energy falsification, over the range of practical applications, through centring of all difference terms and dominant coefficients, achieve without resort to iteration.
2. Second to third-order accurate convective momentum terms, ie. "second and third order" respectively in terms of discretization error in a Taylor series expansion.

The difference terms are expressed on a staggered grid in x, y-space as shown below.



Where p and q are flux densities in x- and y-direction ($m^3/s/m$)=(uh,vh); (u,v)=depth averaged velocities in x- and y-direction.
The equations are solved in one-dimensional sweep, alternating between x and y directions. In the x-sweep the continuity and x-momentum equations are solved, taking ξ from n to n+1/2 and p from n to n+1, n-1 and n+1/2. For the terms involving q, the two levels of old, known values are used, ie. n-1/2 and n+1/2.
In the y-sweep the continuity and y-momentum equations are solved, taking ξ from n+1/2 to n+1 and q from n from n+1/2 to n+3, while terms in p use the value just calculated in the x-sweep at n and n+1.
Adding the two sweeps together gives time centring at n+1/2.

3. Method

It was perhaps the most difficult step because almost nobody really uses MIKE 21 very often in SOPAC. I had moreover to use the new version of the software, which was more userfriendly but totally unknown of the staff of SOPAC. It was not possible to read through the 20 manual books. Thanks to the examples available with the software and the previous studies on the old version of the software, I managed to understand the way MIKE 21 works after two months and several hundreds of tries.
It was important as well for being sensitised to the CPU time because some simulations can take so long that they have to be run during the weekend.

4. MIKE 21 user guide

4.1. Creating a project

An important thing is to organise the work area.

4.1.1. In the explorer

- Creating the first new folder

The user has to create a new folder called **Abaiang_project** for instance, in which all the files of the project will be save.

- Creating the first new folders inside

Then, the folders '**data**' and '**work**' have to be created in **Abaiang_project**

4.1.2. In MIKE 21

- Open MIKE 21

The MIKE Zero window shell appears.
MIKE Zero is the user interface, in which we are working most of the time.

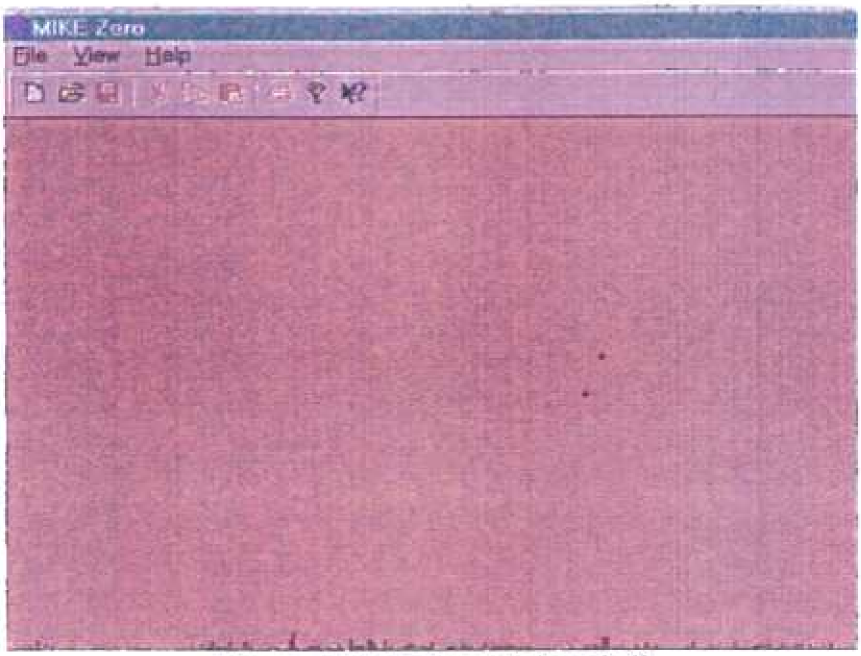


Figure: MIKE Zero window shell

Click on the icon 'new file'
Then, an overview of the different tasks that can be performed from MIKE 21 appears.

Figure: Overview of MIKE Zero and MIKE 21 tasks

4.2. Pre-processing

4.2.1. Creating a bathymetry

- Choose the menu 'bathymetry'

A window of the bathymetry editor appears. This tool provides a work environment for creating, editing and presenting detailed digital bathymetries.
It includes utilities for importing raw data from external sources or to manually create data by using the built-in drawing tools.
Creating a new bathymetry requires that the geographical workspace area be defined. The 'Define Working Area' dialogue is therefore opened.

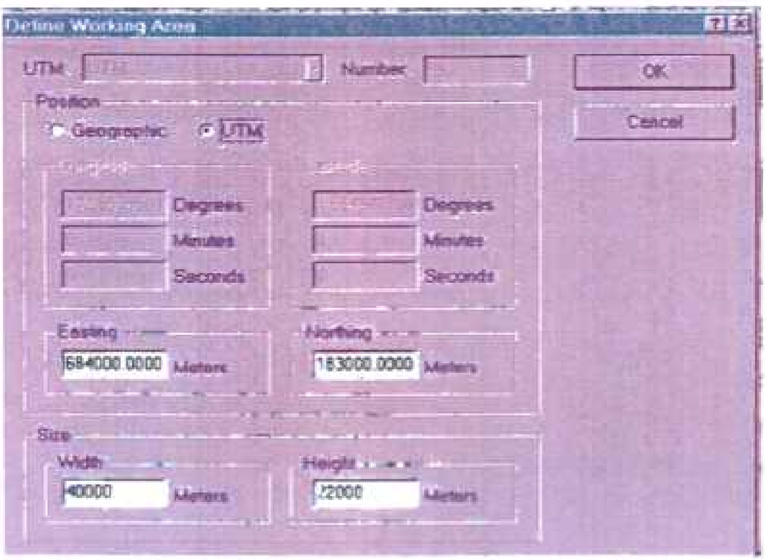


Figure: The Define Working Area dialogue of the Bathymetry Editor

- Importing the data from MzDigi (digitising Software of M21 package)

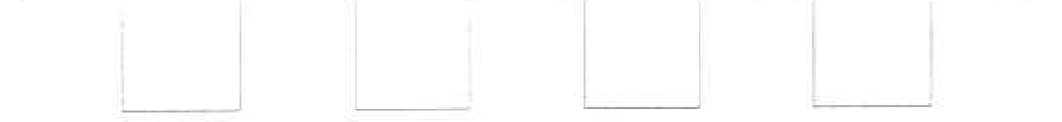
- Creating type 2 data describing the bathymetry

Note: '2' is the wideness of the square matrix we want to work with. It means that a type 1 corresponds with a vector and then type zero with a scalar.

We open the 'Define bathymetry area' from:
Work area->Bathymetry Management->New
Here we have to choose the dimensions of the matrix.

Choosing the grid is not really easy (see later for the case of Abaiang Atoll).
Several higgledy-piggledy pieces of advice to avoid instabilities:

1. The largest grid is the better one to compute properly the wind surge.
2. The flow direction and the open boundaries must be, as far as possible, perpendicular.
3. The bathymetry should be smooth when close to open boundaries.
4. It is better if the open boundaries do not meet in corners of the grid spacing. These corners must not be on a small island compare to the grid spacing.
5. Avoid sudden expansion and contraction of the flow close to an open boundary.
6. If possible, one of the coordinate axes has to be parallel to the main flow direction.
7. The point (0,0) is the most accurately known.
8. Bumps and holes must be as far as possible from the boundaries.
9. Avoid the following kind of boundaries:



➢ The grid spacing

It is the space between two points, or the width of the square that will be given a mean depth. It's very important to be accurate in the model but not too much to be able to run it given the CPU limit.

4.2.2. Creating an interpolated grid

We are still in the Bathymetry editor. We open the 'Define bathymetry area' from:
Work area->Bathymetry Management
Then we click on 'Interpolate'. The dialogue box allows us to choose the type of interpolation for the grid.

If the grid we get is correct, we can finally create the type 2 file by exporting the result of the interpolation.
Then the bathymetry files is ready for the computation.

4.2.3. Creating a flow model

We are back the MIKE Zero window. We click on the 'New' icon and choose the task 'Flow Model'. The following window appears.

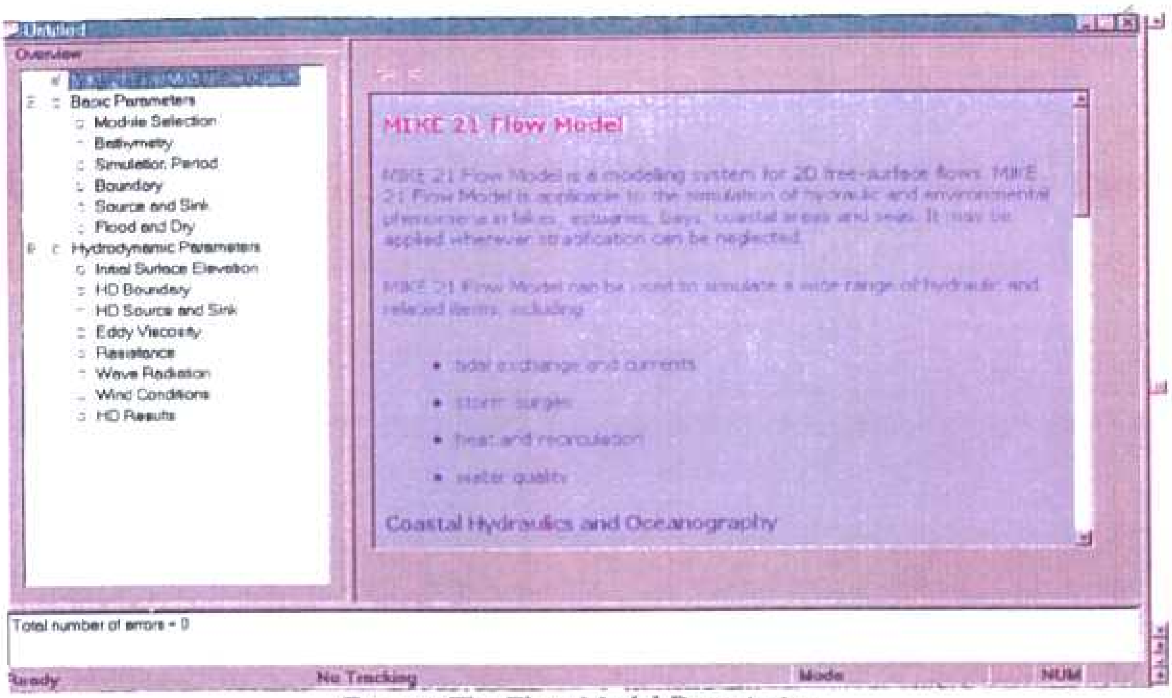


Figure: The Flow Model Description

The 'Flow Model Description' is presented as checklist.

- <u>Basic Parameters</u>

  - ➢ Module Selection

  - ➢ Bathymetry

We have to specify the type 2 file describing the bathymetry we want to work with.

  - ➢ Simulation Period

The time step for a simulation is selected as follows:

- First we have to determine the grid spacing, Δx, as described in *4.2.2*.

- Secondly we decide on the maximum allowed Current number, C_r.

- Then we can determine the maximum time step, Δt_{max}, which can be used in the model from the definition of the Current number:

$$\Delta t_{max} = \Delta x . C_r / c$$

where c is the celerity. For a tidal wave, we have:

$$c = \sqrt{g.h}$$

where g is gravity and h the maximal water depth.

The time step to be used in the model, Δt, can then be chosen as a "convenient" number not greater than Δt_{max}.

Finally we have to check that the Current number based on the current speed, C_U, instead of the wave celerity, is lower than 1 for the time step chosen. This is nearly always the case, but if it is not, we must reduce the chosen time step. C_U is defined as:

$$C_U = U_{max} \Delta t / \Delta x$$

Where U_{max} is the maximum current speed, which occurs during the simulation.

In the same way MIKE 21 calculates the water level and flow in a number of discrete time steps. And just as the grid point should be placed equidistant so should the step, ie. the computation should progress with a constant time increment.

As the information (for water levels and fluxes) in the computational grid travel at a speed corresponding to the celerity, the Current number is an expression of how many grid points the information moves in one time step.

Normally we can have a maximum Current number in the model of up to 7. The maximum value, which can be used without having stability problems, does however depend on the bathymetry. For very smooth bathymetry, MIKE 21 allows Current numbers up to about 20.

- Boundary

- Sources and sinks

- Flood and dry

A very valuable facility in MIKE 21 is its capability to include and exclude computational areas dynamically during the simulation ,ie. , compute flow in an area, which sometimes dries out and is sometimes flooded (e.g. tidal flats).

Continuity is fully preserved during the flooding and drying process as the water depths at the points, which are dried out, are saved and then reused when the point becomes flooded again.

- <u>Hydrodynamic Parameters</u>

  - Initial surface elevation

An initial surface elevation that matches the boundary conditions at the first time step should be specified. The average surface elevation at the open boundaries can be chosen.

- HD Boundary

If the description of the bathymetry is the most important task in the modelling process then the description of the water levels and flow at the open boundaries is the second most important task. The better the boundary conditions are, the better the results and the fewer the instability problems are.

The choice of variation at an open boundary can be either level or flux (the flux is the total amount of discharge passing the open boundary). Actual values, level or flux, at each boundary can be specified in one of five different formats:

- A constant value
- A sine series
- A time series (type 0 file)
- A line series (type 1 file)
- Transferred datum

- Eddy viscosity

The Eddy viscosity was unknown before the computation. As a consequence, it became one of the parameters to be changed in order to reproduce the reality.
It is mainly used to stabilize the solution. If the results are spurious with high frequent oscillations in the water levels, the result can be smoothened by increasing the Eddy viscosity in the area.

Scientific background:

The effective shear stresses in the momentum equations contain momentum fluxes due to turbulence and vertical integration. The terms are included using an Eddy viscosity formulation.

The formulation of the Eddy viscosity in the equations has been implemented in two ways:

- Flux based formulation

$$\frac{\partial}{\partial x}\left\{E\frac{\partial P}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{E\frac{\partial P}{\partial y}\right\} \quad \text{(x-momentum)}$$

where P is the flux in the x-direction and E is the Eddy viscosity coefficient.

- Velocity based formulation

$$\frac{\partial}{\partial x}\left\{h.E\frac{\partial u}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{h.E\frac{\partial u}{\partial y}\right\}$$

where u is the velocity in the x-direction and h the water depth.

Strictly speaking the first formulation is only correct at a constant depth and should be applied with great care in order to avoid falsification of the flow pattern.

The velocity based formulation, which is more correct, is unfortunately also more difficult to implement in the numerical algorithm. This is because the system uses the fluxes as the unknown parameters and not the velocities. Therefore the velocity-based formulation is implemented by using the velocities from the previous time-step. This can, however, lead to stability problems when the Eddy viscosity coefficient E becomes large. The coefficient must fulfil the criterion:

$$\frac{E.\Delta t}{\Delta x^2} \leq \frac{1}{2}$$

Specifying the Eddy viscosity

The Eddy viscosity coefficient E can be specified in three different ways:

- As a constant value for the entire computational domain;
- From a type 2 data file giving the value at each grid point;
- A time-varying function of the local gradients in the velocity field. This formulation is based on the so-called Smagorinski concept, which yields:

$$E = c_s^2 \Delta^2 \left[\left(\frac{\partial U}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 \right]$$

where U, V are the depth average velocity components in the x- and y-direction, Δ is the grid spacing and c_s is a constant to be chosen in the interval of 0.25 to 1.0.

The Smagorinski facility is combined with the following formulation of the shear stresses, i.e.:

$$\frac{\partial}{\partial x}\left\{ h.E \frac{\partial U}{\partial x} \right\} + \frac{\partial}{\partial y}\left\{ \frac{1}{2} h.E \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right\}$$

- Bed and pier resistance

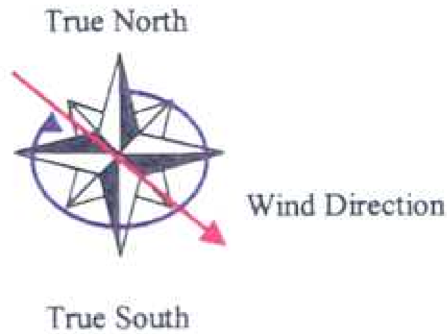
The most important is to know that using a smaller resistance number increases the bed resistance and vice versa. It is hard to choose the constant value or possibly the type 2 file as a Manning or Chezy number because the formula which links both depends on the height:

$$C = M.h^{\frac{1}{6}}$$

Values in the range 20-40 are normally used with a suggested value of 32 $m^{1/3}.s^{-1}$ for the Manning number whereas the range is 30-50 fir the Chezy number. It is better to choose the Chezy number not to increase the computational time by calculating $h^{1/6}$ for each point of the grid.

➢ Wind conditions

Definition of the wind direction:
The degrees have to be calculated like shown with the blue arrow.



There are two ways to import wind data files:

1. A type 0 file has to be edited if the wind is constant in space.
2. A type 2 file has to be edited if the wind varies in time and space.

The condition is having wind data for at least all the simulation period. There is no question of time interval.

➢ HD Results

Here are defined the output specifications. We choose the output areas and periods of the simulation those are going to be simulated in the post-processing.

4.3. Post-processing

4.3.1. Tool boxes

This new version of MIKE 21 has got two interesting tools for pre- and post-processing, especially for specific data analyse.

