

# Hydrodynamic impact assessment of Natadola Beach, Fiji

Sanchez Stephane  
SOPAC Secretariat



SOPAC Training report 83  
September 1999

ACKNOWLEDGEMENTS
------------------

I first express my acknowledgements to the Director of SOPAC Alfred Simpson and all the SOPAC staff, especially Franck Martin and my supervisor Robert Smith.

I would like to also thank the French Embassy for the funds that enabled my placement at SOPAC.

## SOPAC Training Report

### TABLE OF CONTENTS

Acknowledgements	1
Abstract	4
Introduction	5
Warning	6
<b>I. Presentations</b>	<b>8</b>
<b>A. Presentation of SOPAC</b>	<b>8</b>
1. Background	8
2. Mission statement	8
3. Work program	8
4. Resource development program	9
<b>B. Natadola beach</b>	<b>10</b>
1. Description	10
2. Physical Environment	11
a) Tidal Range	11
b) Wave climate	11
c) Currents	12
<b>C. Development</b>	<b>13</b>
1. History	13
2. Development project	15
a) Details	15
b) Prices	16
3. The marina in particular	16
4. E.I.A.	17
5. Own mission	18
<b>II. Data</b>	<b>19</b>
<b>A. The sea is not a laboratory</b>	<b>19</b>
<b>B. Measurements</b>	<b>20</b>
1. GPS measurements	20
a) Principle of the GPS	20
b) Choice of the points	20
2. Bathymetry	21
a) Equipment	21
b) Measurements	21
3. Water level recorders	22
4. Currents	22
a) Aanderaa currentmeters	22
b) Choice of the spot	24
c) Plots	24
<b>C. Bibliography</b>	<b>25</b>
1. Elevation of the sea level	25
2. Wind	25
a) In Nadi	25
b) Winds at Natadola	26
3. Tides	26
4. Review of evapotranspiration and rainfalls	28

## SOPAC Training Report

---

<b>III. Simulations</b>	<b>29</b>
<b>A. Software discovery</b>	<b>30</b>
1. Application areas	30
2. Equations	32
a) Continuity	32
b) Momentum	32
c) Boundary conditions	32
d) Shallow Water Equations	33
e) Numerical Formulation	38
3. Method	40
4. Mike 21 guide	40
a) First step: creating a project	40
b) Preprocessing	41
c) Hydrodynamic module	44
d) Post processing	48
<b>B. Basic simulation</b>	<b>49</b>
1. Setting up of the bathymetry	49
a) Data reading	49
b) Conversion	50
c) Corrections	51
d) Interpolation	51
e) Extracting the data to Mike 21	52
f) Smoothing the bathymetry	52
2. Hydrodynamic simulation	52
a) Time	53
b) Initial elevation	53
c) Drying and flooding	53
d) Eddy viscosity	53
e) Wind	53
3. Plots and analyses	54
a) Importance of time frequency in output specifications	54
b) Viscosity and wind	55
c) Right computation	56
d) Evapotranspiration and rainfalls	57
<b>C. With the marina</b>	<b>58</b>
1. Bathymetry	58
2. Results	59
<b>D. Mud transport simulation</b>	<b>62</b>
<b>E. Software assessment</b>	<b>63</b>
<b>IV. Recommendations</b>	<b>64</b>
Conclusion	64

ABSTRACT
----------

Warmly welcomed in the South Pacific Applied Geoscience Commission, I have been immediately involved in a huge project which aims at building a resort in Natadola Harbor, the most beautiful beach in Viti Levu. This vast complex will comprise four hotels with potential for up to 1000 rooms, an international standard golf course and a marina.

My own mission was indeed assessing the hydrodynamic impact of this last construction thanks to a numerical modeling under Mike 21, a professional modeling software for 2D free surface flows. And it meant being in charge of the whole survey that is to say establishing first the bathymetry and the currents in the field.

After having avoided all the traps of the data processing, I made run two hydrodynamic models, the second encompassing the proposed marina which dimensions stayed nevertheless unavailable. It shows unknown phenomenon like the flux entering the channel at low tide and how the marina will modify the current speeds and directions. All the plots show that there is apparently no major issue in building a marina but some more details about the project development are to be provided to carry out properly the survey.

INTRODUCTION
--------------

Which other beach in the world needs to be more protected than Natadola Beach in Fiji? The people of Fiji themselves recognize Natadola beach as one of the nicest beaches on the island and people travel considerable distances to visit it. In spite of Fiji reputation, beautiful white sand beaches are very rare on the main land. Actually there is only one.

The third step of the proposed development of Natadola Harbor is yet building a marina there. That is why the Fijian Government has commissioned an Environmental Impact Assessment in order to know whether the project will not only have significant economic benefits for Fiji but will also assist in the protection and enhancement of some environmental values.

Being in charge of the hydrodynamic part of the assessment is such an interesting mission for a young engineer, seeing the importance of both the project and Natadola in the heart of Fijians! Especially if the whole survey has to be carried out, from the bathymetry in the field to the hydrodynamic modeling thanks to the software Mike21. Indeed, I carried out a one-week and several one-day surveys measuring the currents, the bathymetry, the water level etc in the warm environment of Natadola; in the not colder atmosphere of SOPAC, I made one model of Natadola Harbor run.

## SOPAC Training Report

---

WARNING
---------

This report is not written respectfully to the chronology of the mission.

The language used is the Australian English.

## **I. Presentations**

### **A. *Presentation of SOPAC***

#### **1. Background**

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

Member 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 Associate 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 the peoples of Pacific island member countries through the application of geoscience to the management and sustainable development of their non-living 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. Resource development program

**Tab1: details of SOPAC units**

Mineral Resources Unit	mineral and aggregate assessments/surveys, deep sea mineral assessments/surveys, promotion of mineral potential, minerals legislation and policy development, hydrocarbons promotion Ex: manganese nodule strategic plan, Cook 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.
Energy Unit	policy and planning, small energy projects, renewable energy projects, monitoring alternative energy developments (OTEC, Wave & Geothermal) Ex: petroleum price monitoring, Guam.
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.
Hazard Assessment Unit	geohazard studies, vulnerability assessments, protection and engineering advice, lagoon/shallow water circulation studies Ex: GIS physical database assembly, Papua New Guinea.
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.
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.
Disaster Reduction Unit	regional coordination, research information Ex: Taveuni Volcano Project, Fiji.
Publications and Library Unit	Editing, publications and reporting, library, public awareness Ex: library assistance to organize mineral exploration reports, Solomon Islands

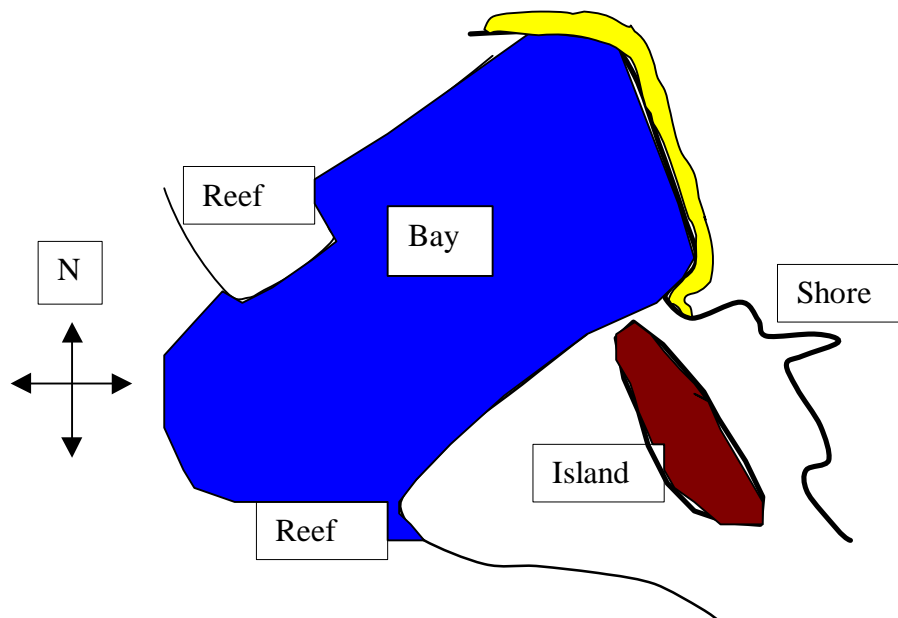
## *B. Natadola beach*

Natadola is located on the Southwest coast of Viti Levu 50 km south of Nadi and 21 km west of Sigatoka. Access to Natadola is via secondary roads that lead off the Queen's Highway, which approach Natadola from either the west or east.

### **1. Description**

Natadola Beach extends across the head of Natadola Harbor, a rectangular embayment with a 900-meter wide opening in the fringing reef between Dubua Point and Navo Island.

**Fig 1: sketch of Natadola harbor**



The beach extends 30-40 m from mean sea level. The area of sand therefore is approximately 70,000 m<sup>2</sup> or 7 ha.

The beach is set back some 2.1 kilometers from the outer reef and forms a barrier across the Tuvu River valley.

Nabewa Reef marks the southeast side of Natadola Harbor, extending seaward to the west of Navo Island. It connects with Raratabu Reef to the east. A shallow passage between Navo Island and the mainland carries wave and wind driven currents from Raratabu and Matanatoga reefs westward into Natadola harbor under some conditions.

The fringing reef off Navo Island pinches out to a distance of approximately 1.2-km from the island compared to the Coral Coast stretch that has a relatively uniform width of approximately 0.5-km. The reef is relatively clean, uniform and level, without any sharp deviations or large crevices. During low tides a major portion of the reef is exposed (Kyaw & Lum 1981).

Sanasana village is located on the coast 1 km to the east. To the eastern side of the beach is Navo, an attractive limestone island.