- MIKE Zero Toolbox editors

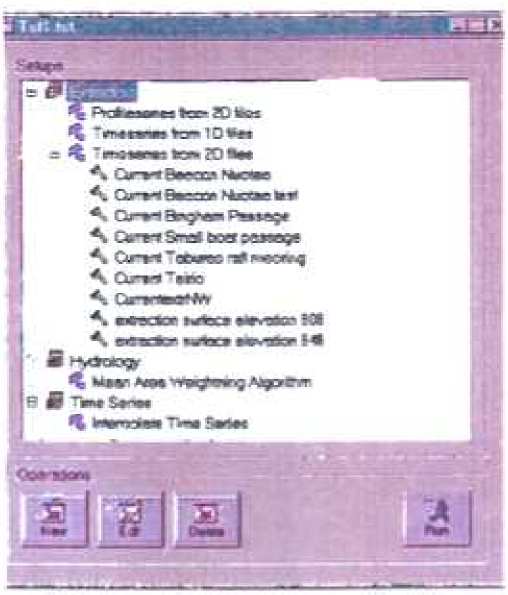


Figure: The MIKE Zero Toolbox

- <u>MIKE 21 Toolbox editors</u>

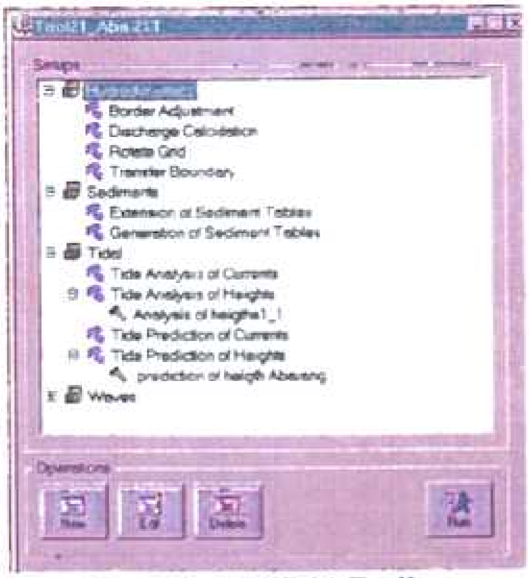


Fig. The MIKE 21 Toolbox

4.3.2. Running the simulation

- <u>Plot Composer Editor</u>

Creating a new plot composition first opens an empty plot.
From: *Plot->Insert New Plot Object*, we then specify which type of plot we want to generate and an empty area corresponding to our specification appears.

To insert a plot into this area, first we have too select this area (left click). A right click in the selected area will open a menu box from which we have to select '**Properties**'.

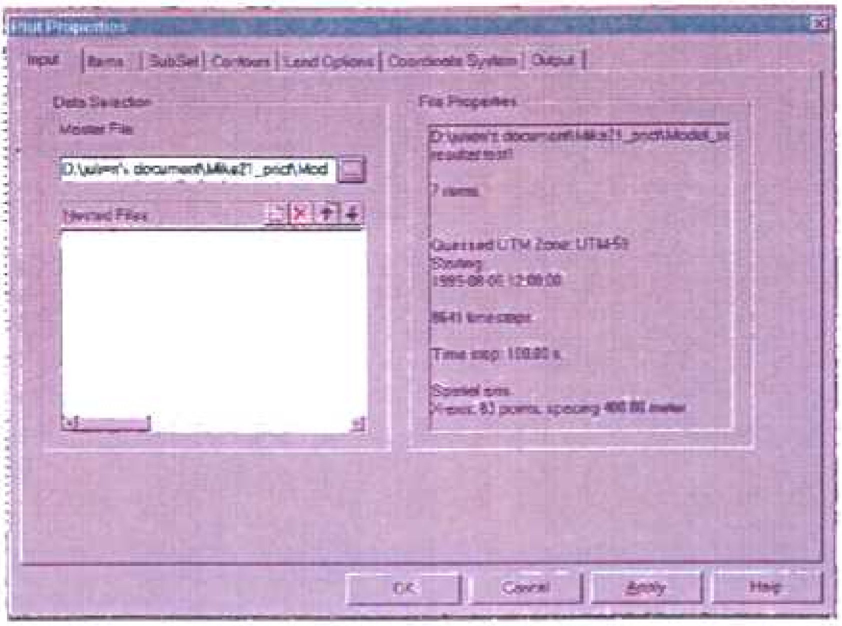


Figure: Plot properties dialogue box

- Data selection

Here we have to select the master file, which the type 2 file that has been executed thanks to the simulation.

- Select item

For each step of the simulation, two pieces of information can be available thanks to the contours and the vectors. Among all the available items, a speed and a flux can not be chosen together.

- Select sub-series

We can select a sub-area and a sub-serie.
The last available set is written by default but can be corrected.
To know how many steps there are in the simulation, we just have to calculate:

Number of steps = Floor (1+(last set – first set)/step)

- Contours definition

It is perhaps better with the isolines and the shading colours. Anyway it is necessary to click on '**Levels/Colours**' then on '**Linear Auto Scale**' to have an appropriate scale.

B. Basic simulation

1. Set-up of the bathymetry

The first step and by far the most important task in a modelling process was setting up the bathymetry model. A few hours less spent in setting up the model bathymetry might later mean extra days spent in the calibration process. Data used for the compilation was sourced from a survey completed in Abaiang atoll in August 1999. (*cf. II.B.2*)

With the old version of MIKE 21, instead of setting up the model directly in the software, the user preferred using the software Quicksurf that is a surface modelling system running inside AutoCAD R14. Quicksurf is package used for generation of contour maps, profiles, and interpolation grids.

Then, after having generated an interpolation grid, the next step consisted in exporting it MIKE 21 after having converted the grid data into a MIKE 21 format using a FORTRAN routine.

The new version of MIKE 21 has new and more powerful tools of map digitizing and grid generation.

1.1 Set-up of the contour map under AutoCAD

First, the coastline and the reef have been digitized under AutoCAD from a 1:25000 series DOS map.
Then, using Quicksurf, we imported the ASCII point files within the model.

Figure: Abaiang Map with imported data under AutoCAD

Some corrections have been necessary to avoid the superposition of some data and to have a coherent bathymetry according to the maps. These corrections have been done mainly on the reef where data was difficult to collect during the survey because it was very shallow. Offshore, we added some points near the open boundary where the bathymetry is known to be very deep. For the purpose of the model we assume a depth of 100m to keep a low courant for the model (100 meters).

After correction all data Chart datum a contour map was generated by Quicksurf and plotted at 1:25000 scale.

1.2 Digitizing of the contour map

This task has been realized with a program of the MIKE 21 package: MzDigi.

The program MzDigi uses a x,y format coordinates system for the model the origin referenced to a known geographical position. Blue Marble Geographic Calculator was used to carry out the transformations from UTM system 3 WGS 1984 to the geodetic system 3 WGS 1984.

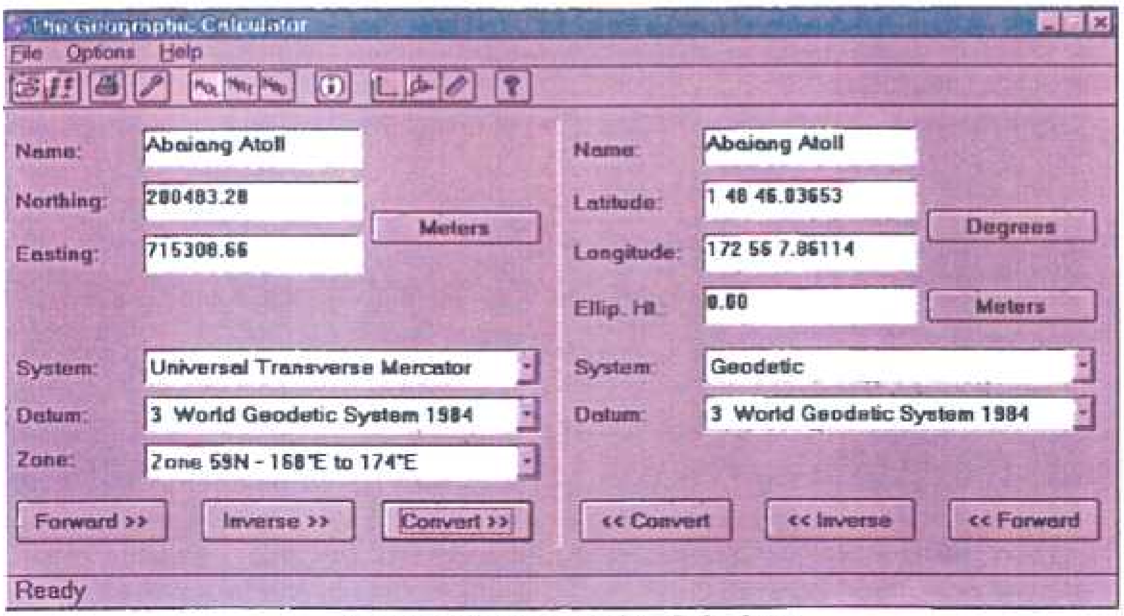


Figure: The Geographic Calculator

This task although time consuming allows the results to interpreted in context of a map co-ordinate system.

1.3 Interpolation

In compiling the bathymetry several interpolations were tried. The first one using AutoCAD was not easy and considered somewhat inefficient when attempting to define the shoreline or land boundary for the model. Using an alternative software package MapInfo with VerticalMapper, interpolation of the bathymetry with the shoreline was easier to define however the more important problem was then exporting this bathymetric model to Mike 21 as this program has very specific file format only common to this program.

However the new windows version of MIKE21 has been develop with a better tools for interpolation and grid generation

At first we chose a grid size of 200 m. per 200 m. but seeing the size of the model, the time of computation (more than 4 hours just for the hydrodynamic module) and the size of the result files (about 3 gigabytes), we have been obliged to choose a 400 m. per 400m. grid size, which was more reasonable.

1.4 Smoothing the bathymetry

Further adjustments to remove incoherent values from the original interpolation to produce a smooth bathymetric model to avoid computational blowups.
Approximately two months of work was required to prepare the bathymetry model.

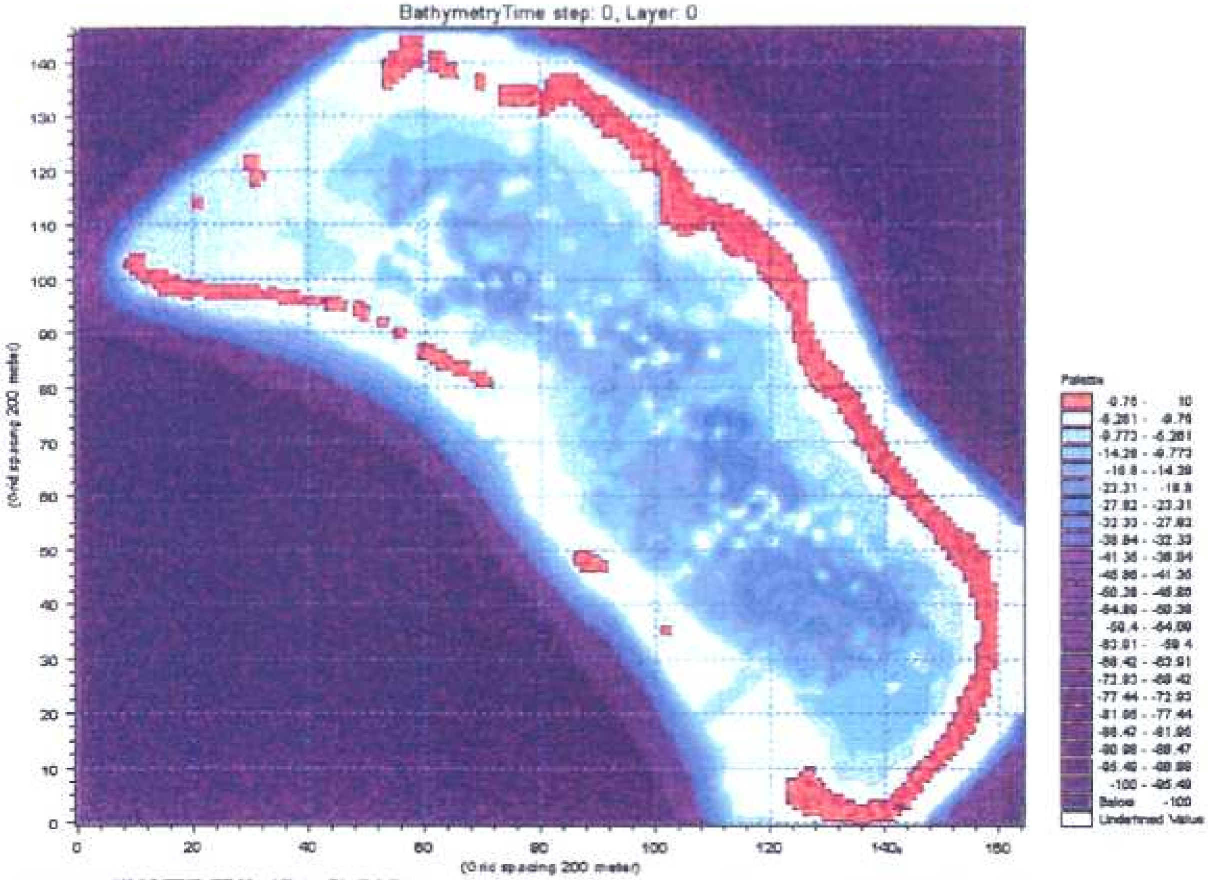


Figure: Bathymetry of Abaiang Atoll under MIKE 21

1.5 Final correction

1.5.1. The open sea

As we did not have data about the bathymetry outside the atoll, noting it deepens rapidly to great depth form the reef crest an assume depth of the sea outside the atoll of 100 meters, decreasing slowly, linearly and continuously as we approach the shore to avoid computational blow up was used

1.5.2 The passages

Of the passages existing the lagoon to the west only one was navigable by the survey boat the other to the south was a small boat passage therefore some assumption as to their depth and were assumed. Channel width and length were scaled from the topographical maps for Abaiang.
These channels are extremely important, as they are the principal conduits for flushing of the lagoon.

1.5.3 The shore

On the present bathymetry, we have four open boundaries surrounding the atoll. Due to the computational structure of MIKE 21 there are a few restrictions to where a boundary can be located.

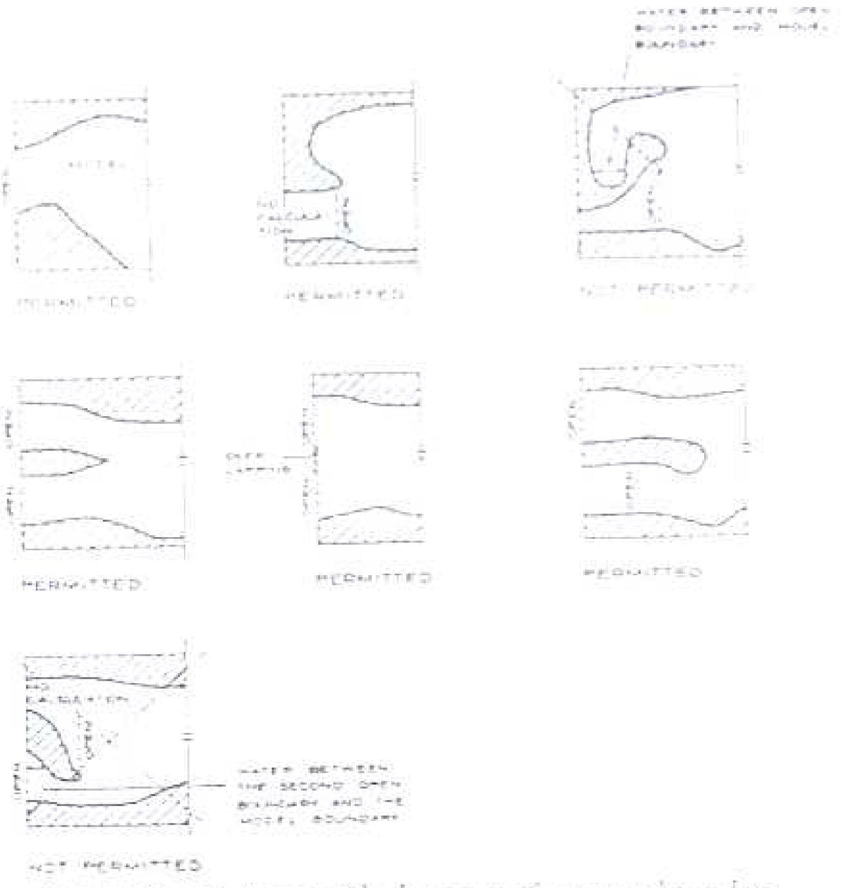


Figure: Restrictions on the location of an open boundary

Our study is limited to lagoon, which is the inside of atoll. We decided to extend the land located on north-eastern and south-eastern part of the atoll till the boundaries of the model in so far this area is not influencing a lot the circulation inside the atoll.

Finally we obtained the following model.