Although Natadola Beach is a special location in Fiji because of being open to the sea, the area adjacent to the beach has suffered considerable environmental change over the past 20 years. The forest behind the beach has either been destroyed or reduced to a poor condition due to fires and removal of all undergrowth. If the current trend in vegetation damage continues the attractiveness of the beach will be drastically reduced whilst its physical stability and resistance to cyclones and floods will be a priori significantly modified.

Natadola year round weather is furthermore excellent.

## **2. Physical Environment**

### **a) Tidal Range**

Fiji has semi-diurnal tides with a relatively low tidal range, of around 1.3 m at springs and 0.9 m at neaps. No tidal information has been measured at Natadola. However, the secondary tide station at Rukua, off the coral coast is likely to be representative of the tides experienced along Viti Levu southern shores (Hydrographic Office, 1997).

**Tab2: tidal range**

Mean High Water Spring	1.70 m
Mean High Water Neap	1.60 m
Mean Sea Level	1.14 m
Mean Low Water Neap	0.70 m
Mean Low Water Spring	0.60 m

### **b) Wave climate**

Local winds, tropical storms (cyclones) and distant swells create waves along the southern coast of Viti Levu. 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.

However in areas such as Natadola Harbor where there is a natural break in the reef, waves propagate to the shoreline and break on the beaches. Therefore this area experiences greater impact from wave action for longer duration.

The only data on wave conditions in the area are limited satellite observations and a couple of years of wave measurements off Kadavu, about 100 km to the southeast (Barstow & Haug 1994).

However, local winds generated waves are predominantly from the southeast, and are expected to lose significant energy due to refraction and diffraction.

During Cyclone Joni, in December 1992 peak offshore significant wave heights of 7.2 m, with an associated peak period of around 10 seconds were measured. Cyclone Raja, in December 1986 produced a peak wave height of around 8 to 9 m. Offshore wave heights of over 10 m have been measured during other cyclonic events (Barstow & Haug 1994).

Cyclones create significant surges and waves that have the potential to propagate directly onshore.

Strong southerlies also occur from time to time that have the potential to generate waves that can impact on the shoreline without significant energy loss. Swell wave heights of around 6 m with associated periods of 15 – 16 seconds were recorded on 10 July 1993. Swells with periods over 20 seconds have also been recorded (Barstow & Haug 1994).

### c) Currents

The main currents affecting shoreline processes in this area are due to wind and waves. Due to the low tidal range tidal currents are not significant within Natadola Harbor. However, the tides are responsible for currents generated by dispersion of water from the lagoons via the various natural breaks in the reef.

No measurements of current were available in this area. However, strong currents were observed along the narrow channel behind Navo Island during the site visit. The formation of a spit at the entrance to Natadola Harbor is evidence of the dynamic processes between diffracted wave propagation into the harbor and current flow from behind Navo Island. Aerial photographs also indicate sediment plumes discharging into the harbor from this area.

**Fig2: photo n°15/111-228. 1951. Example of discharge in the bay**



Rip currents are a common feature of nearshore dynamics at Natadola beach and these currents represent a potential hazard to recreational users of the beach.

The SOPAC report (Forbes et al. 1995) provides the most detailed evaluation of coastal processes within Natadola Harbor, although no information was available for the shoreline until 1999 along the Matanatoga Reef and behind Navo Island. Coastal processes are complex in this area due to varying geomorphology and shoreline orientation.

Situated at the southwestern corner of Viti Levu the shoreline experiences the impacts of cyclones, southern swell and trade winds. Trade winds from the southeast create longshore drift from the southeast to the northwest. Cyclones from the northwest to

southwest create periods of longshore drift to the southeast and may create north to south transport along Natadola beach due to the diffraction and refraction processes.

From observations made during the site visit it would appear that the shoreline along Matanatoga Reef is an area of potential accumulation, although probably subject to high waver forces during cyclonic storms and southern swell due to the relatively narrow fringing reef. The beach areas are controlled by the various limestone outcrops and backed by a fringe of coastal vegetation that assists in the overall stability of the coastal margin.

Wind and tide induced lagoon currents are divided by Navo Island, with some of the tidal stream directed around the back of the Island. The headland along the mainland at the north eastern end of the island represents a tombolo formation based on the wave forces entering Natadola Harbor and the lagoon current diverted around the back of Navo Island. The spit formed by the tidal flows and diffracted wave energy into Natadola Harbor is likely to be very dynamic.

Based on the core sampling carried out in 1994 it would appear that the main Natadola Beach is largely formed from the onshore transport of coral sand most probably deposited in the harbor from both adjacent reefs. In this area cross-shore transport is likely to be the dominant process affecting shoreline change.

Coastal vegetation along Natadola Beach provides shelter and protection, reducing wind forces along the dune ride and promoting accretion along the seaward front of the dune. Maintaining the coastal vegetation is important to provide a natural buffer to maximize beach stability.

### *C. Development*

#### **1. History**

The potential for tourism development at Natadola has been long recognized and the Ministry of Lands started planning for development in this area as early as 1968. Since then the Natadola area has been the focus of two major planning studies. The first study, the 'UNDP Plan' was undertaken in 1973 as part of wider study to expand tourism in Fiji. In 1991 the Department of Town and Country Planning (DTCP) prepared a plan for the Natadola area in response to a proposal for a major resort development by the Shangri-la Group.

In 1973, United Nations Development Programme (UNDP) funded a report entitled "Tourism Development Programme for Fiji", first environmental impact assessment. A component of this document was a supplementary report that considered the development of Natadola Harbour.

The report recommended a development of a major destination resort at Natadola with 15 hotels, residential housing areas of varying densities, Regional Park, marina, and the establishment of a new town with commercial facilities. The master plan for the Natadola area was prepared based on the projected development being over a 15 to 20 year timeframe with the first stage of 3,000 hotel and accommodation units being completed by 1983. The report predicted that Fiji would require 10,000 hotel rooms/units by 1981

## SOPAC Training Report

---

and, projected number of visitors to Fiji would be 800,000 persons per annum with an average annual growth rate of 18%.

No significant development has yet to take place. One of the main reasons for this has been the scale of developments proposed have not been of sufficient size to justify the cost of providing the area with adequate infrastructure, in particular, water.

## 2. Development project

### a) Details

The developer is a French group DB Group Asia Pacific who is based in Indonesia.

The Natadola Marine Resort Limited is proposing to develop a resort complex at Natadola known as the Natadola Marine Resort. The resort will be built on a combination of State lease land and Native lease land on the eastern side of Natadola beach. The resort will comprise four hotels with potential for up to 1000 rooms, an international standard golf course and a marina. The development will be undertaken in a number of phases.

The Natadola area is also the location of other proposed resort developments. The Shangri-La Group plans a similar sized development on the western side of Natadola, while the Fiji Hilton at Malomalo is currently being designed for a site five kilometers to the east of Natadola.

The proposed Natadola Marine Resort development extends from the eastern shores of Natadola Beach to midway between Lalivaka Point and Vatuloa Point along the southwestern shores of Viti Levu. The central portion of the development is situated behind Navo Island.

But the proposal for the Natadola Marine Resort is still in its preliminary stages with only a conceptual plan prepared.

In this instance the information provided only indicates a general activity in a general location with no certainty as to what may eventually happen. The Natadola Marine resort is intended to cover an area of approximately 300 hectares of State and Native land.

**Fig3: Natadola Marine Resort- Development Project**



**Tab3: Natadola Marine Resort – Development Programme**

PHASE 1	PHASE 2	PHASE 3	PHASE 4
Five Star Hotel (150rooms – Villa concept)	Vacation Ownership Time Share Residential villas	Three Star Apartment Club Hotel (180 rooms, 100 apartments)	Three Star Hotel (80 rooms)
Four Star Club Hotel (3-400 rooms)	Second home villas condominiums	Marina	Spa and Thalassotherapy Centre
Golf Course (18 Hole)	Entertainment village		
Sanasana Village Rehabilitation	Equestrian Centre		
Botanical Garden and Nursery			
Navo Island Sanctuary	Rugby field		

#### **b) Prices**

The 5 Star hotel and golf course will cost \$60 M (US). It is hoped the hotel will operational by 2001. 60% of the equity funding for the Hotel has already been obtained. The main source of money is Europe. The Four Seasons group has expressed an interest in becoming equity partners.

The 4 star hotel will cost 40 million \$US. It is funded separately from the 5 Star hotel. The Four Seasons are hopeful that the 4 Star hotel be built the same time as their hotel. Although a developer is yet to be confirmed there is considerable interest for reputable companies.

### **3. The marina in particular**

The proposed marina and access channel is shown as part of the proposed extension to the 5-Star hotel. The access channel is proposed along the alignment of the existing natural channel. Unfortunately, no detailed design is provided on expected vessel size or channel dimensions, therefore simulation and comments are limited to general issues and potential impacts.

The marina is located in a natural embayed area and the main issues associated with this development are due to potential construction effects of suspended sediment during the dredging process and the construction of the seawall.

The channel is likely to be more complex and depend greatly on its desired depth. This area is very dynamic with the position of the spit and depth of the natural channel dependent on wave conditions and tidal flows. Dredging through the coral shelf may also



be required. Field studies should be carried out to investigate the potential for access without dredging through the spit area.

Assuming a design vessel to be a yacht with a length of between 9 m and 15 m. The minimum water depth for these vessels is 2.7 m and 4.0 m respectively with 12 m yachts requiring a water depth of 3.3 m.

Based on existing marinas it is likely that the width of the access channel should be around 25 m (approximately five times the width of a 15-m vessel).

Should dredging through coral rock be a sound option, blasting may be required. In this instance a "box cut" section would be possible, although for ease of navigation a wider channel may be required. If dredging through sand side slopes is required, the angle of the slopes would depend on the grain size of the sediment but typically would be in the order of 6(H):1(V).