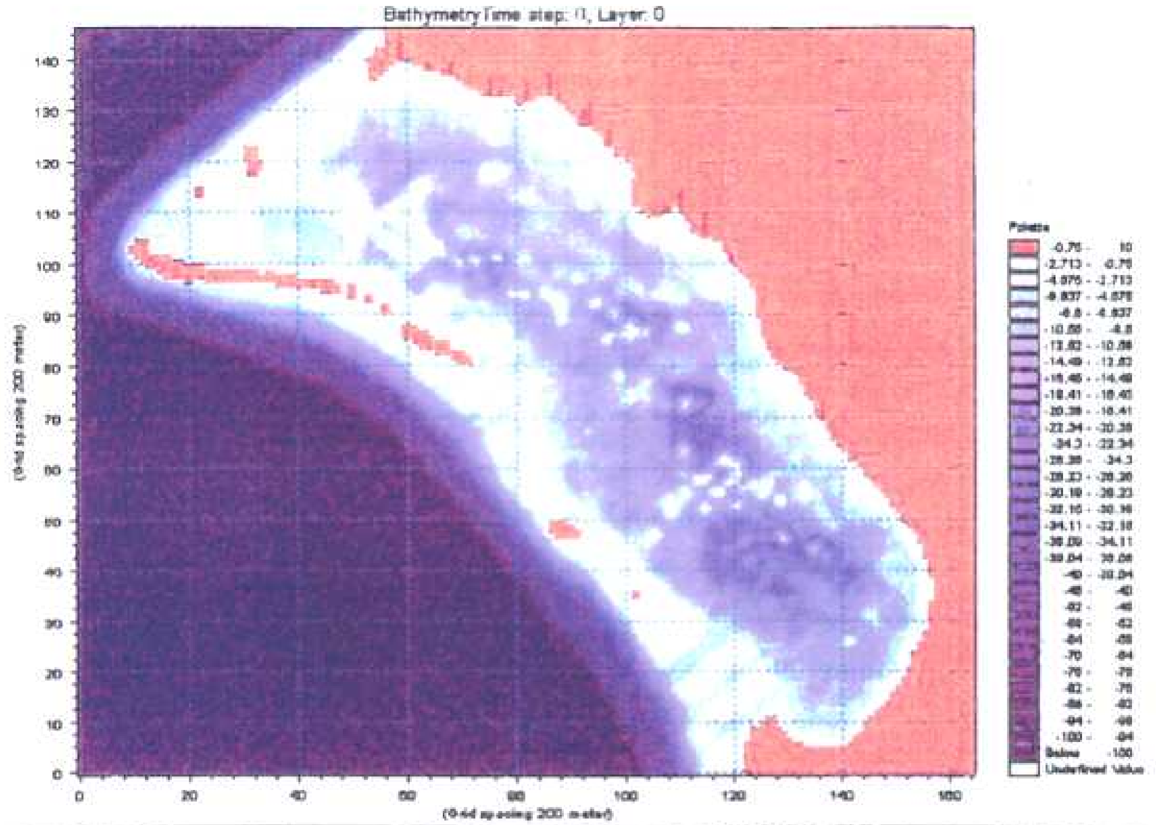


Figure: Bathymetry of Abaiang Atoll under MIKE 21 after final corrections

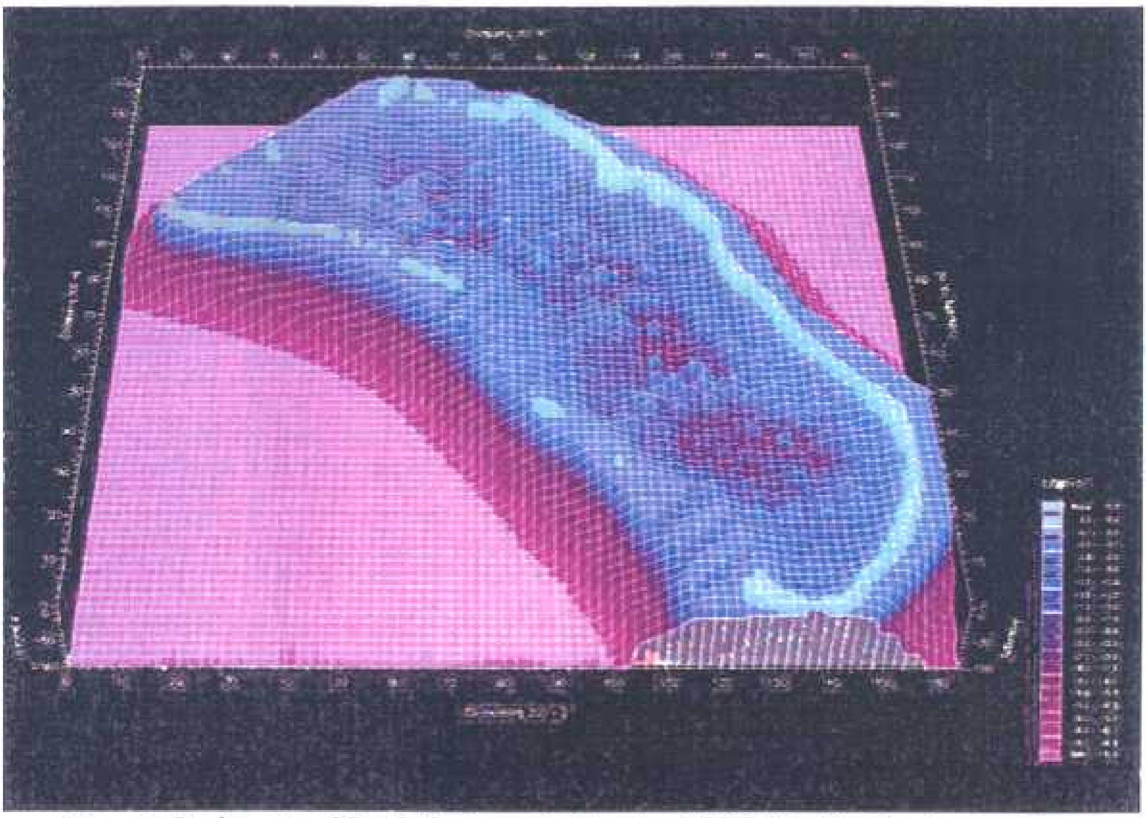


Figure: Bathymetry 3D of Abaiang Atoll under MIKE 21 after final corrections

2. Set-up of the hydrodynamic model

The purpose of the calibration is to tune the model in order to reproduce satisfactorily results which compare well with measured conditions for a particular period known. It is rare that the first few simulations will provide good results as model instability can result in the simulation ending prematurely.

Many parameters can be changed in order to find the same plot with the computer as with the current meter. The main purpose is finding the same plot in specific areas with:

- The 12 hours 25 minutes period;
- The change of flux direction;
- Approximately the same amplitudes.

2.1. Time

Calibration measurements were recorded at an every ten seconds interval over a ten days period. This then defined the simulation period and the time steps for comparing model results with simulated results. It is important because with different time steps or periods, some phenomenon could have been missed.

At the beginning, the simulated plot is too far from the measurement that is why there is no need to wait for a long computation. Then we chose a simulation period of two days. The full simulation period is from the 6th of August 1999 at 12H00 PM to the 16th of August 1999 at 12H00 PM, with a time step of 100 seconds.
This produces a courant number of 7.83, which is a good indicator for model stability. Several hours have been necessary to complete the simulation.

2.2. Initial Surface Elevation

At the beginning of the simulation, the tide is not at the mean level. So the initial surface elevation had to be found that corresponded to the start of the simulation period as so as to have no computational blowup.
By editing the type 0 file of the admiralty tide (*cf. I.B.3.1*), the initial surface elevation was given as the same value as the surface elevation at the open boundary, i.e. 0.446124 m.

In comparing the computed water level form the Admiralty data, the delay is due to the different times when the water level recorders and current meter were switched on, otherwise the admiralty values are provide a good time series for the simulation.

2.3. Drying and flooding

A problem of numerical algorithms is drying zones where some terms in the equations have divisions, which tend to infinity when h tend to 0. The solution is to remove the dry zones from the computational domain.

To enable the possibility of flooding and drying areas, the depths where the computational points should be taken out or reentered into the computations has to be chosen. The value given as default that is 0.2 m. for the drying depth and 0.3 m. for the flooding depth fits perfectly to the situation.

2.4. Eddy viscosity

For our studies, we specified a type 2 file to describe the turbulent viscosity for the whole flow field. In our model, the turbulence was important and using a constant eddy viscosity model was too simple

2.5. Wind conditions

Like the Eddy viscosity, there is no wind measurement available except for data summarized in chapter *I.B.3.4* of this report but it is not accurate enough. However during the and for model purposes the wind was from an easterly direction with an average speed of 15 knots. According to the requirements of MIKE 21 the direction has been fixed to 90 degrees. Later, we ran simulations with the wind blowing from north, south and west, and without wind.

3. Plots and analyses

After having run several simulations, corrected the bathymetry in order to avoid blow ups which end the simulation prematurely and calibrated the model, output graphs of water elevation and velocities can be analyzed.

3.1. Water level elevation

The following graph compares the measured and the computed water elevation. It clearly shows little difference between the two curves.

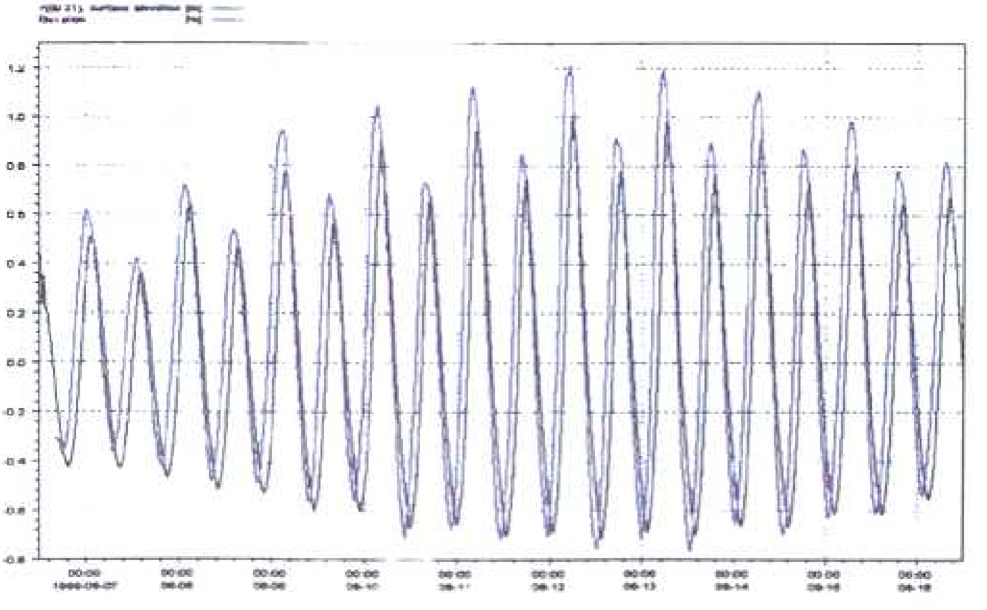


Figure: Comparison of measured and computed water elevations of point (69,31)

Additional points from the model were examined and similar if not better correlation were produced between the measured and the computed water elevation except in one area of the atoll.

Indeed on the northwesterly part of the lagoon (Beacon Nuotea), there is an important difference of phase

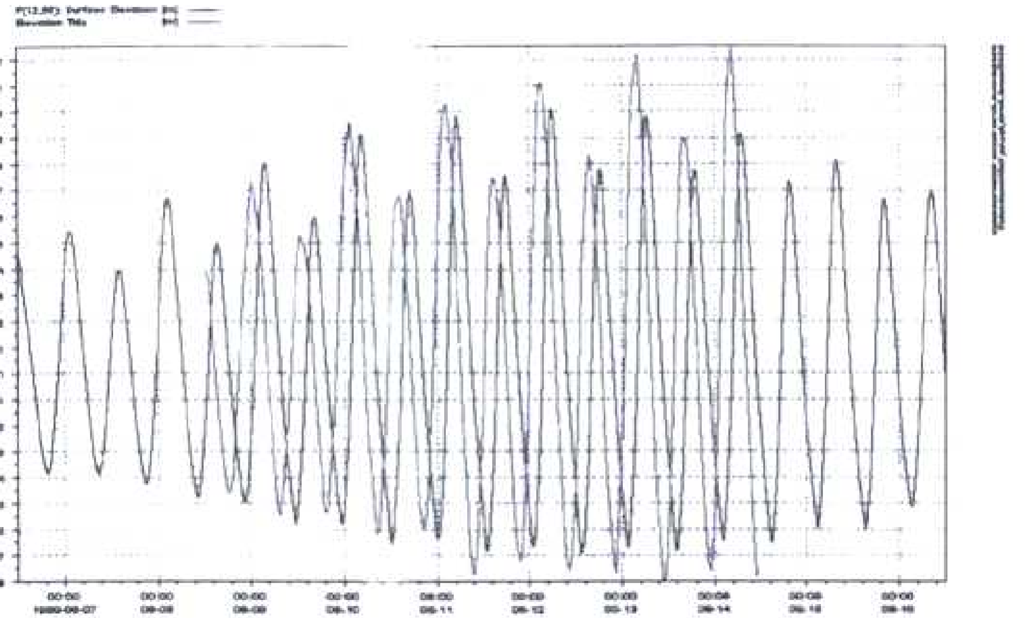


Figure: Comparison of measured and computed water elevations of point (12,55)

This difference of phase comes essentially from the fact that during the survey, the water level recorder (848) has been moored just behind a growth of coral, which disrupt the flow locally. It was not possible for us to modelise such a local phenomenon because of the size of the grid.

3.2. Velocities

An analysis of the 2D velocities maps shows that the flow is linear at almost every time steps.

In examining the velocities at different grid points in the model, it can be observed that the current follows the tide well. The fact that the velocities are more important in the small passages is not surprising because they are the spot where are localised the inflows and outflows due to the tides Concerning the shape of certain curves, the large peaks observed just before low tide or just after high tide may be due to the effect of *flooding and drying* in the model (*cf. III.B.2.3.*).

The whole model seems to reproduce velocities that are coherent.

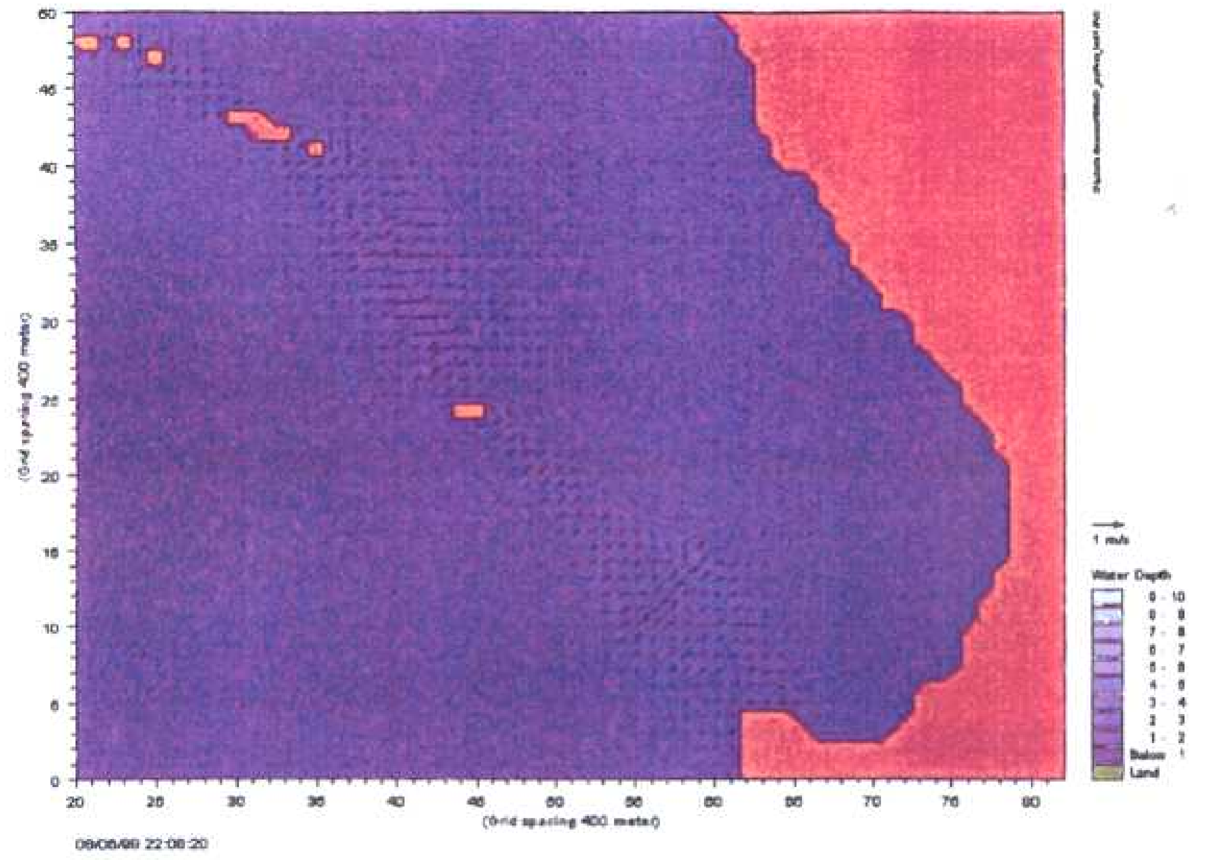


Figure: Flow in the southwester passages of Abaiang Atoll during high tide

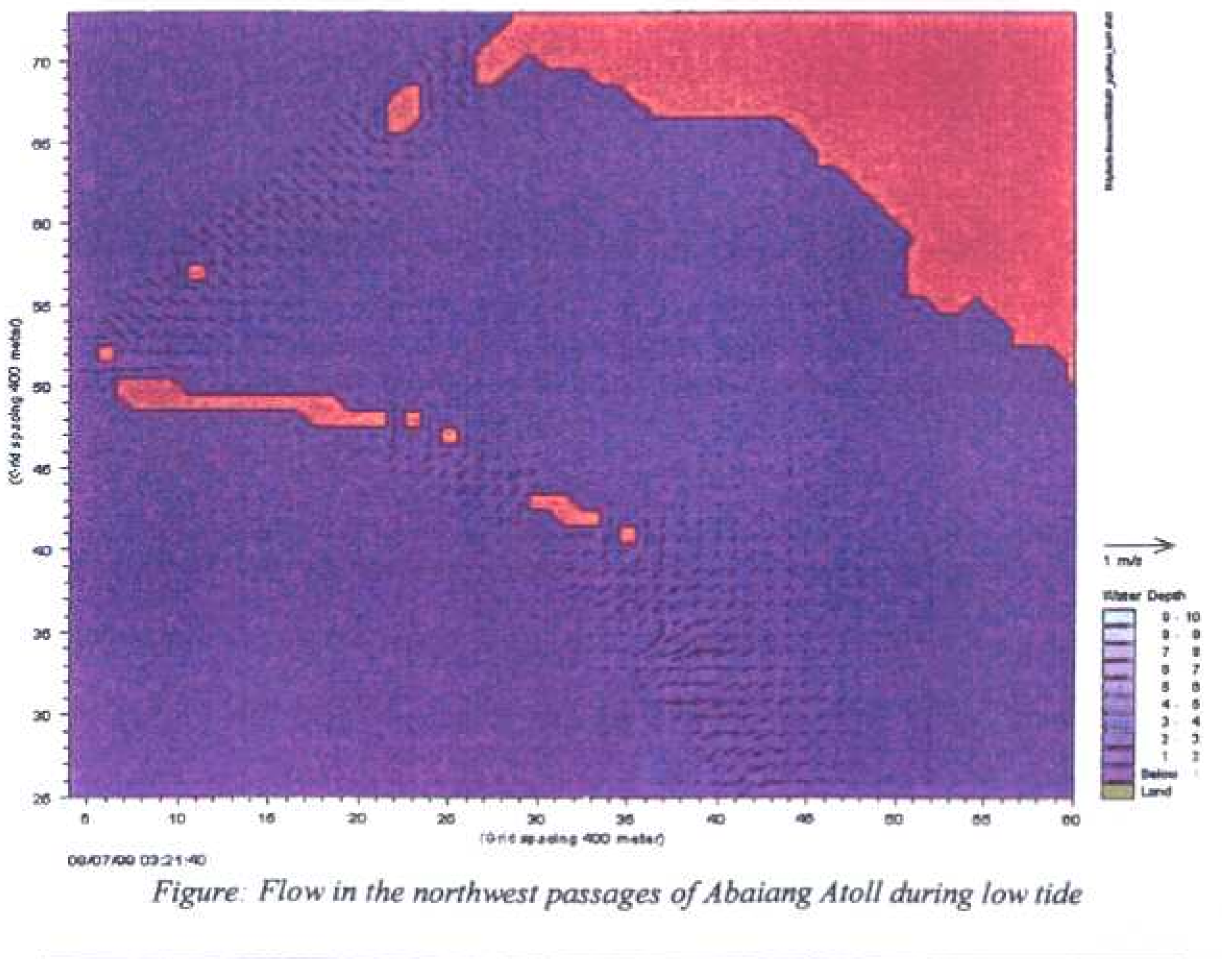
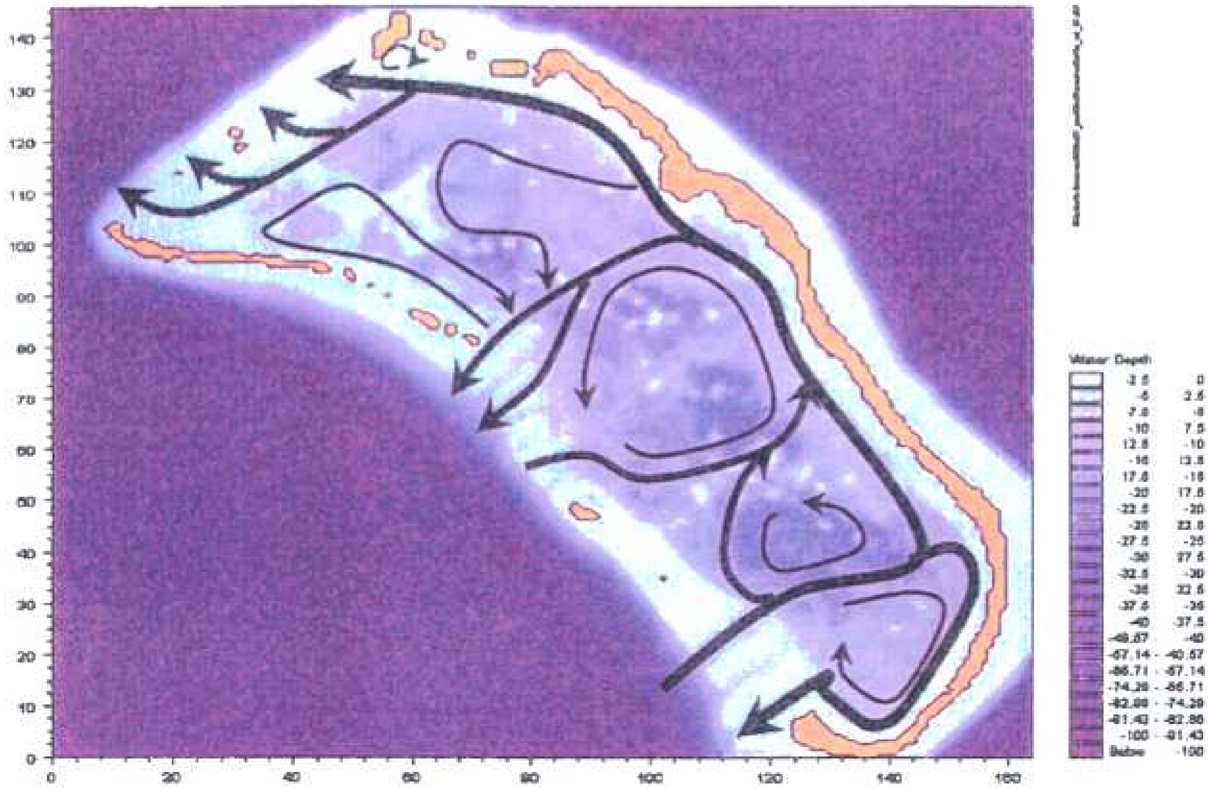


Figure: Flow in the northwest passages of Abaiang Atoll during low tide

The plots comparing the measured and calculated speed in different spots of the lagoon can be found in Annexe 4

3.3. Description of the circulation in the lagoon

Using one of the options of the *Plot Composer* of MIKE 21: *Track Flow Visualisation*, we have been able to draw conclusions as to the circulation pattern of the lagoon based on the 2-D model for different wind conditions. This generalised circulation for the lagoon appears to be quite complex as a reflection of the complicated bathymetry as illustrated in the figure below for an easterly wind of 10 knots.



In the figure above the principal in flow regions are associated with the breaks in the barrier reef to the west. The more important inflow of water is in an area to the south reef break (Bingham Passage). The major outflow region of the lagoon is over the large open northwestern reef flat.

A strong longshore current along the eastern margin form the south to the north of the lagoon is also evident from the model. In the field it was noted there was a build-up of sediment occurring on the southern side of a coastal structures, groins, and seawall structures protecting reclamation projects in the northeastern section of the island.

We can remark the stream along the shoreline of the main island, which has an important influence on certain spots of aquaculture (*cf III.D.*).

For a westerly wind of 5 knots we can remark an inversion of the direction of the flow compare to the previous figure (*cf Figure Annex 4*).

C. Water Quality simulation

1. Introduction

The water quality module of MIKE 21 is used to investigate the environmental problems connected to pollution sources such as domestic and industrial sewage and agricultural run-off in coastal areas.

The model describes the resulting concentrations of bacteria, which threatens bathing water quality, oxygen depletion due to the release of BOD, excess concentrations of nutrients, chlorophyll-nutrient interactions and degradation of chemical substances.

The water quality module is integrated with the advection-dispersion module, which describes the physical transport processes at each grid-point covering the area of interest. Other data required are concentrations at model boundaries, flow and concentrations from pollution sources, water temperature, etc.

The system solves the process equations using a rational extrapolation method in an integrated two-step procedure with the advection-dispersion module.

2. Applications

The water quality module is used for a range of environmental investigations.

For the project in its globality, the applications are:

- Temperature and salinity.
- Oxygen conditions affected by BOD, ammonia and other oxygen consuming substances.

For this study, we will just process the temperature and the salinity in the lagoon.

3. Set-up of the model

3.1. Initial and boundary conditions

In this part of the work, the main difficult task has been to define the boundary and initial conditions, using the data collected during the survey.

Thanks to the twenty-seven stations in lagoon, which were monitored for salinity, temperature, and dissolved oxygen, we have been able to create two initial maps of the temperature and the salinity in the lagoon for the computation.

For the boundary conditions, we took the salinity at 2.5 m. for open ocean waters and a temperature equal to the average surface temperature of the open ocean.

- S = 35.0413 ‰
- T = 28.4000°C

3.2. Wind conditions

As written in *III.B.2.5.*, there is no wind measurement available. Even if during the survey the wind was blowing mainly easterly at an average speed of 15 knots, there are long periods without wind or with westerly winds. That is why we ran three simulations:

Simulations	1	2	3
Wind speed ($m.s^{-1}$)	7.72	2.1	0
Wind direction (°)	90	270	-

3.3. Spots location

The seaweed cultures are located in five areas of the lagoon as shown below.

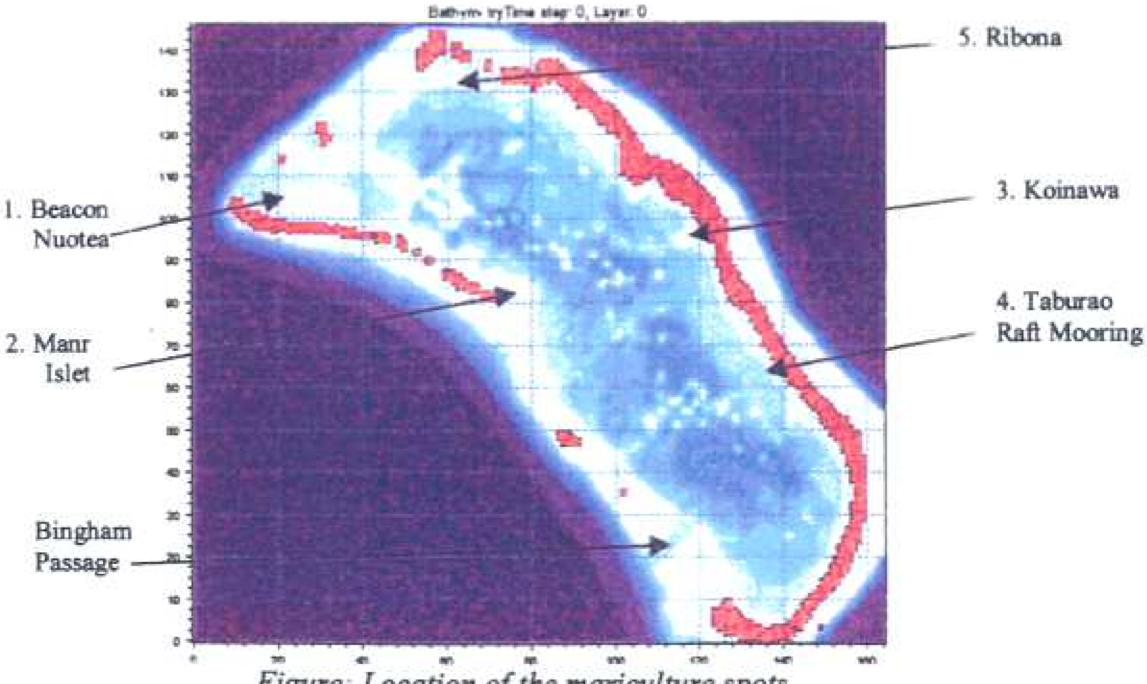


Figure: Location of the mariculture spots

Spot	Northing	Easting	Latitude	Longitude
	UTM 59 – WGS 72		Geographical coordinates in WGS84	
Ribona	214399.2	709394.0	1 56.32	172 52.95
Koinawa	211371.9	705689.0	1 54.68	172 50.95
Taburao Raft Mooring	200866.67	724247.69	1 48.97	173 00.96
Manr Islet	205316.1	711639.5	1 51.39	172 54.16
Beacon Nuotea	209688.56	700572.79	1 53.77	172 48.20

Table: Spots location data

4. Plots

At first, we compared the computed and measured temperatures in the locations of the four long-term loggers.

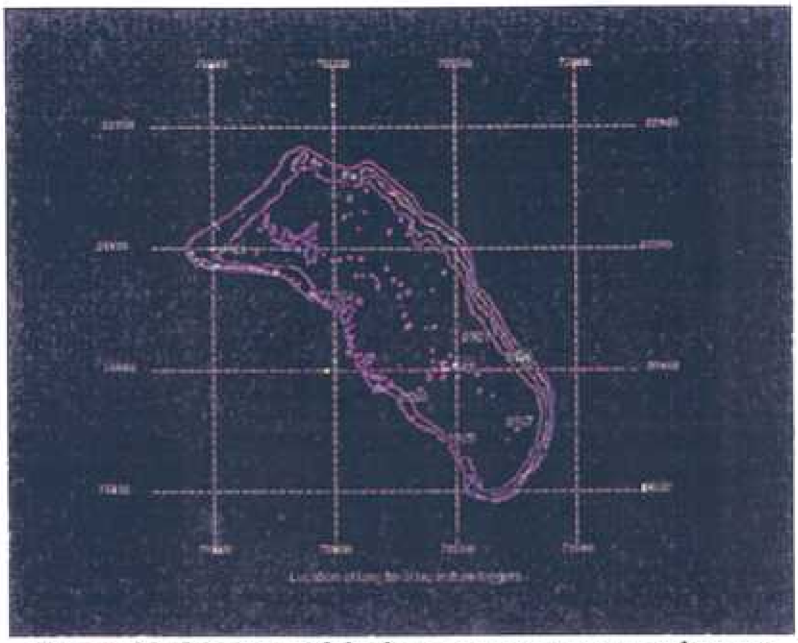


Figure 15: Location of the long-term temperature loggers

For the period of simulation, we obtain the following curve.

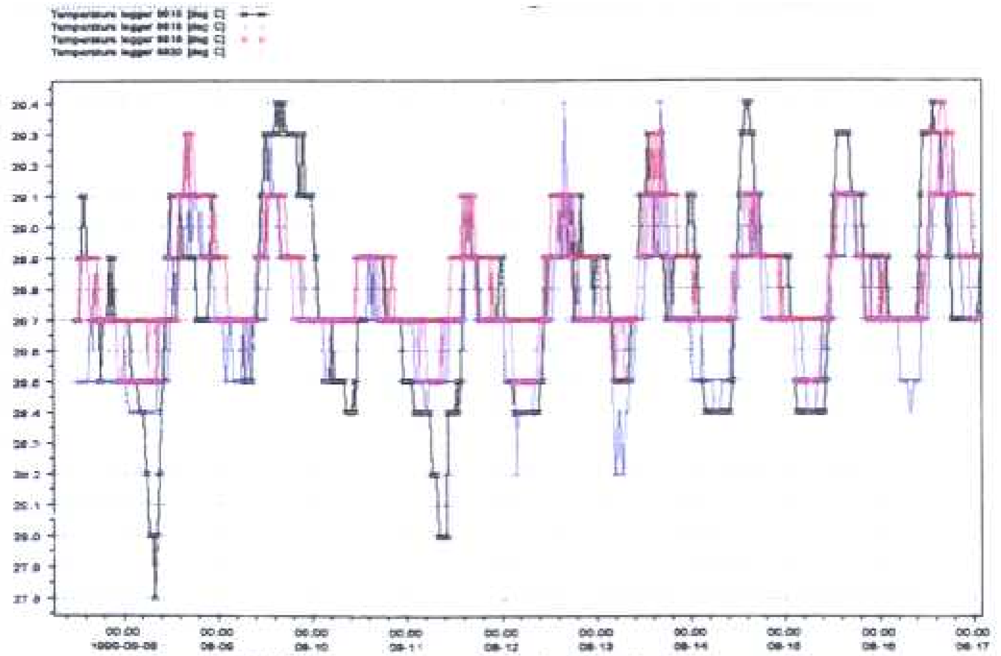


Figure 16. Temperature recorded by the long-term loggers

This graph shows that the evolution of the temperature for this period is almost the same in the four spots. But if we check the entire curve, we can see that the temperature recorded by the logger 8920 is one degree higher than the other one.

Then, thanks to the MIKE 21 Toolbox, we have been able to extract time 0 series describing the evolution of the temperature and the salinity in different spots of the lagoon during the simulation.

5. Analyses

As said above, we obtained quiet good results in terms of hydrodynamic modelisation. For the water quality simulation, we are more lukewarm.