Rapid sedimentation on the channel could be expected, especially at the entrance to Natadola harbor. This would require regular maintenance, or the provision for more structural controls. However structural controls would compromise the natural character of the area and may have an impact on local wave conditions and therefore shoreline movement.

The dredging of the channel has potential to adversely impact upon the fringing reefs adjacent to Navo Island and the coral / algae assemblage within the existing channel. The loss of either of these habitats would reduce the tourist appeal of the area.

The operation of the marina could also lead to adverse impacts on the environment these adverse impacts are associated with the following type of activities;

- Fuelling of vessels resulting in spills of fuel;
- Maintenance and repairs to vessels can result in the discharge of hazardous substances to the marine environment; and,
- Maintenance of channels can result in the generation of significant amounts of suspended sediments.

#### **4. E.I.A.**

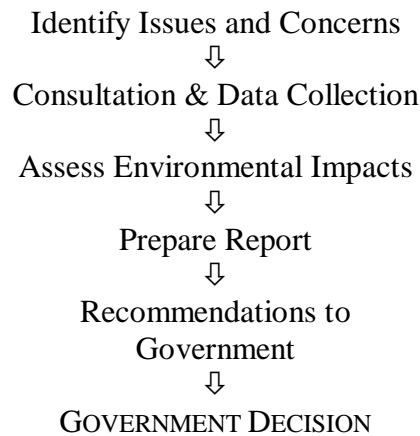
The environmental Impact Assessment is a survey, which purpose is mitigating or removing the impacts of a proposed development.

After having reviewed the competing demands and their environmental impacts, the consultants make recommendations that will protect the environment, the interests of local residents, current users and the economic well being of the country.

There is no legislation about the E.I.A. in Fiji but it is made on behalf of either the government itself or the developers.

Commissioned by the Ministry of Finance of the Fiji Government, the effects on the village community, the state of the marine and coastal environment, the status and cumulative effects of other resorts at Natadola, and beach use by the general public has to be assessed.

**EIA PROCESS**



## **5. Own mission**

Constructing a marina and, in particular, an access channel across the spit-tombola between the mainland and Navo Island requires feasibility and design studies to ensure that it can be constructed without impacting on the Natadola environment. This has been identified as a dynamic area, which is sensitive to change.

The field 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 bay along the developments' shoreline;
- Measure hydrodynamic conditions to improve the understanding of the existing situation, especially in relation to water levels, currents and sediment transport; and,
- Model existing situation and proposed modifications to assess effects and allow design optimisation 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 where the relevant data of GPS or of bathymetry must be collected points, considering what is eventually required for the simulations under Mike 21. It is a great opportunity for a young engineer to see not only the modeling phase but also the measurements step and then to see the project through.

The purpose of the different surveys are establishing the bathymetry inside both the reefs on each side of the harbor and, measuring the water level and the currents to compare them with the model values.

We took CTD measurements Dissolved O<sub>2</sub>, turbidity, temperature, and salinity as well but for another project.

Further than the theoretical aspect of choosing the measurement spots, it is such a difficult task to plan everything for a one-week survey. Once on the boat or even away from the workshop, nothing from the screwdriver to the GPS can miss otherwise it is impossible to carry out the experiments while it is still low tide.

### A. *The sea is not a laboratory*

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 a 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 we had to dive to tow the current meter, which had drifted, and of course we decided in rough sea what to do at the surface before going deeper. Even though, it was very difficult to find the right place with all the sediments in suspension.

It is furthermore impossible to reproduce a phenomenon.

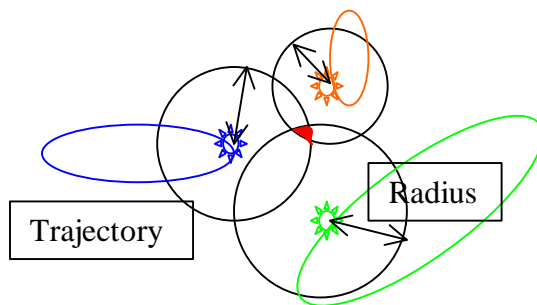
## *B. Measurements*

### **1. GPS measurements**

#### **a) Principle of the GPS**

Developed by the US Department of Defense, the Global Positioning System or GPS is a world wide navigation system. GPS receivers use four 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 the 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. A star represents the satellite and its trajectory has the same color.

**Fig4: system of global positioning**



I have taken the measurements 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.

**Tab4: accuracy of the different GPS**

System	Accuracy
GPS	10 meters
DGPS	1 meter
DGPS + atmosphere composition	1 centimeter

#### **b) Choice of the points**

In the perspective to establish the evolution of the beach profiles, common points to all the pictures have to be found. It is not so easy because the vegetation and the roads have changed since 1951.

## 2. Bathymetry

In all hydrodynamics situations, geographical configuration and bathymetry are the principal controlling factors that determine the hydraulics. Part of the bathymetry has been set up in 1996 by Robert Smith.

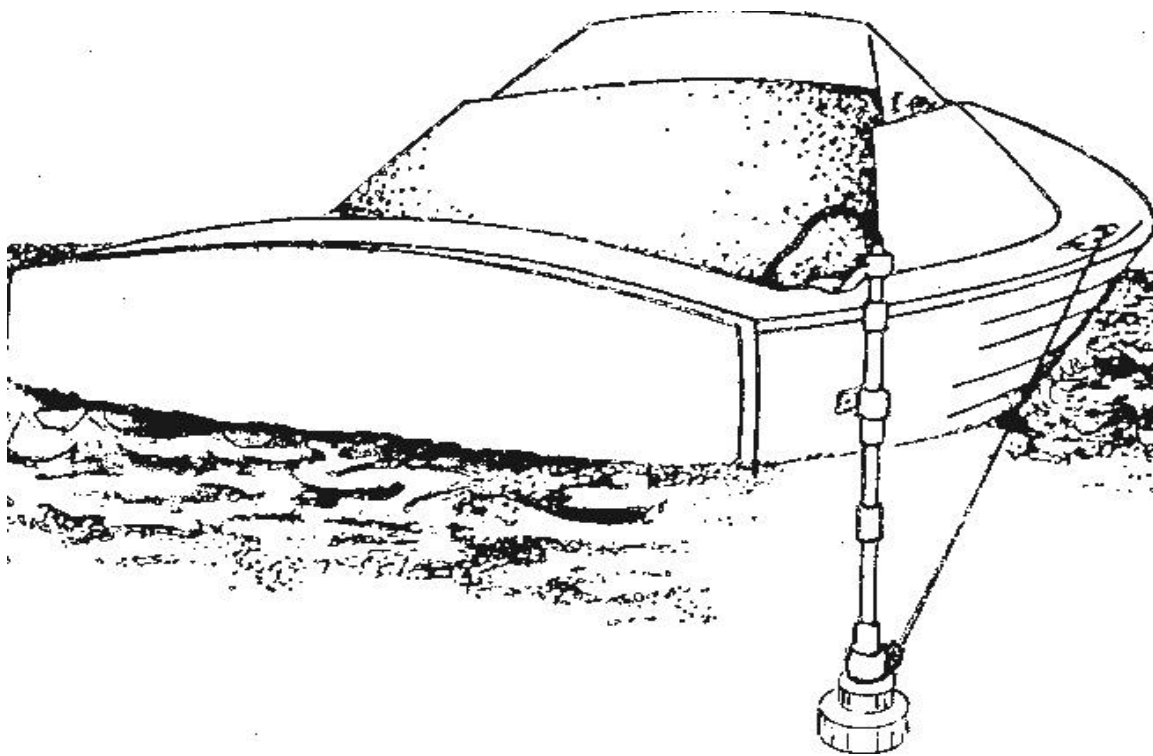
The bathymetry on both side of the bay was required. That was the main purpose of the one-week survey.

### a) Equipment

Special equipment had to 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 we took a simple transducer called DE-719B from Raytheon Marine.

Echo depth sounding is a method of measuring water depth by computing the time interval required for sound waves to travel.

**Fig5: anchorage of the transducer**



### b) Measurements

With the above equipment, we steered the boat all around the reef. Every approximately twenty seconds, GPS measurements were taken. The depths were drawn on the chart paper in real time.

### 3. Water level recorders

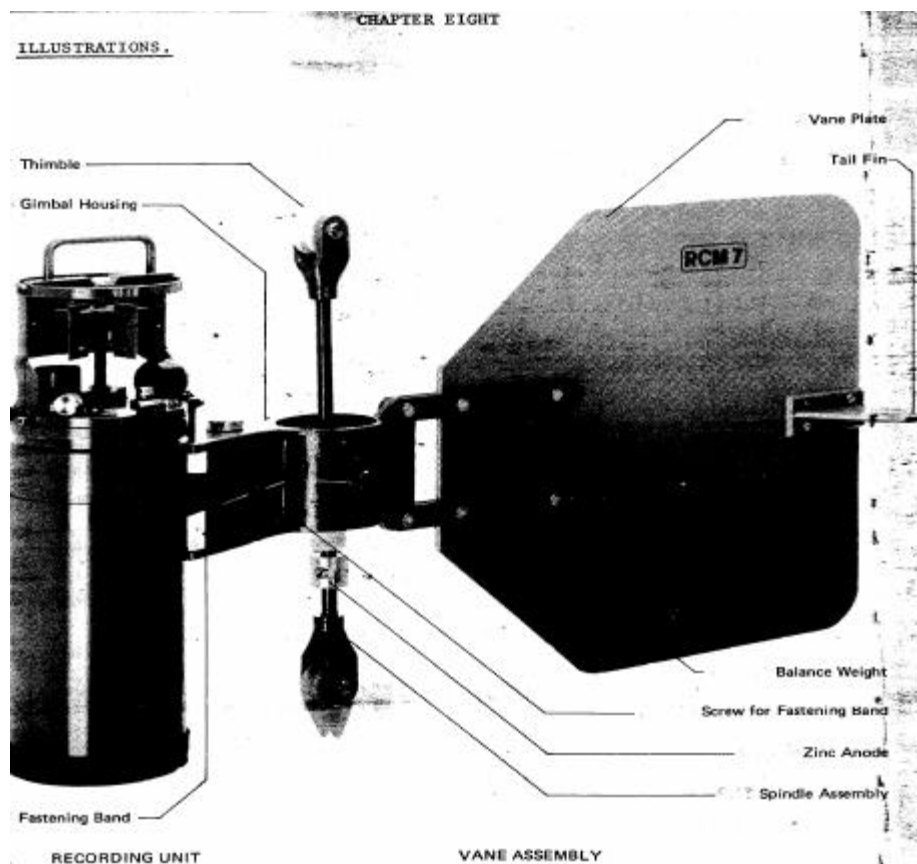
Two water level recorders have been installed at the boundaries of the grid. Their measurements of pressure enabled to compare the theoretical and practical tides. See fig7.