Indeed, as we can see on the different graphs (*cf. Graphs in Annex 4*), the computed values are very different of the reality. Of course, it is impossible to reproduce exactly the reality, but we can afford some explanations about these differences.

- The lack of data

The surface temperature of the sea depends on many parameters. It is impossible to consider all of these in a modelisation. However the most influent parameters can be defined.

> - The air temperature can be defined but just as a constant value. It is not possible to input it as a time serie to modelise the fluctuations of between night and day. And no data were available for Abaiang anyway.
> - The surface heat transfers are very depending on the wind. For this parameter, no data were available too.
> - No data about the rainfalls and the evapotranspiration.

- Initial conditions

The set-up of the initial conditions of temperature and salinity was a very important and difficult task. The modelisation of temperature and salinity circulation is based on the resolution of a differential equations system, which is very sensitive to initial conditions.

- Flooding and drying

Certain points where the temperature and the salinity are analysed are close to a flooding and drying area; then just before being dry (0.2 m.) some points of this area are removed from the calculation and replaced when the water depth reaches a certain value (0.3 m.). It is the effect of these operations that creates the spurious results at these points.

However, the results we obtained, allowed us to formulate conclusion about the evolution of the temperature and the salinity in the lagoon. Indeed, the graphs available in Annex 4 show us the average values of temperature and salinity in the different spots we are interested in.

D. Summary of the main results

In the following tables, we can find the main results of the simulation and of the survey concerning the Seaweed cultivation criteria (*cf. I.B.4.3.*). All the results can be found in the Annexes.

The seaweed cultivation spots are: (*cf. III.C.3.3.*)

1. Beacon Nuotea
2. Manr Islet
3. Koinawa
4. Taburao Raft Mooring
5. Rabona

Spots	Data Origin	Temperature (°C)			Salinity (ppt.)		
		Min.	Max.	Mean.	Min.	Max.	Mean.
1	S.E.W.(1)	28.4851	32.3589	**29.9845**	35.0588	39.7130	**36.4343**
	S.W.W.(2)	27.5905	30.3506	**29.1210**	33.9445	37.1820	**35.5511**
	Survey	**27.7319**	**28.5547**	**28.1924**	35.0218	35.1727	**35.0510**
2	S.E.W.	28.5901	29.5300	**28.9474**	35.0920	35.9881	**35.3124**
	S.W.W.	28.9452	29.6067	**29.1233**	35.0250	35.9557	**35.2865**
	Survey	**27.9390**	**28.9289**	**28.1976**	35.0820	35.3762	**35.3511**
3	S.E.W.	28.6046	28.8340	**28.7130**	35.1031	35.1586	**35.1225**
	S.W.W.	28.7760	28.8551	**28.8250**	35.1003	35.1370	**35.1268**
	Survey	**27.7980**	**29.3940**	**28.7741**	35.0155	35.3629	**35.3198**
4	S.E.W.	28.5373	28.8195	**28.6685**	35.0900	35.2452	**35.1192**
	S.W.W.	28.5433	28.7765	**28.6624**	35.0994	35.1939	**35.1374**
	Survey	**28.5000**	**29.2930**	**28.7719**	35.0179	35.2589	**35.0697**
5	S.E.W.	28.5747	28.9974	**28.8047**	35.0256	35.3206	**35.1801**
	S.W.W.	28.9413	29.7423	**29.3159**	35.1610	36.2501	**35.6687**
	Survey	27.8309	28.7809	**28.7790**	35.0368	35.3085	35.1280

Table: Values of computed and measured temperatures and salinity

(1) S.E.W.: Simulation Easterly wind
(2) S.E.W.: Simulation Westerly wind

	Spots	Speed (m.s⁻¹)			Direction (°)	
		Min.	Max.	Mean.	Incoming tide	Outcoming tide
Current	1 S.E.W.	0	0.1888	**0.0594**	135	280
	S.W.W.	0	0.1895	**0.0543**	110	280
	2 S.E.W.	0	0.3358	**0.1773**	010	190
	S.W.W.	0	0.3356	**0.1765**	010	190
	3 S.E.W.	0	0.0948	**0.0356**	330	170
	S.W.W.	0	0.0790	**0.0348**	010	180
	4 S.E.W.	0	0.0949	**0.0100**	050	270
	S.W.W.	0	0.0403	**0.0100**	-	-
	5 S.E.W.	0	0.1324	**0.0368**	-	-
	S.W.W.	0	0.1208	**0.0322**	150	020

Table: Computed values of current speed and direction

1. Beacon Nuotea

The area of Beacon Nuotea is very shallow (between -0.75 and -3 m.) and close to the barrier reef. The currents are strong there; the water is fresh because of the inflow of water from the open sea. However, at low tide and with no wind, the waters in this area can reach high value (>30°C) that can be bad for the cultivation.

In the simulation, we can notice an important difference of temperature with the reality because of the *Flooding and Drying* effect. The simulation shows that, in case of westerly winds, temperature and salinity are higher than for easterly winds.

On the map describing the circulation in the lagoon (*cf. III.B.3.3.*) we can remark that one of the main flux follows all the coastline of the main island till this area. In case of pollution on the shoreline, this area is exposed especially in case of easterly winds.

Globally, this area respects the seaweed cultivation criteria.

2. Manr Islet

The area of Manr Islet is located on the western part of the lagoon close the main passages of the barrier reef. The water depth is about -3 m.

The water circulation is important with strong currents in this part of the lagoon. The current is very high.

The simulation results in term of temperature and salinity are quiet good in this area. However, we can notice important fluctuations of the salinity compare to other areas.
The important circulation of water assures a good quality of water according to the Seaweed cultivation criteria.

3. Koinawa and Taburao Raft Mooring

These areas are located close to the main island of the atoll and present very similar results. The depth in these areas is about -3 m.

The current speeds are low compared to the other areas. The two spots are located close to the circulation flux following the shoreline of the main island.

The results in term of salinity and temperature are very stable.

4. Ribona

This area is located in the northwest of the lagoon. The location is quiet shallow (between -0.75 and -3 m.).

The mean value of the current is very low (about 0.037 $m.s^{-1}$). The study of the circulation in this area shows that, especially for westerly winds, there is a phenomenon of recirculation of the water. It means that globally, the water is stagnant.

We remark too that the circulation flux following the shoreline of the main island finishes its way next to this area. In case of pollution on the shoreline, this area is exposed as *Beacon Nuotea* does.

Conclusions

The areas 1 and 2 appear to satisfy best all the criteria needed for an area in which to cultivate seaweed. Although *Beacon Nuotea* under westerly conditions does appear to have reduced flushing.

The area adjacent to *Ribona* is likely to be a sink for pollutants.

E. Advection-dispersion modelling

Next we run a simulation of a catastrophic scenario of pollution close to the shore of the main island. The decay of the pollutant is very weak. The wind is blowing from the east at 10 knots.
The following picture shows the circulation of the pollutant (days 1, 3, 8 and 9).

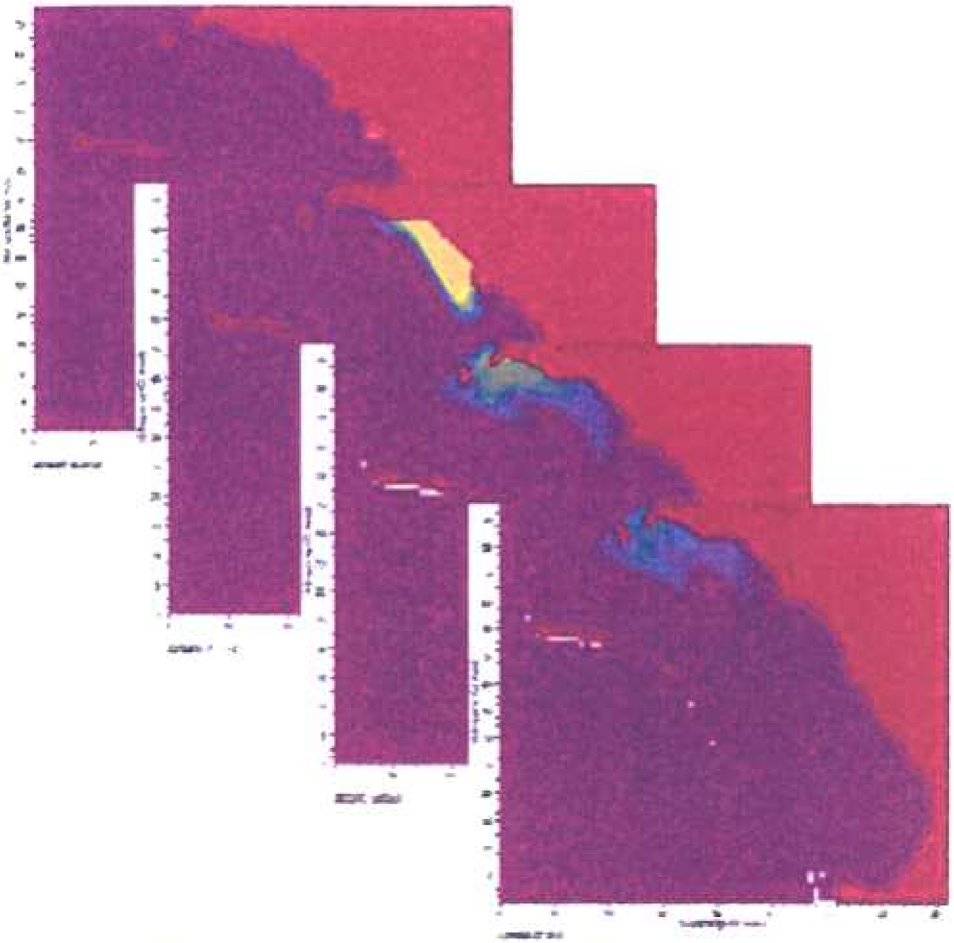


Figure: Circulation of a pollutant (days 1, 3, 8 and 9)

F. Software Assessment

This software is very unfriendly for many reasons, even if the new windows version is easier to use than the Unix one. The most tricky one is the definition of the terms: for example for the time, the same specification can be named two or three times differently.

The equation (50) (*cf. III.A.2.4*) is clearly a limitation of the Shallow Water Equations: if the horizontal velocity varies too much along the vertical, the average value will have no physical meaning. For example, a contaminant will have the same velocity if it travels near the surface or near the bottom. It is a property of long wave to have a constant velocity along the vertical. For this reason the Shallow Water Equations are well suited for the computation of floods, tides, and tsunamis.
In the case of Abaiang it is acceptable because even if the maximal depth is 100 m., this area of the grid is not very important because over the reef.

In term of hydrodynamic modelling, the issue is more a question of current number. To avoid instabilities, the current number has to be as low as possible that is to say the grid spacing Δx the highest. As a consequence the best compromise is a gridspacing of 400 m. but Abaiang has very short passages and a complex bathymetry. At these spots, the current speed for example is given for an area of 400×400 m^2 !

Globally, this new version of MIKE 21 is more friendly than the old one but unfinished. We can regret the lack of data input possibilities in the Water Quality module.

IV. Recommendations

In order to improve the accuracy of the computed Water Quality results, a long term survey, measuring temperature, salinity, dissolved oxygen, nutrients etc. has to be done in Abaiang Atoll, especially in the areas of seaweed cultures. A data base has to be done in term of wind conditions, rainfalls, evapotranspiration etc.

A cheap solution could be to install long term loggers in the seaweed cultivation fields. A more expansive solution could be to install an In-situ Nutrient Analyser which is a very good tool for the assessment of tidal nutrient dynamics.

It is necessary to anticipate the required steps of the modelling before going in the field.

CONCLUSION

A hydrodynamic model has been set up through MIKE 21. It is covering the area of Abaiang Atoll with a 400-meters gridspacing. It has been calibrated with the speed and the direction of the current measured at different spots of the lagoon during the survey and comparing the computed to the measured water level elevation. The corresponding plots correlate well with the measurements in the field.

A major part of this study has been also concentrated on the set up of the bathymetry of the model under AutoCAD R14 using the data of the survey done in August 1999 by Robert Smith.

Good results were obtained for the comparison of water elevation. Good results were also obtained for velocity after having calibrated the model with the Eddy viscosity and after having smoothed the water elevation used for the open boundaries.

The Water Quality modelling has been a very difficult task because of the lack of data to calibrate the model.

However, the results we obtained in term of water quality, allowed us to formulate some conclusion regarding the evolution of the temperature and the salinity in the areas of seaweed cultivation.

The numerical model described in this study is therefore an efficient tool to obtain an overview of the instantaneous currents.

The next task is to collect water quality data (temperature, salinity, dissolved oxygen, BOD...) to complete the calibration of the model and to include the topography within the model to assess the impact of tsunami.

Being in charge of this hydrodynamic part this project was such a great pleasure. It included many domain of coastal engineering, and allowed me to increase my knowledge in this domain.

ANNEXES

Annex 1:
Republic of Kiribati – Abaiang Atoll.

Annex 2:
SOPAC Survey in Abaiang Atoll – Measurements.
(number KI9401)

Annex 3:
MIKE 21 Software.

Annex 4:
Plots

Annex 5:
References.

Annex 1
Republic of Kiribati - Abaiang

- General information:

LONGITUDE	169 32' E 150 14' W
LATITUDE	443' N 11 25' S
LAND AREA	726 km^2
OCEAN AREA	3,550,000 km^2
PHYSICAL FEATURES	comprises 33 Pacific coral islands: the Kiribati (Gilbert), Rawaki (Phoenix), Banaba (Ocean Island), and three of the Line Islands including Kiritimati (Christmas Island); island groups crossed by Equator and International Date Line
CAPITAL CITY	TARAWA
POPULATION	80,000 (1996)
INDEPENDENCE DAY	July 12th, 1979
POLITICAL POSITION	Independent country (republican)
POLITICAL SYSTEM	Liberal democracy
MAIN LANGUAGE	Kiribati, English
CURRENCY	Australian $
CHIEF INDUSTRIES	Agriculture (copra), fishery
GNP	52,000,000 US$ (1992)
GNP per Person	700 US$ (1992)
TRADE REVENUE AND Export	5,400,000 Australian $ (1993)
EXPENDITURE Import	3,730 Australian $ (1993)
MAJOR TRADE PARTNER	EC, Australia, Republic of Fiji, Japan, USA

Annex 2:
SOPAC Survey in Abaiang Atoll - Measurements

Current meter location data

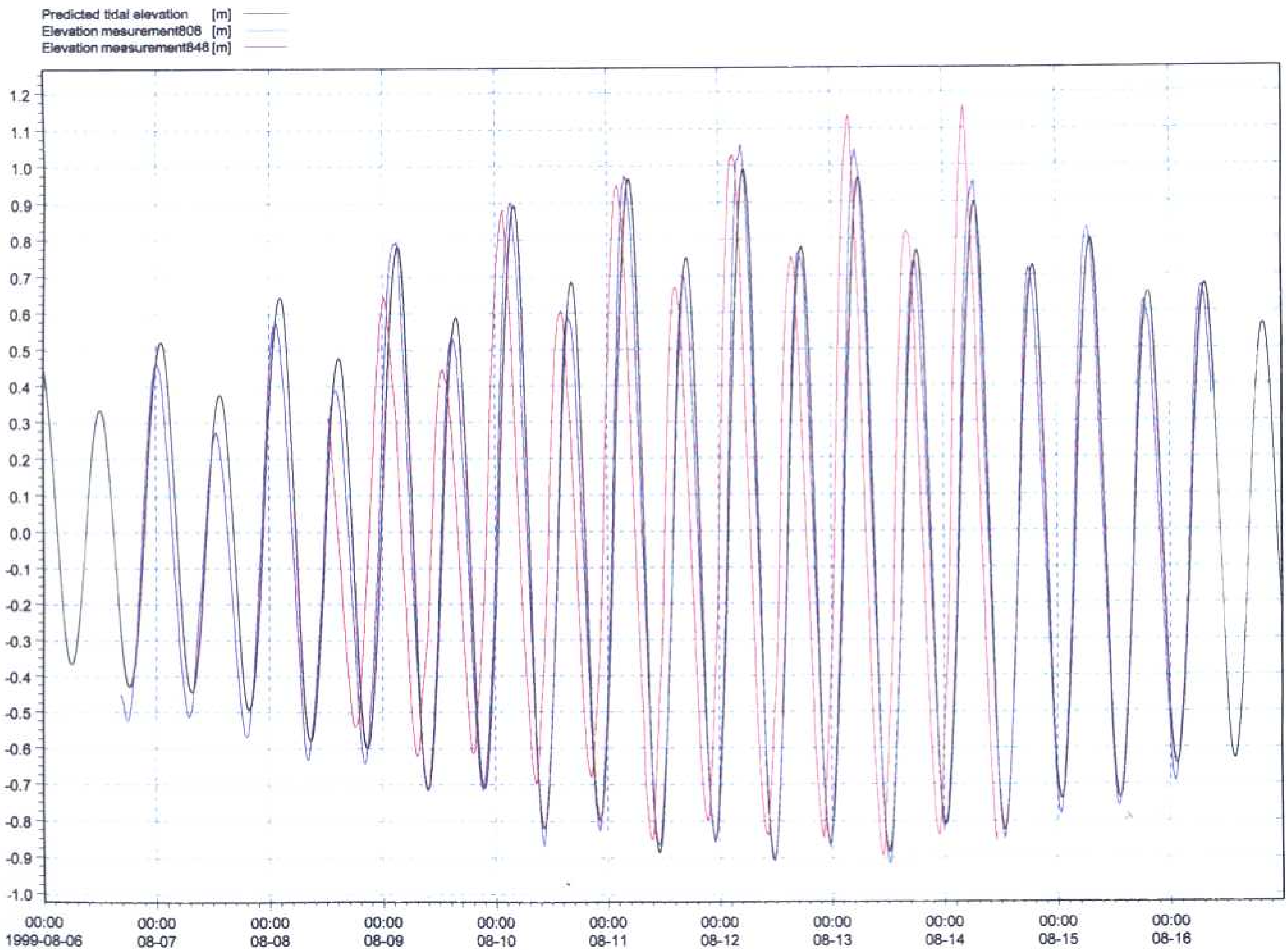
Temperature loggers	Location	Latitude N-wgs84		Longitude E-wgs84		Date & Time in	Date & Time-out	WD	
8915	Beacon Bingham passage	1	45.3	172	58.3	06-08 program-note		3m	
8916	Taburao raft mooring	1	48.97	173	0.96	06-08 program-note		3m	
8917	Taamaiki	1	46.06	173	0.96	06-08 program-note		3m	
8918	Tenio	1	47.19	172	56.23	06-08 program-note		3m	
8919	Line 2	1	48.58	172	58.05	06-08 program-note		3m	
8920	Evena	1	49.84	172	58.99	06-08 program-note		3m	
8921	Nuotaea Beacon	1	53.774	172	48.2	8/11/99 9 30		3m	
8922	Maiu Islet	1	51.747	172	52.927	8/11/99 12 30		3m	
Temp loggers-programed to start 12:00 7/8/99 Local									
Current metres	Current metres								
7286	Bingham passage	1	45.3	172	58.3	8/6/99 13 23	8/16/99 13 58	7m	
7285	Tenio	1	48.751	172	56.131	8/7/99 10 48	8/13/99 14 50	20.1m	
10148	Beacon Nuotea	1	53.774	172	48.2	8/7/99 13 24	8/13/99 12 25	3m	
7285	Taburao raft mooring	1	48.751	172	56.131	8/13/99 15 50	8/16/99 10 09	3m	
10148	hotel-small boat passage		721336	191156		8/13/99 17 50	8/16/99 7 50	3m	off at 06 18
Water level recorders	Water level recorders								
842	Beacon Nuotea	1	53.774	172	48.2	8/7/99 13 43	8/13/99 12 29	3m	1416 09 19 off
808	Taburao raft mooring	1	48.97	173	0.96	8/6/99 16 50	8/16/99 10 06	3m	

Sample location – CTD samples

Sample	Northing	Easting	Latitude		Longitude		CTD-file	DATE	CTD- cast		tempera ture	D-O2	Turbidity average ftu			Grabsample
Station#	UTM 59 - WGS72		Geographical coordinates in WGS84					of cast	time-on	time-off	Degrees C	mg/l	down	up		
1	214399.3	709394.1	1	56.32093	172	52.95938	aba0407	8/11/99	9:55	9:56	29	2.8	4.4	3.8	3.4	yes
2	212829.8	707485.4	1	55.47028	172	51.92927	aba0408	8/11/99	10:13	10:14	29	5.5	6.2	5.4	4.2	yes
3	211371.9	705689.1	1	54.68037	172	50.95979	aba0409	8/11/99	10:22	10:28	28.5	5.5	4	4	3.5	yes
4	209689.8	703443.6	1	53.76902	172	49.74802	aba0410	8/11/99	10:39	10:40	28.5	4.9	4.3	3.3	3.15	yes
5	212269.1	713772.7	1	55.16229	172	55.31908	aba0411	8/11/99	11:15	11:16	29	5.1	6.2	4.7	3.85	yes
6	210586.9	711527.2	1	54.25103	172	54.10733	aba0412	8/11/99	11:29	11:30	29	5.5	8.29	6.6	4.8	yes
7	209383.3	709618.6	1	53.5829	172	53.07746	aba0413	8/11/99	11:41	11:43	29	5.9	9.9	6.7	4.65	yes
8	207783.3	708720.4	1	52.73163	172	52.59224	aba0414	8/11/99	11:53	11:54	29	5.7	7.3	5.9	4.45	yes
9	209341.2	717253.1	1	53.51748	172	57.19387	aba0422	8/11/99	3:22	3:23	29	6	5.9	4.8	3.9	yes
10	208231.9	715344.5	1	52.97107	172	56.16416	aba0417	8/11/99	1:38	1:39	29	5.7	10.6	8.6	5.8	yes
11	206774	713483.9	1	52.18129	172	55.13419	aba0416	8/11/99	1:25	1:27	29	5.7	8.9	7.7	5.35	yes
12	205316.2	711639.5	1	51.39141	172	54.16476	aba0415	8/11/99	1:12	1:13	29	7.7	4.4	4.4	3.7	yes
13	205428.3	719947.7	1	51.4473	172	58.64438	aba0421	8/11/99	3:06	3:07	29	5.9	5.2	4.7	3.85	yes
14	204306.9	717389.9	1	50.84033	172	57.37251	aba0420	8/11/99	2:53	2:55	29	5.9	7.3	5.9	4.45	yes
15	203185.4	715681.3	1	50.23306	172	56.34278	aba0419	8/11/99	2:40	2:42	29	6.1	10.2	8.7	5.85	yes
16	201279	714221.8	1	49.19962	172	55.55473	aba0418	8/11/99	2:22	2:24	28.5	5.9	10.3	8.9	5.95	yes
17	201951.9	722529.9	1	49.55975	173	0.03453	aba0403	8/10/99	3:22	3:23	29	5.9	7.1	6.1	4.55	yes
18	200269.7	720396.7	1	48.64845	172	58.88344	aba0402	8/10/99	3:10	3:11	28	5.9	8	6.8	4.9	yes
19	198387.5	718824.9	1	47.73679	172	58.03501	aba0401	8/10/99	2:56	2:58	28	5	8	6.5	4.75	yes
20	197017.5	717589.9	1	46.88575	172	57.36826	aba0400	8/10/99	2:31	2:34	29	6	7.3	6.9	4.95	yes
21	198139	725449	1	47.48951	173	1.60684	aba0404	8/10/99	3:38	3:39	31	6.1	7.15	5.4	4.1	yes
22	196569	723428.1	1	46.63899	173	0.51558	aba0406	8/10/99	3:50	3:52	31	6	10.2	8.6	5.8	yes
23	195223.2	721968.6	1	45.90979	172	59.72791	aba0424	8/12/99	11:02	11:04	28.5	7.3	10.4	9	6	yes
24	194438.2	720172.2	1	45.48496	172	58.75899	aba0423	8/12/99	10:46	10:47	28	7.4	3.4	3.4	3.2	no
25	194438.2	726347.2	1	45.48136	173	2.08807	aba0427	8/12/99	12:10	12:12	29	6.9	4.2	3	3	yes
26	192643.9	724775.4	1	44.50889	173	1.23964	aba0426	8/12/99	11:37	11:39	28.9	7.6	6.5	4.7	3.85	yes
27	191073.9	725203.6	1	43.65807	173	0.39135	aba0425	8/12/99	11:26	11:22	28.8	7.6	4.4	3.2	3.1	yes
28	193313.8	713484.5	1	44.75	172	57.82	aba0428	8/16/99	13:45	13:48	na	na	na	na	na	no

Annex 4:
Plots

- **Water elevation / Tides:** Comparison between simulation and measurement
- **Current:** Comparison between simulation and measurement at the current meters location spots
- **Temperature:** Comparison between simulated data and long-term loggers data
- **Temperature and Salinity:** Comparison between simulated values at the seaweed cultivation spots for different wind directions
- Miscellaneous



Predicted tidal elevation [m]
Elevation mesurement808 [m]
Elevation measurement848 [m]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
00:00 1999-08-06
00:00 08-07
00:00 08-08
00:00 08-09
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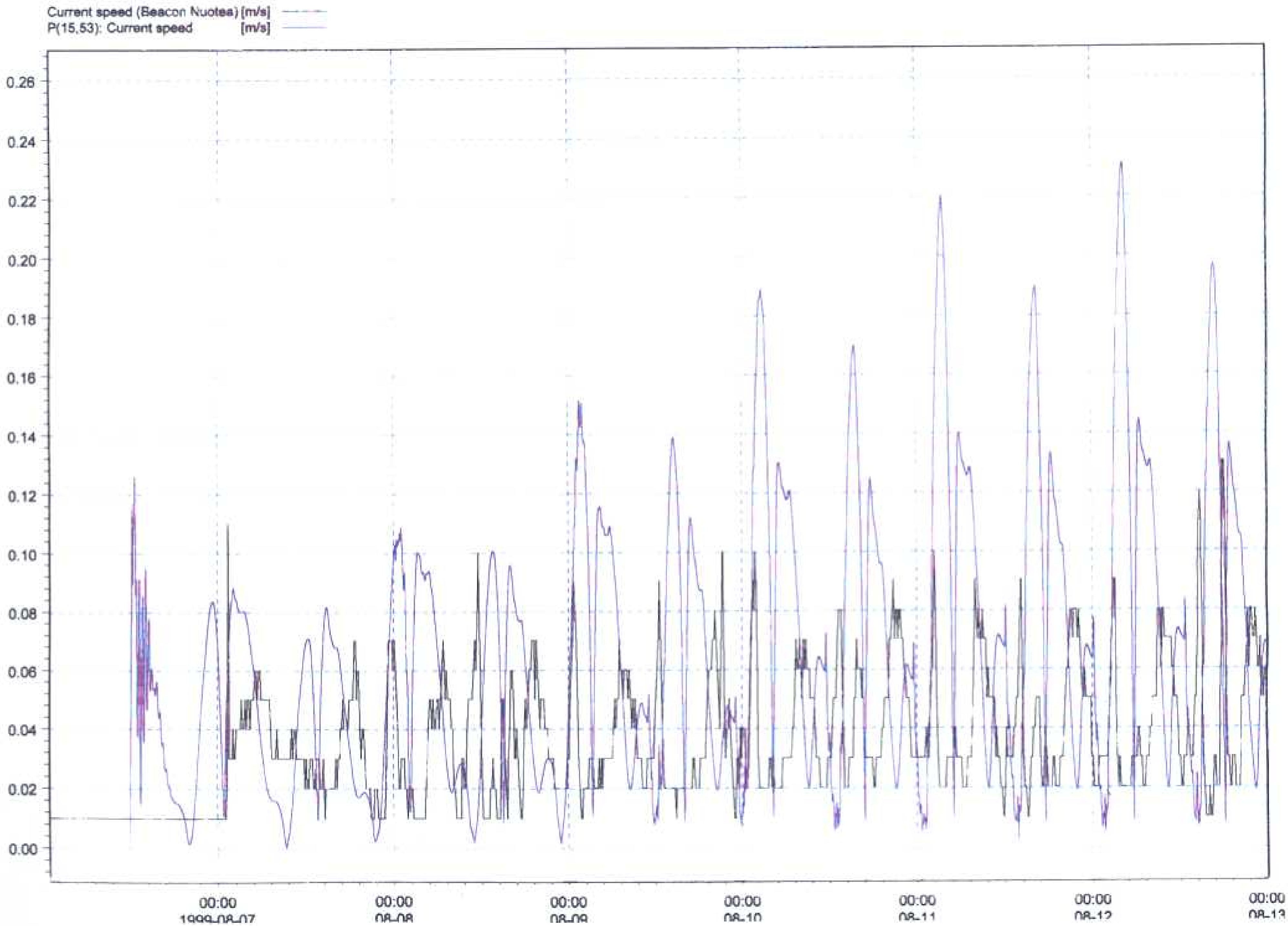
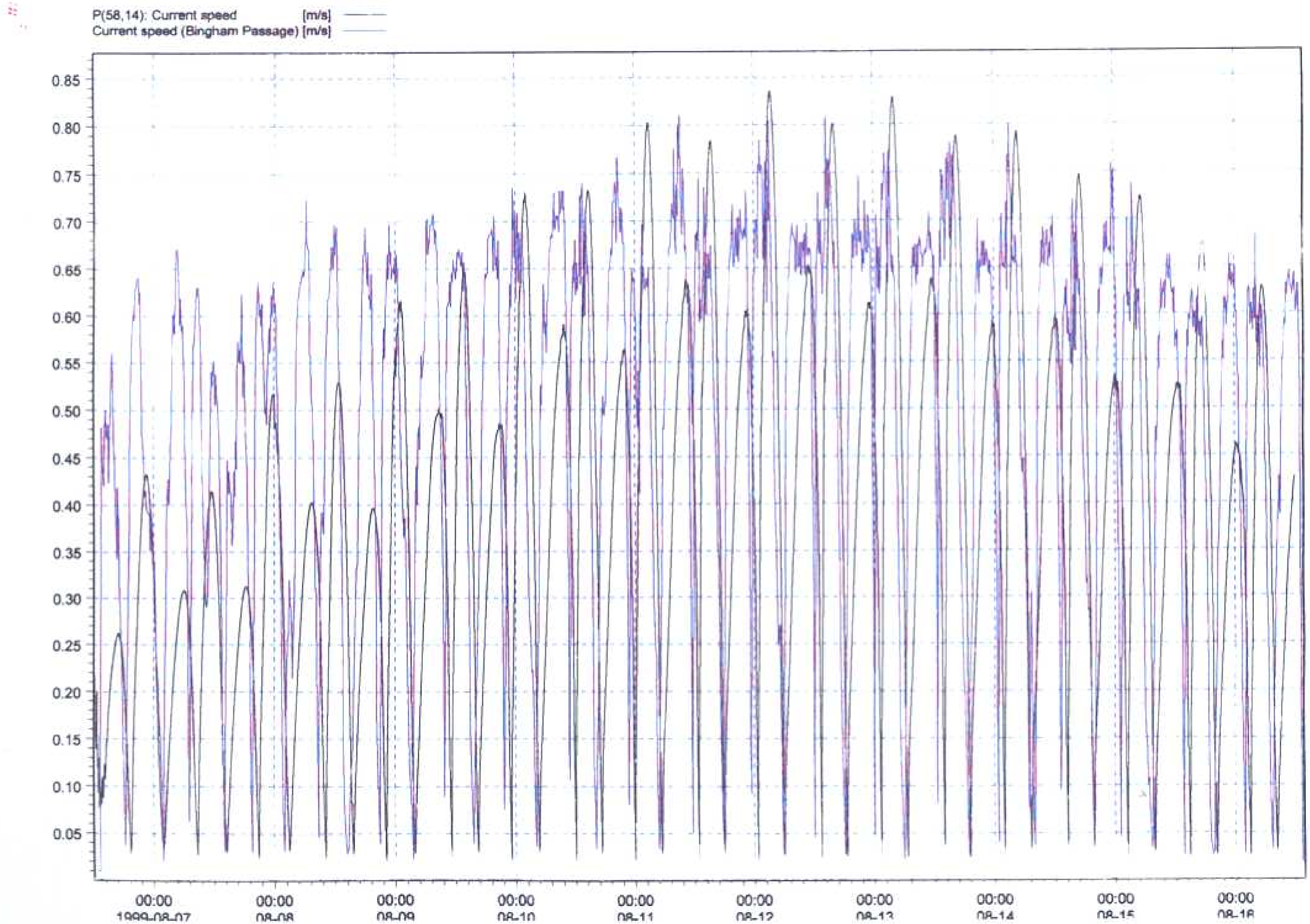
00:00 08-15
00:00 08-16



Current speed (Beacon Nuotea) [m/s]
P(15,53): Current speed [m/s]
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
00:00
1999-08-07
00:00
08-08
00:00
08-09
00:00
08-10
00:00
08-11
00:00
08-12
00:00
08-13