### 4. Currents

During the one-week survey we laid out three Aanderaa currentmeters in Natadola Harbor. One of them had an acoustic release because of the high price of the device. The model will be checked thanks to the one-week recordings.

#### a) Aanderaa currentmeters

**Fig5: current meter used in the field**



The current meters we used are eulerian. We let them at a precise place where they are supposed to stay during one week. All the sensors 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.

The measuring consists of six channels in sequence: reference, temperature, conductivity, pressure, current direction and current speed.

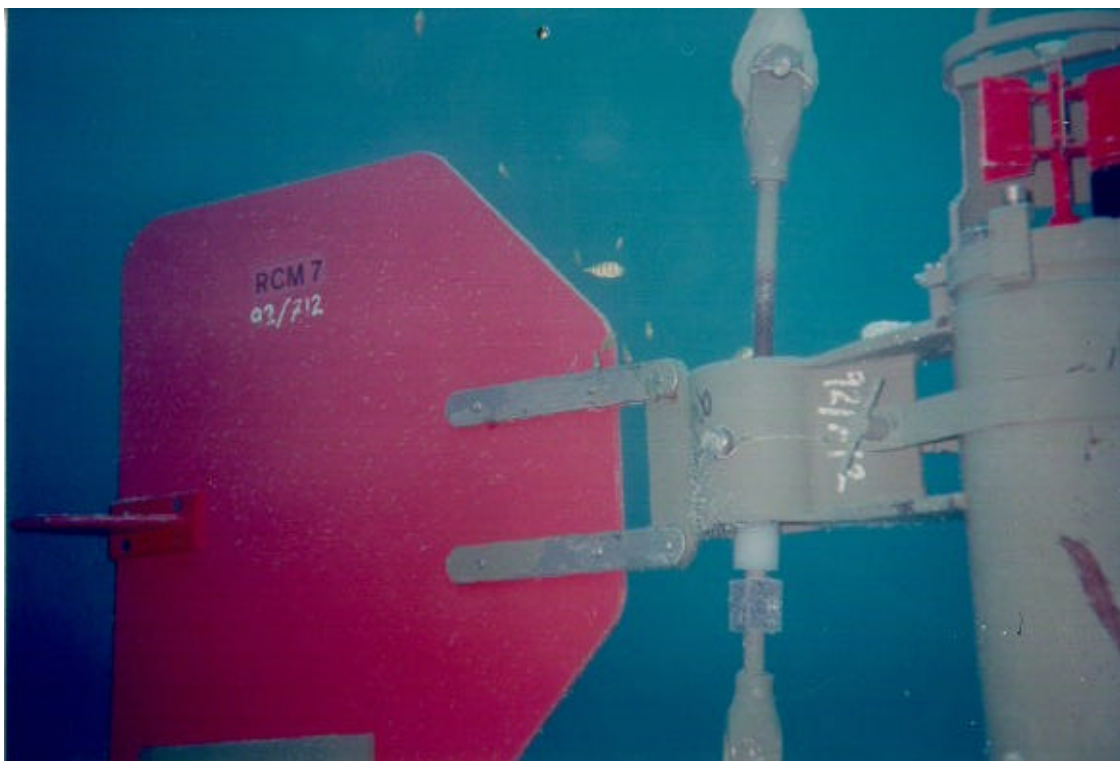
The complete instrument is free to swing around the spindle thanks to the *coefficient de trainee*. RCM7 depth capability is 2000 meters. As the current meter aligns itself in the current, the direction is measured by the orientation of the instrument. The direction sensor is a compass located at the 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.

**Tab5: accuracy of the current meter**

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

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

**Fig6: current meter undersea photograph**



**b) Choice of the spot**

Three current meters were available for the one-week survey. At least one had to be at the entry of the bay in order to have measurements at the boundary to compare with the model.

The photographs taken since 1951 show a major flow between the island and the shore. Then, a current meter was installed there in order to assess the speed of this current.

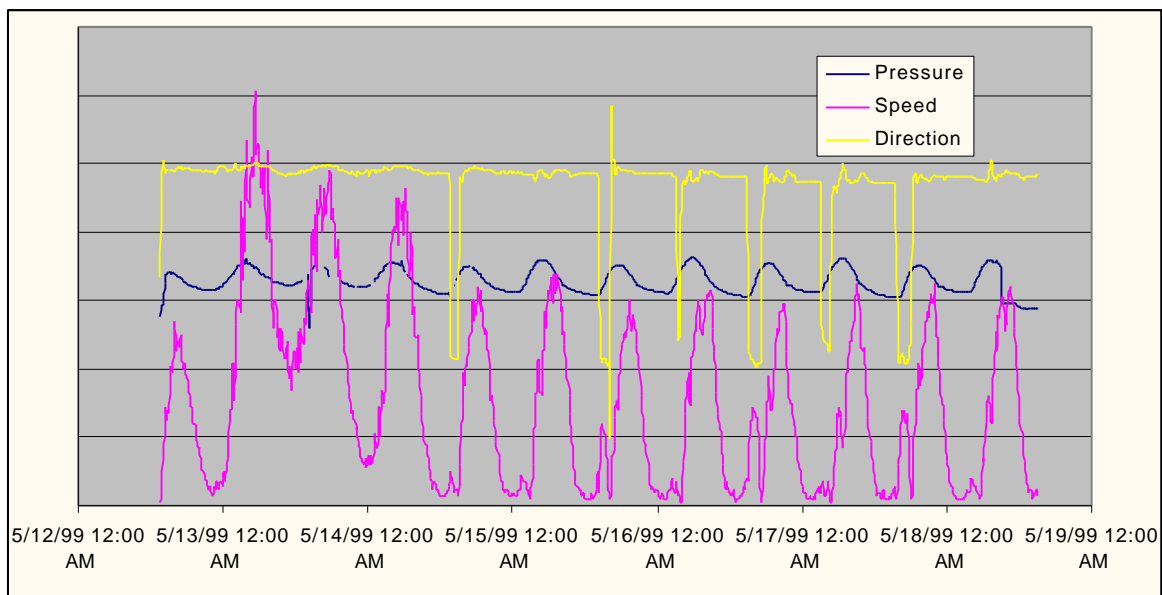
According to some reports, some swimmers had noticed some rip currents not so far away from the coast hence the position of the third current meter. Unfortunately, this one was not enough ballasted and it drifted. We found it very close to the reef two days after the installation and we towed it to its original place by diving at ten meters deep.

**c) 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 according to the aerial photographs, and where the marina is supposed to be built.

**Fig7: Channel current meter measurements**



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 line of the direction is a constant equal to 300 degrees except at the level of the small peaks of the speed plot when it reaches 120 degrees.

It is easy to explain this phenomenon with the pressure plot: at low tide, that is to say at the minimum of the pressure, the water comes from the bay to the channel. This phenomenon is very interesting insofar as the projected marina would be directly involved: the marina would not be dried out but could suffer from strong fluxes coming from outer reef.



## C. Bibliography

### 1. Elevation of the sea level

There is much debate and uncertainty about the increasing levels of CO<sub>2</sub> and other gases in the atmosphere and their effects on the climate (the Greenhouse Effect). The potential effects are variation in rainfall patterns and regimes 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 a result of the enhanced greenhouse effect, sea level will rise (relative to its 1990 level) 0.18m by the year 2030 and 0.44m by the year 2070. This means that the future rate of sea level rise will probably increase to between 4.5 mm/year and 5.5mm/year.

### 2. Wind

#### a) In Nadi

Wind speeds throughout Fiji are typical of the tropics with only small variation throughout the year. During the dry season (May to October) the winds are, on average, slightly stronger than those of the wet season. This is because the South Pacific Convergence Zone is further north during the dry season so that stronger southeast tradewinds occur in the latitudes of Fiji. The wind speeds tend to be highest in the early afternoon and lowest during the night, due to the land/sea temperature contrast which is greatest in the early afternoon.

No wind measurement was taken because of the simple lack of anemometers and no wind data is available for Natadola. The most appropriate wind data for Natadola is from Nadi Airport, which has the most comprehensive climate data for Fiji. Nadi Airport meteorological station is situated approximately 1 kilometer from the coast at 16 meters above sea level, and lies approximately 35 kilometers north north east of Natadola. As such it provides a data record that can be applied with some confidence to the project site. At Nadi Airport, an anemometer has been recording wind speeds regularly since 1946.

**Tab6: Average Wind Speed at Nadi Airport (1960-1984)**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Knots	5.1	5.1	4.6	4.6	4.7	4.9	5.9	6.0	6.3	6.6	6.0	5.5
m/s	2.7	2.7	2.4	2.4	2.4	2.6	3.1	3.1	3.3	3.4	3.1	2.9

From the Nadi Airport wind data a series of annual maximum gusts have been estimated by the Gumbel Method for different return periods. For a 100-year return period, the extreme wind gust is predicted to be 131 knots. In any given year, therefore, there is a 1-% chance of a 131 knot wind occurring. Since the data record used for these estimates was only 39 years long (1946-1985), the reliability of the long-term estimates for the longer return periods are inevitably not very good. Rare, very high gusts may occur during hurricanes, and the anemograph may not be located where the hurricane's highest winds occur. It is believed the rarest most intense hurricane gusts may approach 150 knots.

**Tab7: Estimated Wind Gusts at Nadi Airport**

	Return Period (years)					
<b>Gust Speed</b>	2	5	10	20	50	100
<b>Knots</b>	52	73	87	100	118	131
<b>(m/s)</b>	27	38	45	51	61	67

Source FMS 1985

Winds from the south and east dominate the wind regime, occurring around 47% of the time, and are almost always less than 18 knots in velocity. Winds from the southwest, west and northwest sectors occur around 22% of the time, most frequently during the afternoon. Wind speeds from these directions are less than 18 knots for 99% of the time, and between 3 and 10 knots 67% of the time. Calms occur about 23% of the time, most frequently at night.

#### b) Winds at Natadola

While the extreme wind characteristics of Natadola are considered unlikely to vary greatly from those recorded at Nadi Airport, the normal wind characteristics are believed to vary quite significantly from those at Nadi Airport, but there are no substantive data to illustrate this. Preliminary data from three wind monitoring stations close to Sigatoka, a location with an aspect similar to that of Natadola, indicate that the average wind speed at **5.63 m/s** may be approximately twice that of Nadi Airport. In addition the wind pattern appears to be much more heavily weighted towards the southeast quadrant (Dept. of Energy, 1999). As a consequence, I have decided a wind speed equal to 10 m/s, constant in time and space.

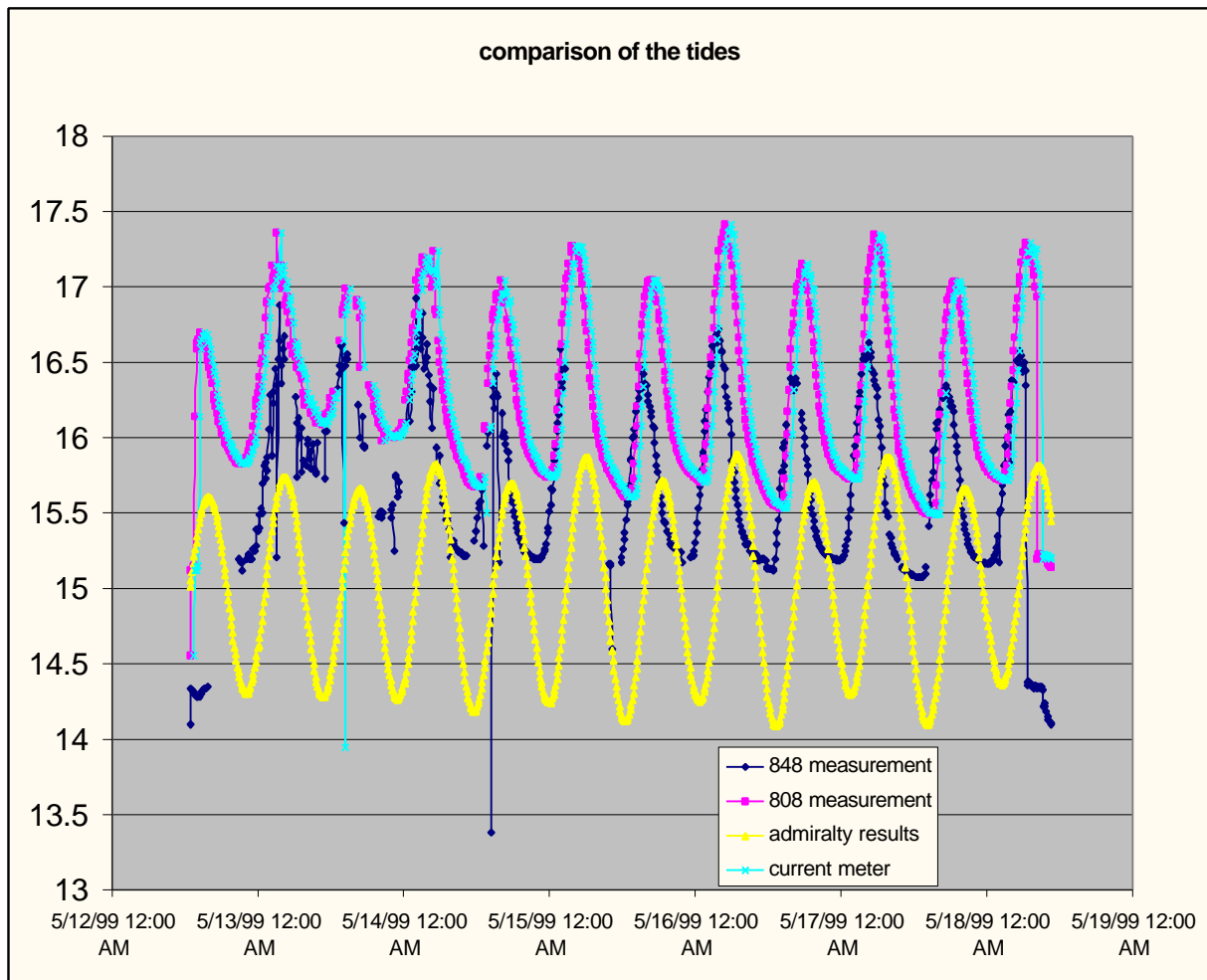
### 3. Tides

Seeing that measurements have periodic plots, the tide had to be taken into account. Even if there is no available measurement for the tide in Natadola, the values of the harmonics given for Suva and Nadi are close enough to consider that the tide is quite the same in Natadola. The Admiralty tide table (volume 4) gives these values for the first harmonics:

**Tab8: Constituent specifications**

Phase (in degrees)	Amplitude
186	0.56
216	0.1
239	0.09
210	0.05
204	0.02

**Fig8: Comparison of measured and theoretical tides**



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.

- The period is quite the same: approximately 12 hours and a half.
- The relatively small peaks happen at about the same period.

#### 4. Review of evapotranspiration and rainfalls

The climatic regime of Fiji is strongly influenced by the southeast trade winds, which are maritime in origin and lose most of their moisture in the highlands of Viti Levu before passing over the drier, western side of the island.

A summary of rainfall data for Nadi Airport recorded between 1942 and 1985 is given. Average annual rainfall is 1867mm, which is approximately 40% of the annual total for the southeastern side of Viti Levu. The table shows that most of this rain falls during the wet season from November to April. The winter dry season extends from May to October, during which less than 450 mm falls, on average.

Average monthly potential evapotranspiration figures (in mm/day) for Nadi Airport and Lautoka Mill are listed below. These figures equate to an annual average of between 1500-1550 mm. Subtracting this from the annual rainfall yields a net water balance of 260-340 mm/year. However, there is potential for a deficit in the eight month period from May through to December. The deficit will range between 6 and 55 mm/month.

**Tab9: Review of evapotranspiration and rainfalls**

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
rainfalls	Average	309	285	353	173	86	73	49	60	82	97	134	166	1867
	Highest recorded	598	606	918	406	288	266	190	286	279	342	461	398	2983
	Lowest recorded	41	46	75	22	2	0	0	0	0	6	7	21	864
evapo transpi ration	Nadi Airport	161	155	136	124	105	93	84	118	140	164	171	171	1621
	(1947-1985)	164	161	140	124	99	84	84	105	124	146	161	167	1559
	Lautoka Mill	161	152	136	121	102	90	93	109	130	149	158	161	1562
	(1971-1988)	171	164	143	127	102	90	87	102	130	152	164	167	1600
	Average	164	158	139	124	102	89	87	109	131	153	164	167	1586
deficit (mm)		-145	-127	-214	-49	16	16	38	49	49	56	30	0.6	-281

### **III. Simulations**

In recent years with the development of powerful computers, numerical models are increasingly being used to simulate the processes of nature or as a tool in which to assess the likely hazards. These predictions are essential to assess sustainable urban planning of the city and surrounds.

Mike 21 is but one example of professional modeling software for 2D free surface flows and comes in modular form with four main application areas, coastal hydraulics and oceanography, waves, sediment processes and environmental hydraulics.

As harbors 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 the data sets available, seasonal variations and cost. Numerical modeling 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.

Additional monitoring and studies are required both to understand the existing situation especially related to spit dynamics, and to model potential modifications to the system.

The purpose of the following simulations is to produce a basic hydrodynamic model (HD) that can be used for the set-up of a water quality, sedimentary transport. It can also give an idea of the current velocities and the flux in the model. Comparing the results with measured sea level and currents assesses the validity of the hydrodynamic model.

The scope of works has been decided very early and quite easily. Seeing the complexity of Mike 21, one month was necessary to understand how it works. Then it was time to go in the field to find out the parameters required for making the simulation run.

The first task of the simulation itself is the set up of a hydrodynamic model.

So that this report may be useful for any future Mike 21 user, the parameters specified for the simulations are detailed as well as the problems that have occurred during this work.

## A. *Software discovery*

Actually the first thing done as soon as arrived, it was very important to understand all the data needed before going in the field.

### 1. **Application areas**

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 modeling 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 harbors, harbor 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 harbors 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, harbor entrances, coasts, river ports, etc.

**Tab10: computational modules of Mike 21**

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

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 result of an advection-dispersion model or a sediment transport model, for instant, is reliant on the quality of the hydrodynamic model.