P(58,14): Current speed [m/s]
Current speed (Bingham Passage) [m/s]
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
00:00
1999-08-07
00:00
08-08
00:00
08-09
00:00
08-10
00:00
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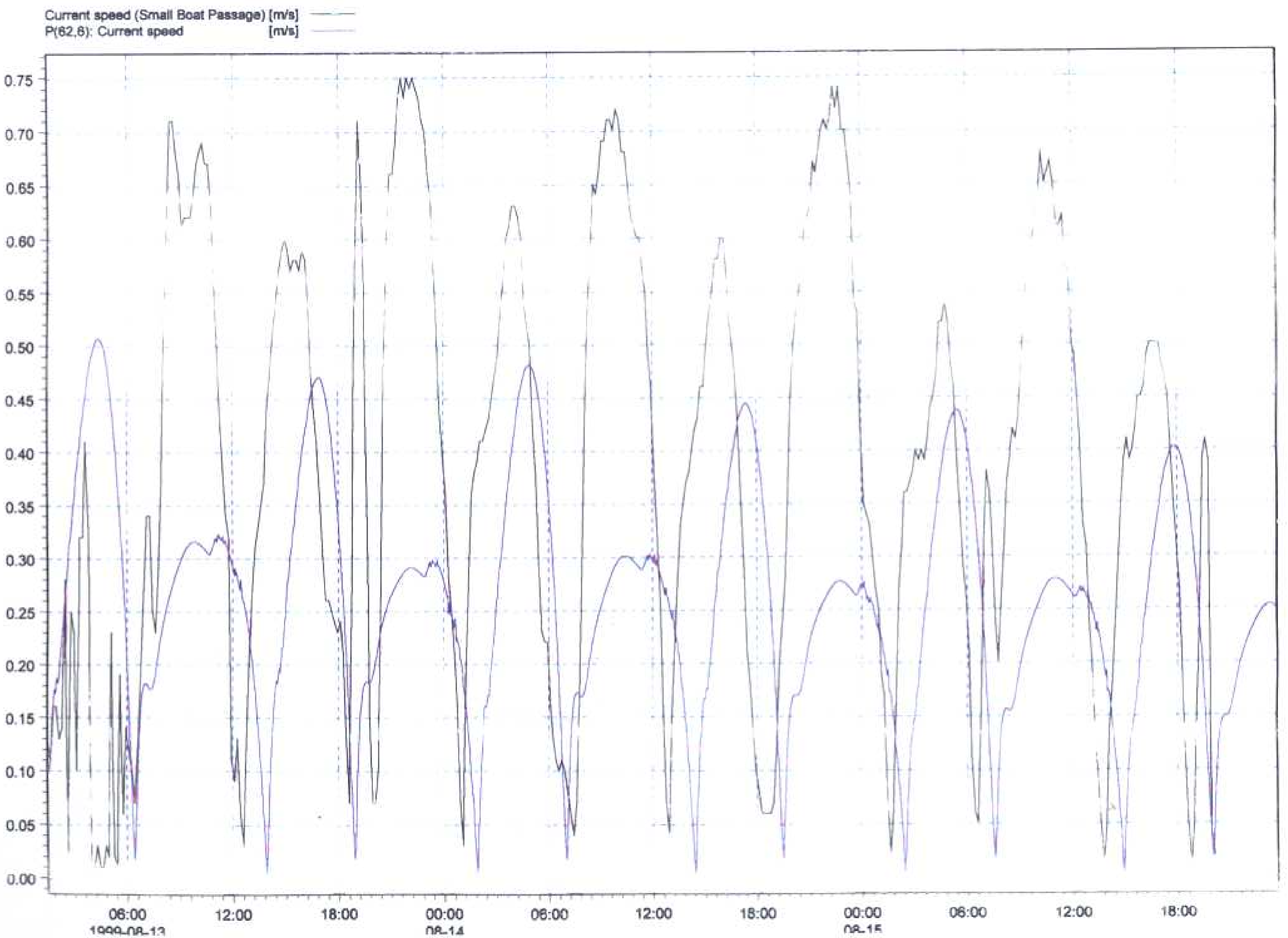
08-15
00:00
08-16


Current speed (Small Boat Passage) [m/s]
P(62,6): Current speed [m/s]
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
06:00
1999-08-13
12:00
18:00
00:00
08-14
06:00
12:00
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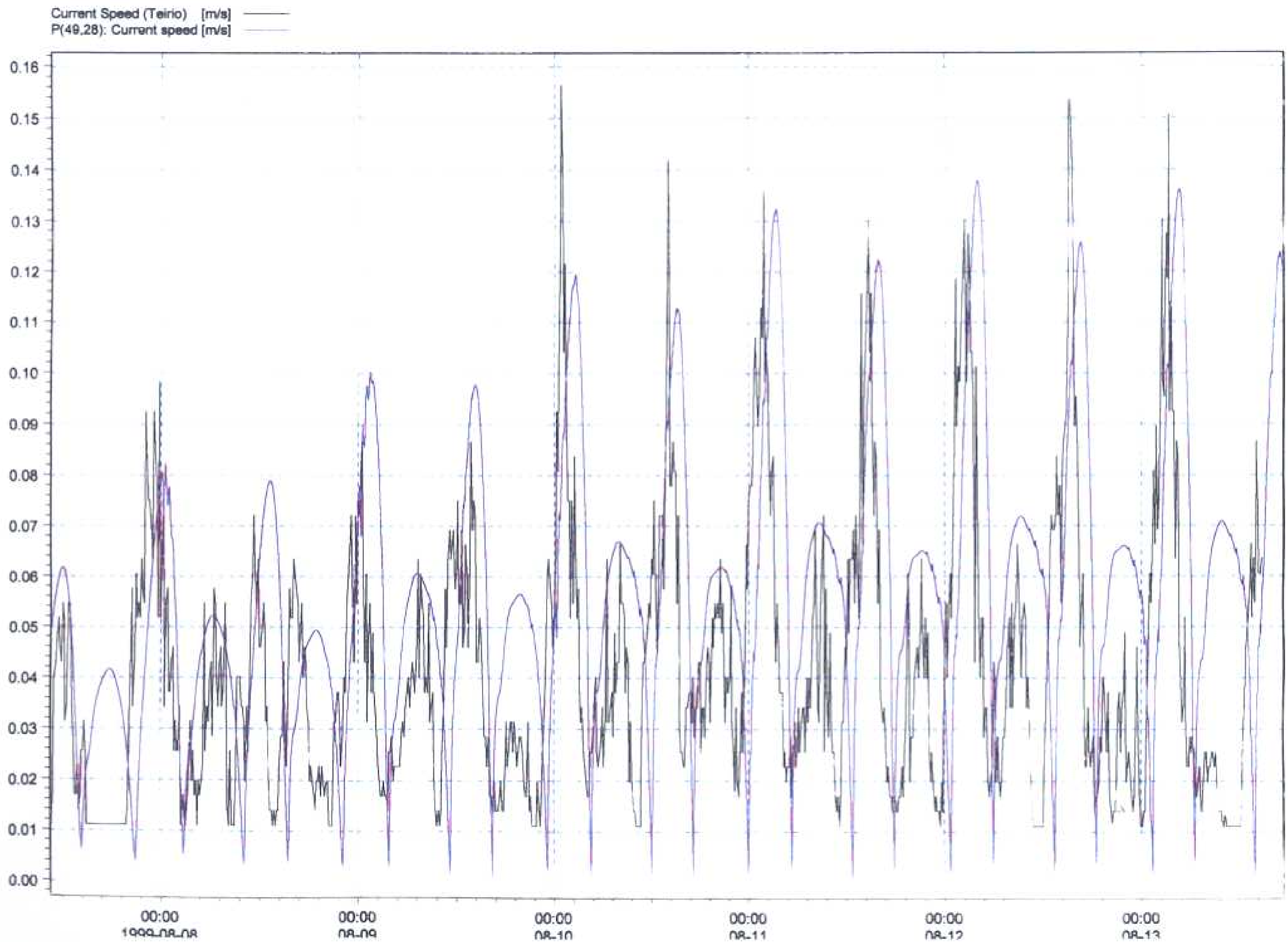
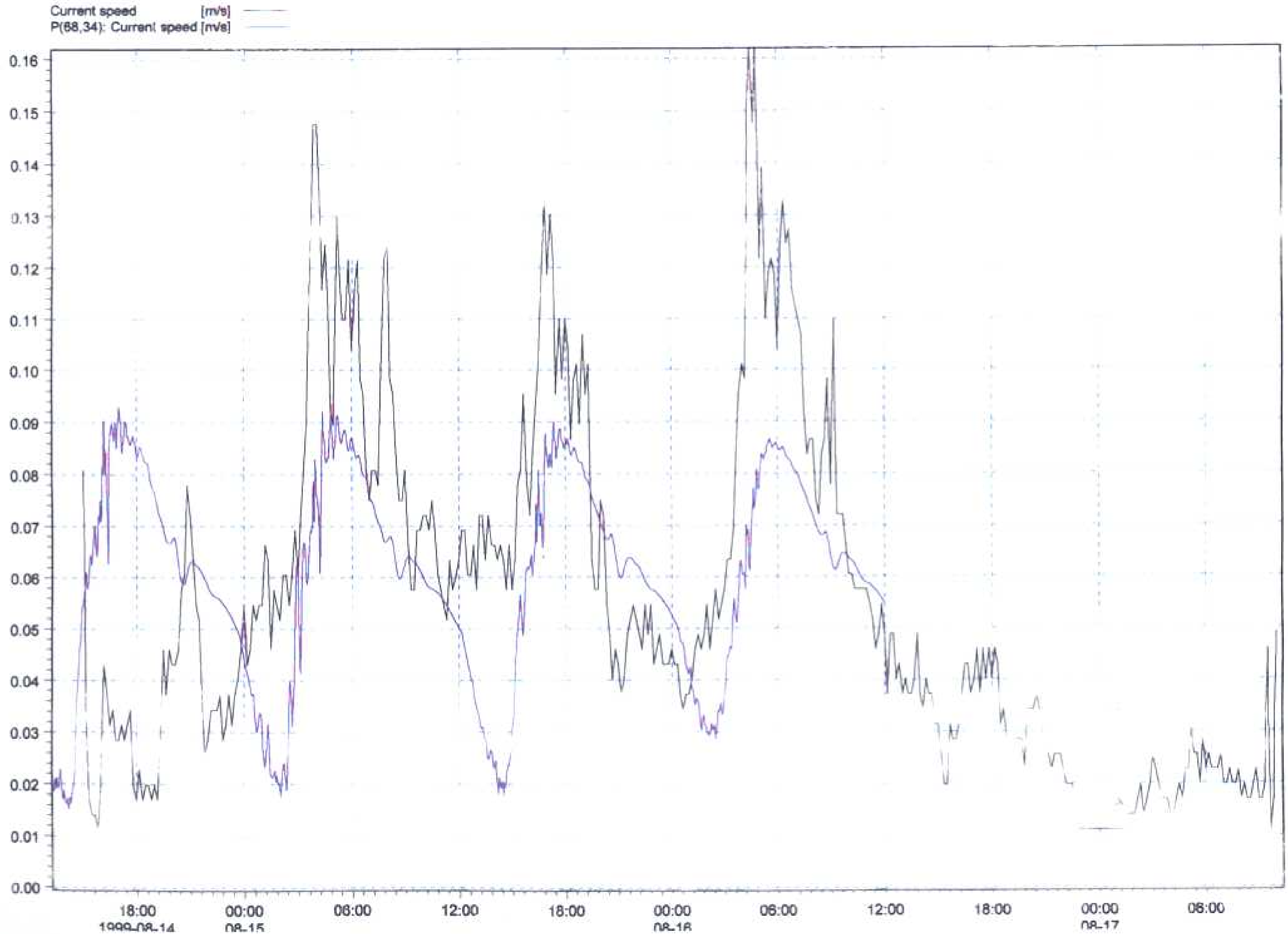
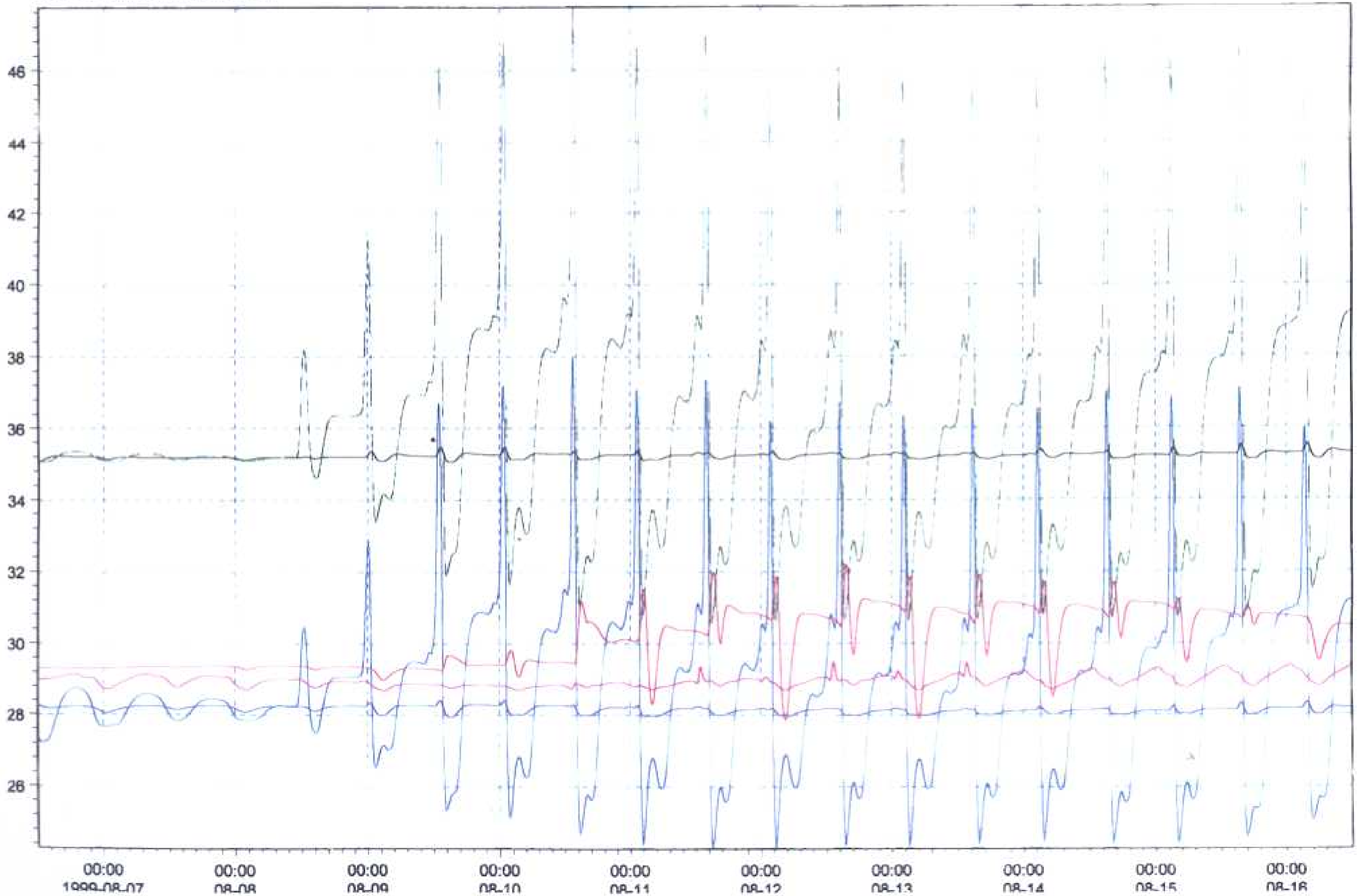
06:00
12:00
18:00

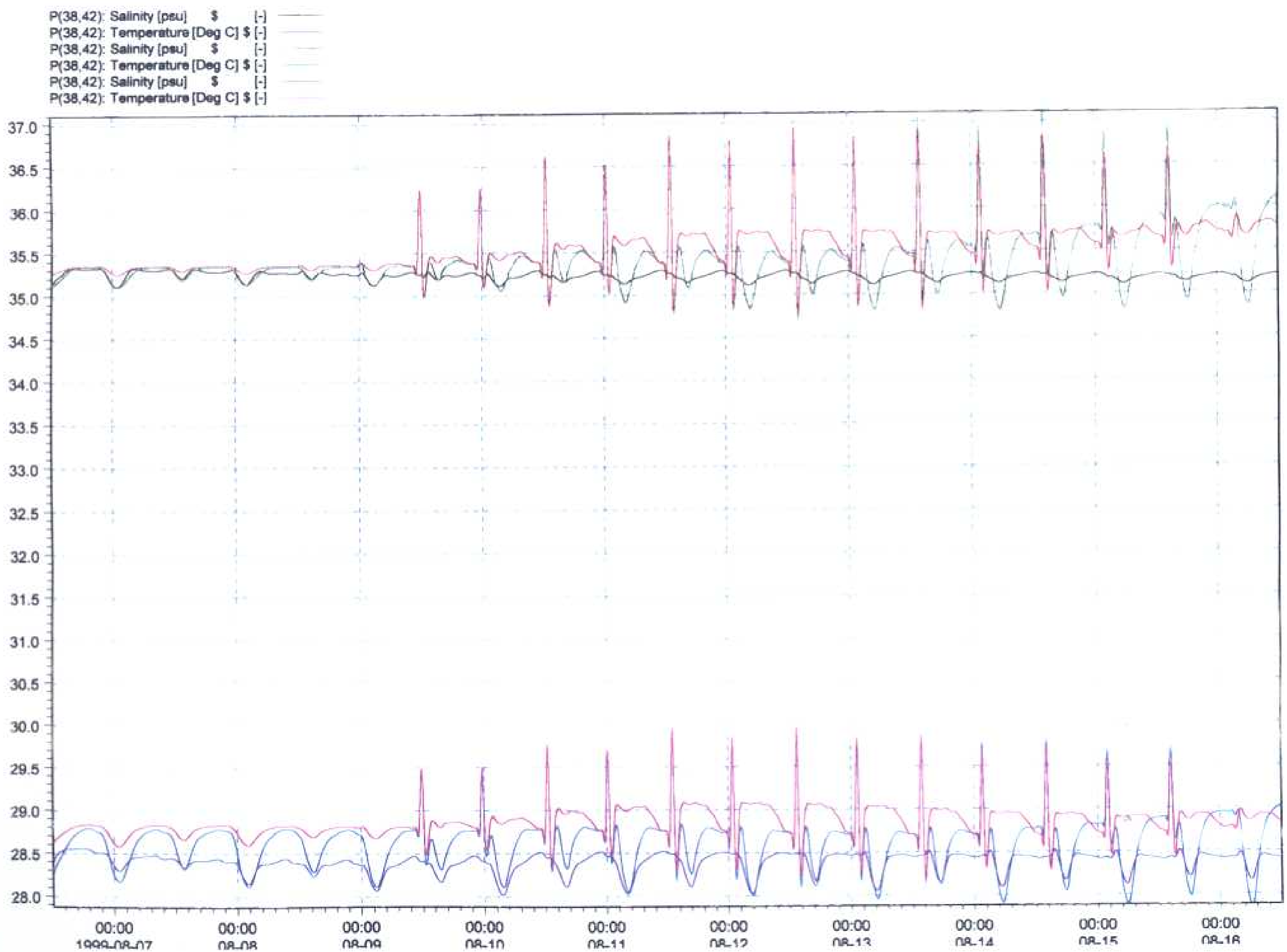

Current Speed (Teirio) [m/s]
P(49,28): Current speed [m/s]
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
00:00
1999-08-08
00:00
08-09
00:00
08-10
00:00
08-11
00:00
08-12
00:00
08-13