## 2. 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:

### a) Continuity

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

### b) Momentum

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

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} = \frac{-1}{\mathbf{r}} \frac{\partial p}{\partial y} + \mathbf{u} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (3)$$

$$\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial vw}{\partial y} + \frac{\partial w^2}{\partial z} = \frac{-1}{\mathbf{r}} \frac{\partial p}{\partial z} + \mathbf{u} \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) - g \quad (4)$$

### c) Boundary conditions

Free surface condition:

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

Bottom condition:

$$u=v=w=0 \text{ pour } z=-h \quad (6)$$

Where  $x, y, z$  denote the space coordinates,  $u, v, w$  represent the three components of the velocity,  $\mathbf{r}$  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 Mike21 is based on it.

#### d) Shallow Water Equations

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

$$U(x, y, t) = \int_{-h}^z u dz \quad V(x, y, z) = \int_{-h}^z v dz \quad (7)$$

Where  $z$  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:

$$\frac{\partial}{\partial t} \int_{z_1}^{z_2} u dz = \int_{z_1}^{z_2} \frac{\partial u}{\partial x} dx + u(z_2) \frac{\partial z_2}{\partial x} - u(z_1) \frac{\partial z_1}{\partial x} \quad (8)$$

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

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

*Integration of the continuity equation:*

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

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

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

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

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

Taking the average we finally obtain:

$$\frac{\partial \bar{\mathbf{z}}}{\partial t} + \frac{\partial \bar{U}}{\partial t} + \frac{\partial \bar{V}}{\partial t} = 0 \quad (13)$$

*Integration of the vertical movement equation:*

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

$$\int_z^z \left( \frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial vw}{\partial y} + \frac{\partial w^2}{\partial z} \right) dz = \int_z^z \frac{-1}{\mathbf{r}} \frac{\partial p}{\partial y} dz + \mathbf{u} \int_z^z \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) dz - \int_z^z g dz \quad (14)$$

From the Leibnitz rule, we obtain the expressions:

$$\int_z^z \frac{\partial w}{\partial t} dz = \frac{\partial}{\partial t} \int_{-h}^z w dz \quad (15)$$

$$\int_z^z \frac{\partial uw}{\partial x} dz = \frac{\partial}{\partial x} \int_z^z u w dz - u(\mathbf{z}) w(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial x} \quad (16)$$

$$\int_z^z \frac{\partial vw}{\partial y} dz = \frac{\partial}{\partial y} \int_z^z v w dz - v(\mathbf{z}) w(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial y} \quad (17)$$

$$\int_z^z \frac{\partial^2 w}{\partial x^2} dz = w^2(\mathbf{z}) - w^2(z) \quad (18)$$

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

$$\int_z^z g dz = g(\mathbf{z} - z) \quad (20)$$

The free surface condition shows that:

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

Moreover, the pressure at the free surface is taken to be equal to zero, i.e.  $p(z=\mathbf{z})=0$ .

Summing up all the terms, we obtain:

$$\frac{\partial}{\partial t} \int_z^z w dz + \frac{\partial}{\partial x} \int_z^z u w dz + \frac{\partial}{\partial y} \int_z^z v w dz - w^2(z) = \frac{1}{\mathbf{r}} p(z) - g(\mathbf{z} + h) + v \int_z^z \Delta w dz \quad (22)$$

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 steep slopes should be avoided when they are facing the flow.

$$\overline{\frac{\partial}{\partial t} \int_z^z w dz} = \frac{\partial}{\partial t} \int_z^{\bar{z}} \bar{w} dz = 0 \quad (23)$$

$$\overline{v \int_z^z \Delta w dz} = v \int_z^{\bar{z}} \Delta \bar{w} dz = 0 \quad (24)$$

$$\overline{\frac{\partial}{\partial x} \int_z^z u w dz} = \frac{\partial}{\partial x} \int_z^{\bar{z}} (\bar{u} + \tilde{u}) \bar{w} dz = \frac{\partial}{\partial x} \int_z^{\bar{z}} \tilde{u} \bar{w} dz \quad (25)$$

$$\overline{\frac{\partial}{\partial y} \int_z^z v w dz} = \frac{\partial}{\partial y} \int_z^{\bar{z}} (\bar{v} + \tilde{v}) \bar{w} dz = \frac{\partial}{\partial y} \int_z^{\bar{z}} \tilde{v} \bar{w} dz \quad (26)$$

$$\frac{\overline{p(z)}}{\mathbf{r}} = \frac{P(z)}{\mathbf{r}} \quad (27)$$

$$\overline{g(\mathbf{z} - z)} = g(\mathbf{z} - \bar{z}) \quad (28)$$

This gives the following result:

$$\frac{P(z)}{\mathbf{r}} = g(\mathbf{z} - \bar{z}) + \frac{\partial}{\partial x} \int_z^{\bar{z}} \tilde{u} \bar{w} dz + \frac{\partial}{\partial y} \int_z^{\bar{z}} \tilde{v} \bar{w} dz - \bar{w}^2(z) \quad (29)$$

*Integration of the horizontal momentum equations:*

The derivation is detailed term by term for the first momentum equation:

$$\int_{-h}^z \left( \frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} \right) dz = - \int_{-h}^z \frac{1}{\mathbf{r}} \frac{\partial p}{\partial x} dz + \mathbf{u} \int_{-h}^z \left( \frac{\partial u^2}{\partial x^2} + \frac{\partial u^2}{\partial y^2} + \frac{\partial u^2}{\partial z^2} \right) dz \quad (30)$$

$$\int_{-h}^z \frac{\partial u}{\partial t} dz = \frac{\partial}{\partial t} \int_{-h}^z u dz - u(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial t} \quad (31)$$

$$\int_{-h}^z \frac{\partial u^2}{\partial x} dz = \frac{\partial}{\partial x} \int_{-h}^z u^2 dz - u^2(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial x} - u^2(-h) \frac{\partial h}{\partial x} \quad (32)$$

$$\int_{-h}^z \frac{\partial uv}{\partial y} dz = \frac{\partial}{\partial y} \int_{-h}^z uv dz - u(\mathbf{z}) v(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial y} - u(-h) v(-h) \frac{\partial h}{\partial y} \quad (33)$$

$$\int_{-h}^z \frac{\partial uw}{\partial z} dz = u(\mathbf{z}) w(\mathbf{z}) \quad (34)$$

$$\int_{-h}^z \frac{\partial p}{\partial x} dz = \frac{\partial}{\partial t} \int_{-h}^z p dz - p(-h) \frac{\partial h}{\partial t} + p(\mathbf{z}) \frac{\partial \mathbf{z}}{\partial x} \quad (35)$$

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

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

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

$$\frac{\partial}{\partial t} \int_{-h}^z u dz + \frac{\partial}{\partial x} \int_{-h}^z u^2 dz + \frac{\partial}{\partial y} \int_{-h}^z uv dz + \frac{\partial}{\partial x} \int_{-h}^z \frac{p}{\mathbf{r}} dz - \frac{p(-h)}{\mathbf{r}} \frac{\partial h}{\partial x} = \mathbf{u} \int_{-h}^z \Delta u dz \quad (37)$$

Taking the mean of each term:

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

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

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

$$\mathbf{u} \int_{-h}^z \Delta u dz = \mathbf{u} \int_{-h}^z \Delta \bar{u} dz \quad (41)$$

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

$$\bar{p} = P(-h) - \mathbf{r}g(\bar{\mathbf{z}} + h) \quad (42)$$

Hence :

$$\frac{p(-h)}{\mathbf{r}} \frac{\partial h}{\partial x} = \bar{p} \frac{\partial h}{\partial x} + \frac{\partial}{\partial x} \left( \frac{1}{2} g(h + \bar{\mathbf{z}})^2 \right) - g(h + \bar{\mathbf{z}}) \frac{\partial \bar{\mathbf{z}}}{\partial x} \quad (43)$$

$$\frac{\partial \bar{U}}{\partial t} + \frac{\partial}{\partial x} \int_{-h}^z \frac{\partial \bar{u}^2}{\partial t} dz + \frac{\partial}{\partial y} \int_{-h}^z \bar{u}\bar{v} dz = \frac{\partial}{\partial x} \left( \int_{-h}^z \tilde{u}^2 + \frac{p}{\mathbf{r}} dz - \frac{1}{2} g(h + \bar{\mathbf{z}})^2 \right) - \frac{\partial}{\partial y} \int_{-h}^z \tilde{u}\tilde{v} dz \quad (44)$$

$$- g(h + \bar{\mathbf{x}}) \frac{\partial \bar{\mathbf{z}}}{\partial x} + \bar{p} \frac{\partial h}{\partial x} + \mathbf{u} \int_{-h}^z \Delta u dz \quad (45)$$

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

$$S_{xx} = \int_{-h}^z \overline{p + \mathbf{r}\bar{u}^2} dz - \mathbf{r}g(\bar{\mathbf{z}} + h)^2 \quad (46)$$

$$S_{yy} = \int_{-h}^z \overline{\mathbf{r}\tilde{u}\tilde{v}} dz \quad (47)$$

Or for the second momentum equation:

$$S_{yy} = \int_{-h}^{\bar{z}} \overline{p + r\bar{v}^2} dz - \frac{r\bar{g}}{2} (\bar{z} + h)^2 \quad (48)$$

$$S_{yx} = \int_{-h}^{\bar{z}} \overline{r\bar{v}\bar{u}} dz \quad (49)$$

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

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

$$\int_{-h}^{\bar{z}} \bar{u}^2 dz = \bar{u}^2 (\bar{z} + h) = \bar{u}\bar{U} \quad (50)$$

$$\int_{-h}^{\bar{z}} \bar{u}\bar{v} dz = \bar{u}\bar{v} (\bar{z} + h) = \bar{u}\bar{V} = \bar{U}\bar{v} \quad (51)$$

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

$$\frac{\partial \bar{z}}{\partial t} + \frac{\partial \bar{U}}{\partial t} + \frac{\partial \bar{V}}{\partial t} = 0 \quad (52)$$

$$\begin{aligned} \frac{\partial \bar{U}}{\partial t} + U \frac{\partial \bar{U}}{\partial x} + U \frac{\partial \bar{U}}{\partial y} = & -g(\bar{z} + h) \frac{\partial \bar{z}}{\partial x} + \frac{\mathbf{t}_{xx}}{\mathbf{r}} + \frac{\mathbf{t}_{xy}}{\mathbf{r}} + \frac{\mathbf{t}_{bx}}{\mathbf{r}} + \frac{\mathbf{t}_{wx}}{\mathbf{r}} + \frac{\partial}{\partial x} \left( \mathbf{u}_{xx} \frac{\partial \bar{U}}{\partial x} \right) \\ & + \frac{\partial}{\partial y} \left( \mathbf{u}_{xy} \frac{\partial \bar{U}}{\partial y} \right) + f\bar{V} \end{aligned} \quad (53)$$

$$\begin{aligned} \frac{\partial \bar{V}}{\partial t} + U \frac{\partial \bar{V}}{\partial x} + U \frac{\partial \bar{V}}{\partial y} = & -g(\bar{z} + h) \frac{\partial \bar{z}}{\partial x} + \frac{\mathbf{t}_{yx}}{\mathbf{r}} + \frac{\mathbf{t}_{yy}}{\mathbf{r}} + \frac{\mathbf{t}_{by}}{\mathbf{r}} + \frac{\mathbf{t}_{wy}}{\mathbf{r}} + \frac{\partial}{\partial x} \left( \mathbf{u}_{xy} \frac{\partial \bar{V}}{\partial x} \right) \\ & + \frac{\partial}{\partial y} \left( \mathbf{u}_{yy} \frac{\partial \bar{V}}{\partial y} \right) - f\bar{U} \end{aligned} \quad (54)$$

with

$\mathbf{t}_{ij}$  : component of effective shear stress

$\mathbf{t}_{bi}$  : bottom friction stress

$\mathbf{t}_{wi}$  : wind friction stress

$\mathbf{u}_{ij}$  : 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  $C$ .

$$t_b = rg \frac{U^2 + V^2}{C^2} \quad t_{bx} = rg \sqrt{\frac{U^2 + V^2}{C^2}} U \quad t_{by} = rg \sqrt{\frac{U^2 + V^2}{C^2}} V$$

### e) Numerical Formulation

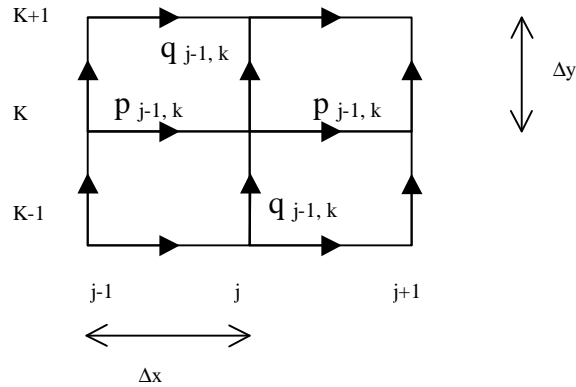
The numerical model is a finite-difference schema using an A.D.I (Alternating Direction-Implicit) technique to integrate the equation for mass and momentum conservation in the space-time domain. A Double Sweep (DS) algorithm resolves the equation matrices.

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 centering of all difference terms and dominant coefficients, achieved without resort to iteration.
2. Second to third-order accurate convective momentum terms, i.e. “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.

**Fig9: difference grid in x,y space**



Where  $p$  and  $q$  are flux densities in x- and y-direction ( $m^3/s/m$ )= $(u_h, v_h)$ ;  $(u, v)$ =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  $\zeta$  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, i.e.  $n-1/2$  and  $n+1/2$ .

## SOPAC Training Report

---

In the y-sweep the continuity and y-momentum equations are solved, taking  $\zeta$  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 centering at  $n+1/2$ .

### 3. Method

Perhaps the most difficult step because almost nobody really uses Mike 21 very often in SOPAC, It was not possible to read through the 20 manual books. Thanks to the examples available with the software, I managed to understand the way Mike 21 works after almost one month and sure several hundreds of tries. The result of this discovery is presented as the “Mike 21 guide”, which follows. It is also available on Internet.

It was necessary to anticipate the required steps of the modeling before going in the field. It was important as well for being sensitized to the CPU time because some simulations can take so long that they have to be run during the weekend.

### 4. Mike 21 guide

#### a) First step: creating a project

(1) In the explorer

- Creating the first new folder

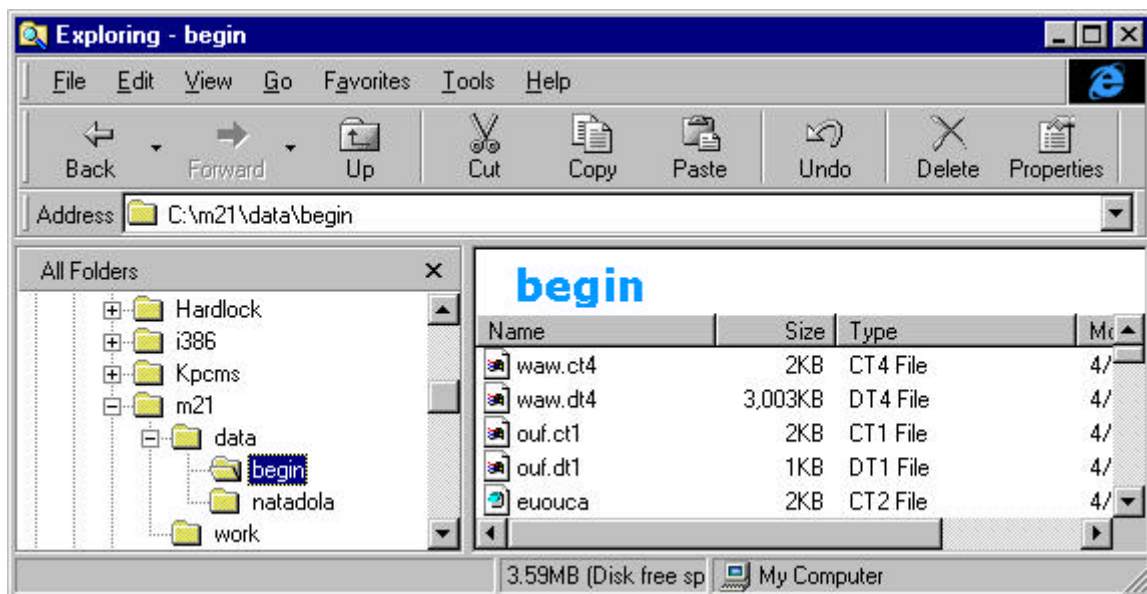
The user has to create a new folder called M21 for instance different from Mike 21 but at the same level where all the files will be saved.

- Creating new folders inside

Then, the folders “data” and “work” have to be created in C:\M21 and an other one called “Nataadola” inside “data”.

Ex:

**Fig10: creation of folders before starting Mike 21**



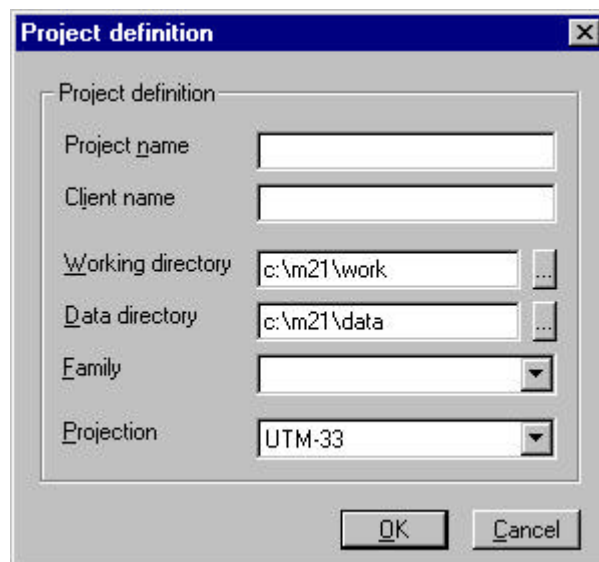
Note: “Nataadola” will be the name of the family. See later.



(2) In Mike 21

- Open Mike 21
- File-new project
  1. The project name Natadola will not appear in the explorer. It will appear at the top of the main Mike 21 window while computing. It is possible to access only to the files created under this name.
  2. The data directory and the working directory are C:\M21\data and C:\M21\work.
  3. The name of the family can be chosen among the folders in C:\M21\data.
  4. It can be a good idea to choose the same name for the family and the project because the project name will appear at the top of the main window but not in the explorer. It is the contrary for the name of the family.