Current speed [m/s]
P(68,34): Current speed [m/s]
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
18:00
1999-08-14
00:00
08-15
06:00
12:00
18:00
00:00
08-16
06:00
12:00
18:00
00:00
08-17
06:00

P(13,53): Salinity [psu] $ [-]
P(13,53): Temperature [Deg C] $ [-]
P(13,53): Salinity [psu] $ [-]
P(13,53): Temperature [Deg C] $ [-]
P(13,53): Salinity [psu] $ [-]
P(13,53): Temperature [Deg C] $ [-]




P(38,42): Salinity [psu] $ [-]
P(38,42): Temperature [Deg C] $ [-]
P(38,42): Salinity [psu] $ [-]
P(38,42): Temperature [Deg C] $ [-]
P(38,42): Salinity [psu] $ [-]
P(38,42): Temperature [Deg C] $ [-]
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
31.0
30.5
30.0
29.5
29.0
28.5
28.0
00:00 1999-08-07
00:00 08-08
00:00 08-09
00:00 08-10
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00:00 08-12
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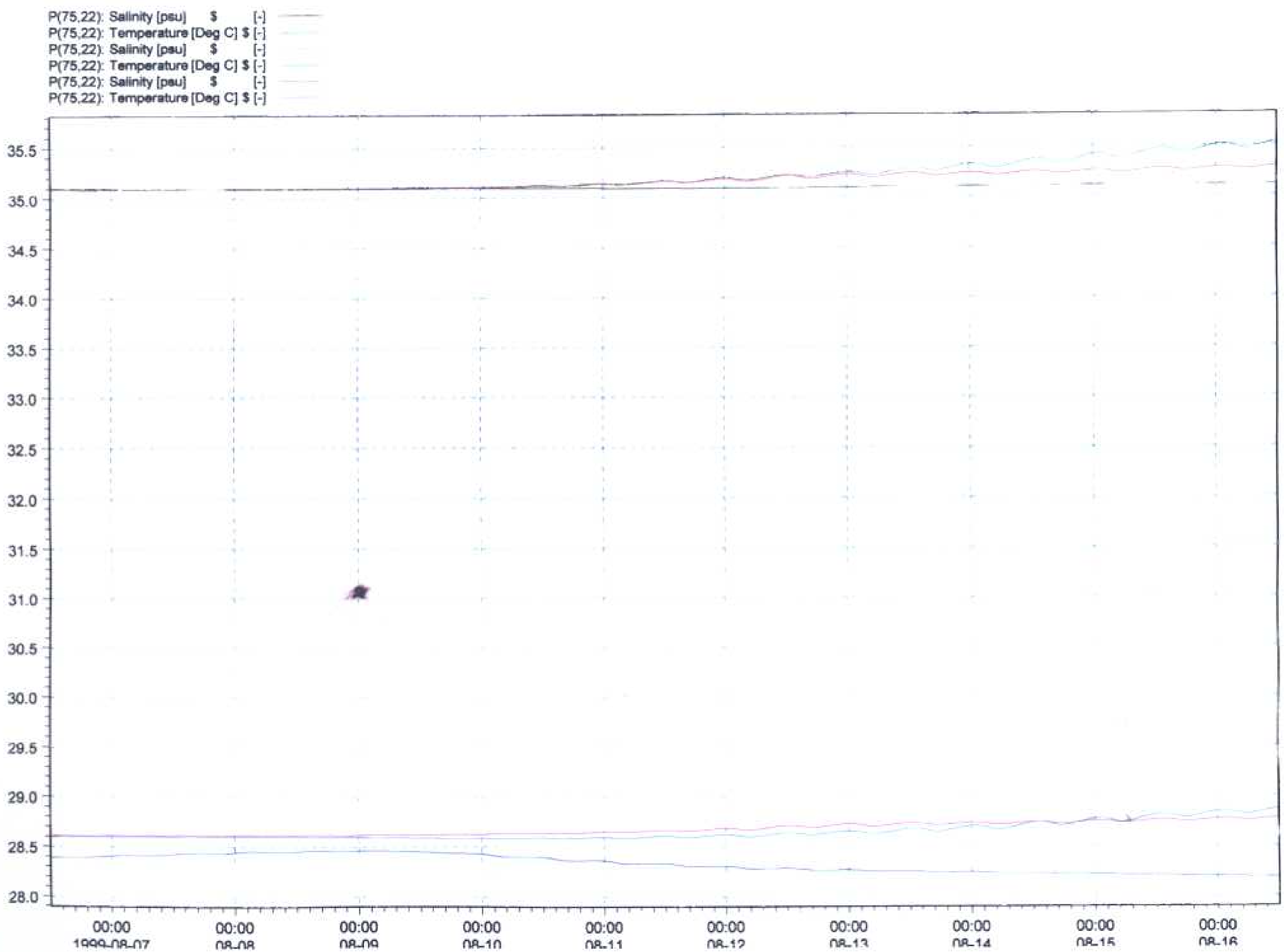
00:00 08-14
00:00 08-15
00:00 08-16


P(75,22): Salinity [psu] $ [-]
P(75,22): Temperature [Deg C] $ [-]
P(75,22): Salinity [psu] $ [-]
P(75,22): Temperature [Deg C] $ [-]
P(75,22): Salinity [psu] $ [-]
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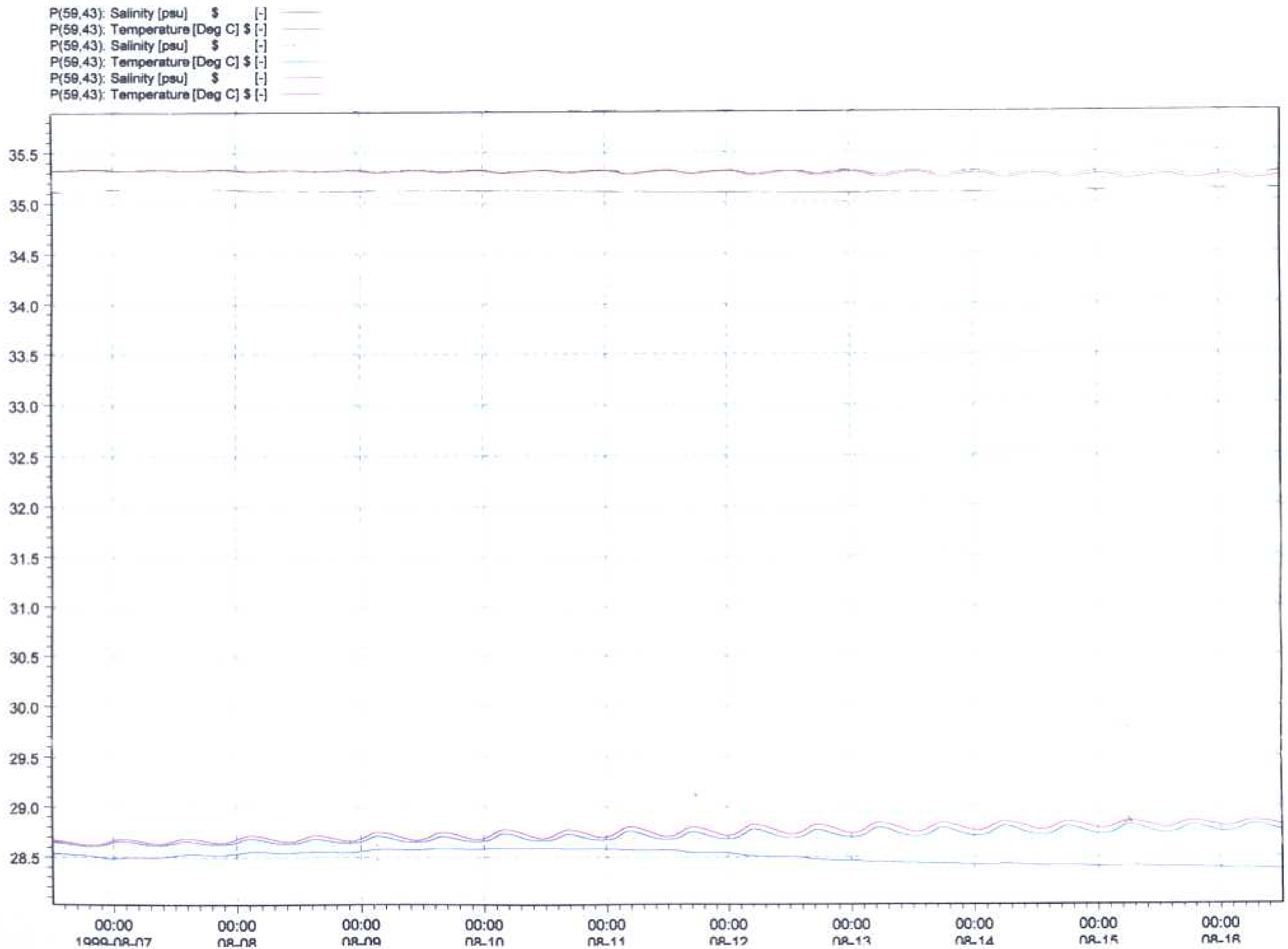
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P(59,43): Temperature [Deg C] $ [-]
35.5
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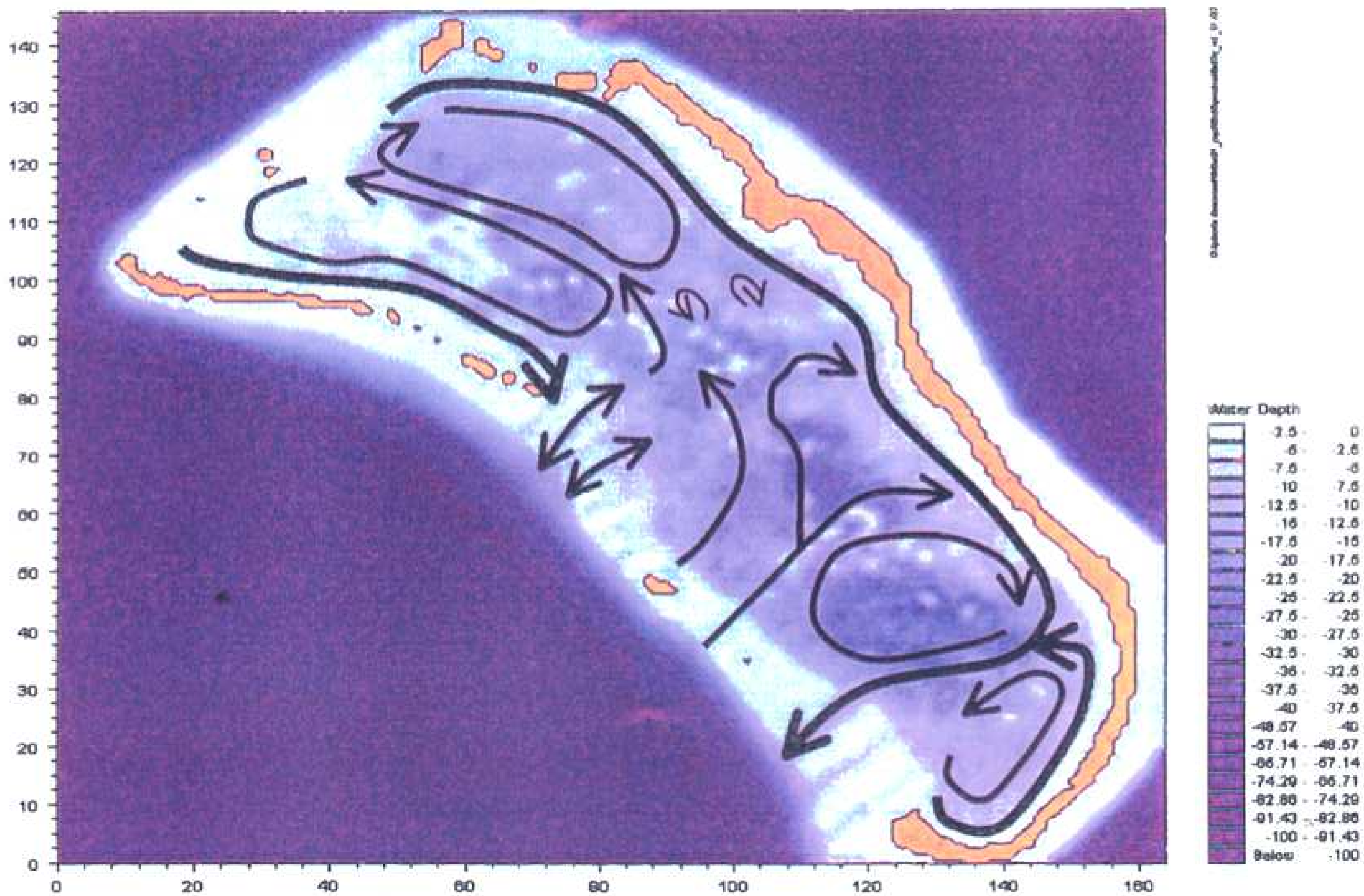
ABAIANG ATOLL
WATER CIRCULATION FOR WESTERLY WIND OF 5 KNOTS



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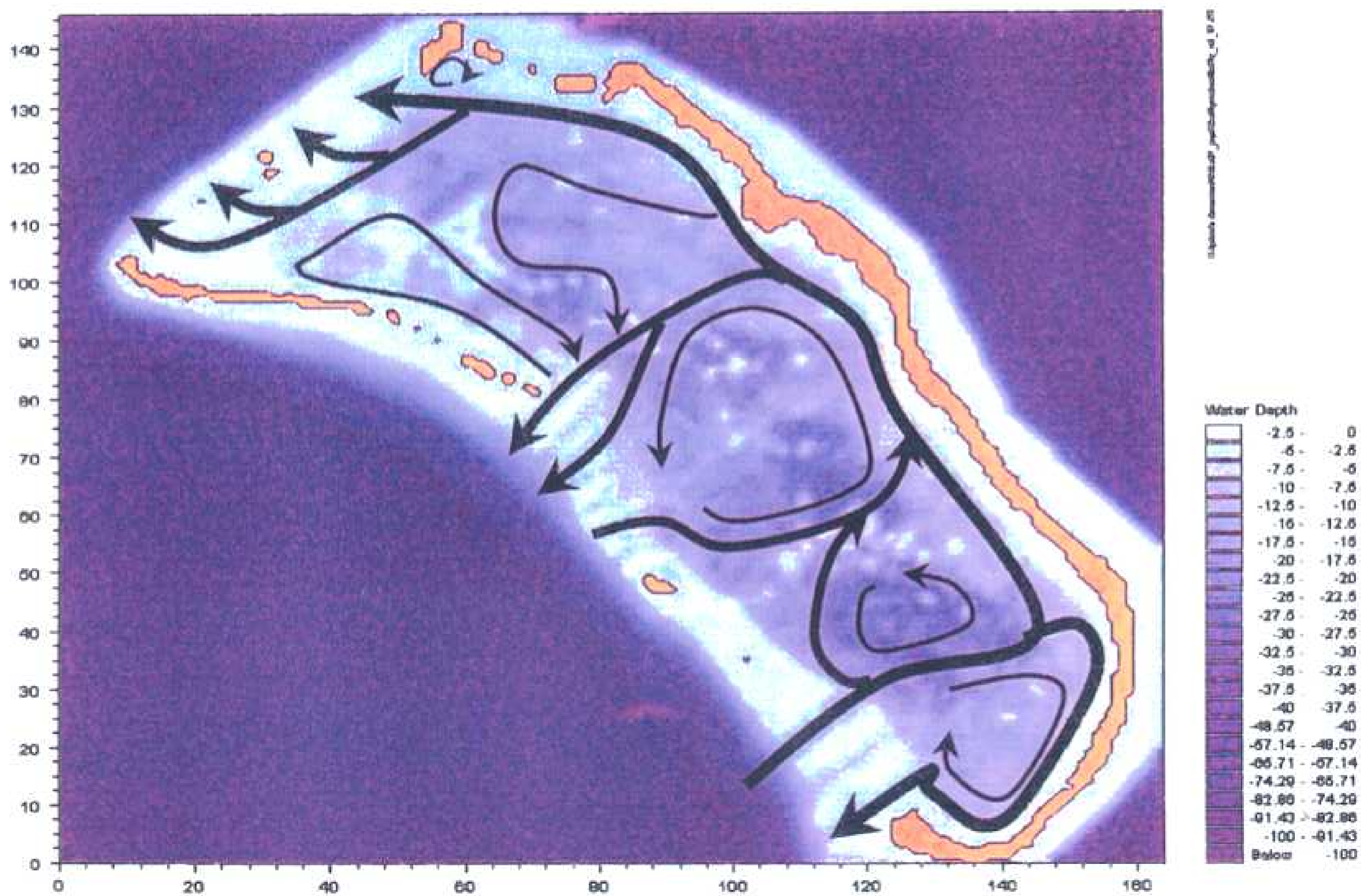

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