**Fig11: project definition window under Mike 21**



**b) Preprocessing**

(1) Opening a project

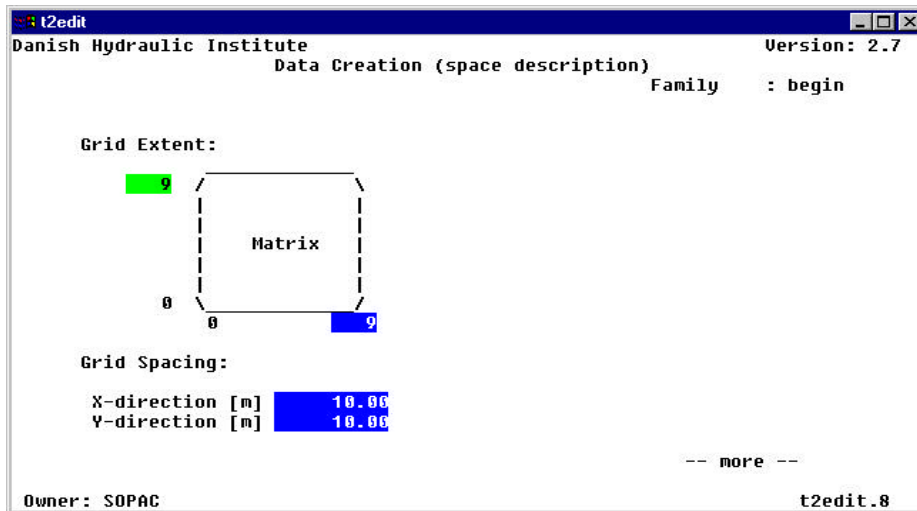
(2) Creating a bathymetry

- “Utilities-edit type 2 data” or “select type 2 data”

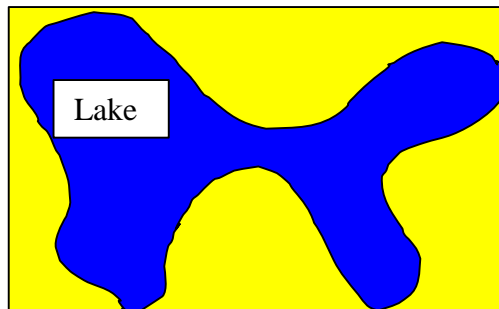
Note: ‘2’ is the wideness of the square matrix you want to work with. It means that 1 corresponds with a vector and then 0 with a scalar.
- Create data-user defined
  - The matrix

Here you have to choose the dimensions of the matrix.

**Fig12: data creation under Mike 21**



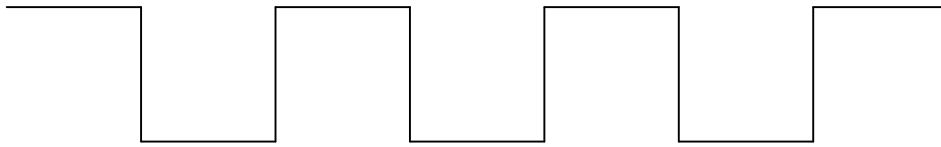
Choosing the grid is not really easy (see later for the case of Natadola) but at least it must be chosen like on the following drawing:



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. If tidal simulation...to be found.
5. 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.
6. Avoid sudden expansion and contraction of the flow close to an open boundary.
7. If possible, one of the coordinate axes has to be parallel to the main flow direction.
8. The point (0,0) is the most accurately known.
9. Bumps and holes must be as far as possible from the boundaries.
10. Avoid the following kind of boundaries:

## SOPAC Training Report



### ➤ The grid spacing

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

### ➤ Number of time steps

In most of the cases, the bathymetry does not move: only one time step.

But if it is not the case, a type 2 file has to be created

### ➤ Latitude and longitude

For Fiji, the latitude is about  $-18$  and the longitude is about  $177$  degrees. The minus should be forgotten because it would change the Coriolis orientation.

### ➤ Name

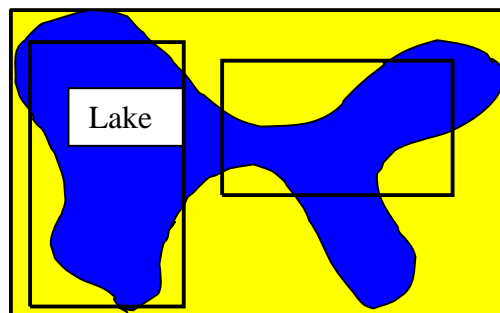
It is important to be noticed because at the beginning of the hydrodynamic module, a bathymetry is needed. For instance, we baptize it *startbth* to be sure afterwards that it is a bathymetry file.

- Selecting time step

The time step number is nearly always 0 because:

$0 = \text{time step number} < \text{number of time sets.}$

- Subarea selection



The subarea selection can be all the dash rectangles included in the grid. The bathymetry will be then edited in them. It helps for sharing the project and as a matter of fact the CPU time. The subarea selection is useful when some depth corrections are needed for a part of the grid like for a dredged channel.

- Editing data

The subarea or the total grid has to be filled in. You can either enter each number one at a time or use the available tools:

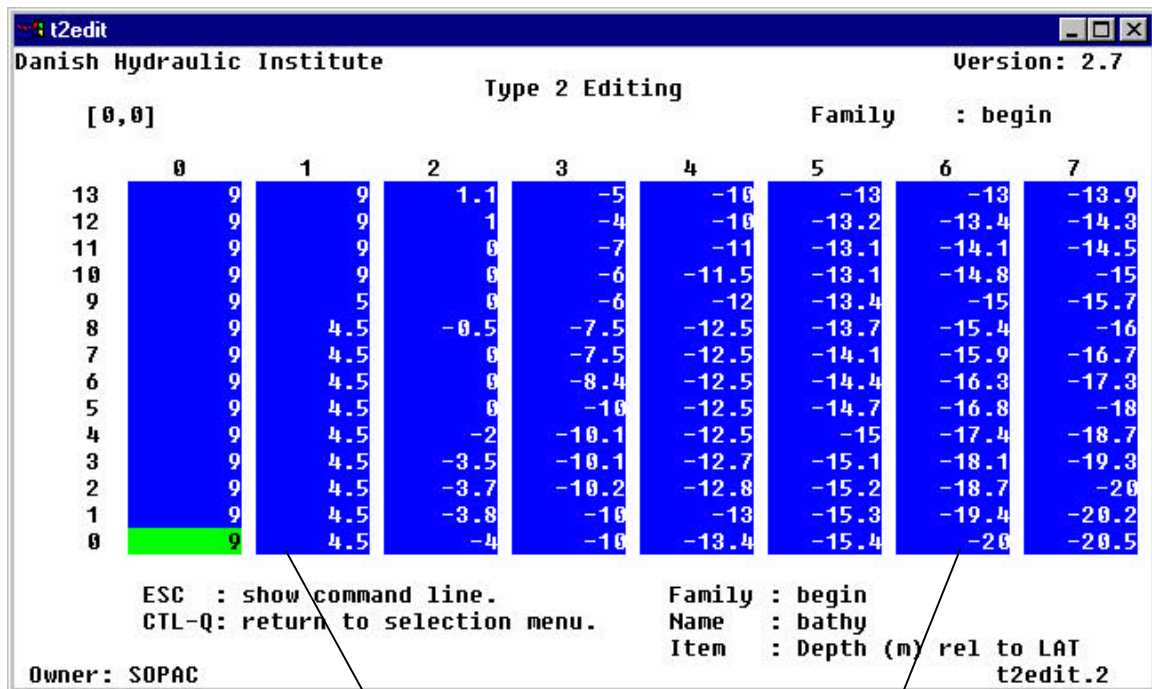
### ➤ Each time you want to write a command, press escape.

### ➤ Then, the list of commands can be found in typing help.

- Copying data

Only a part of the values can be copied and from different source data.

Fig13: copying data under Mike 21



The two first columns copied from

The two last ones from another

- Writing data

The user has to make sure that the arrow points “update data file” and can then exit.

### c) Hydrodynamic module

#### (1) Open it

After having clicked on the hydrodynamic icon and then on the standard hydrodynamics bar (the only one hydrodynamic module available), the user has to choose the bathymetry he wants to work with, in select bathymetry-cold start: *startbth*.

Note: hot start can be used if a hydrodynamic model has already been run. Not really interesting a priori.

#### (2) Hydrodynamic specifications

- Area description

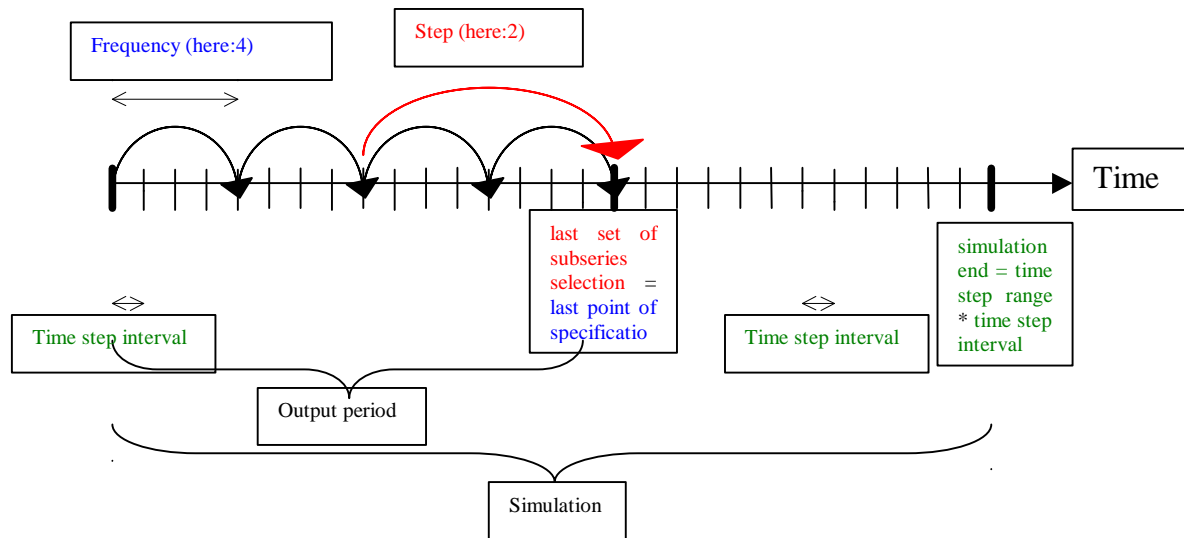
This menu is not interesting except for simulating flooding and drying. If it is the case, some rules have to be respected:

- Flooding depth = drying depth + 0.1
- 0.1= drying depth = 0.2
- 0.2= flooding depth = 0.4

- Simulation period
  - Time issue

Here are all the time values needed or calculated by default in the simulation period but also later in output specifications or in subseries selection.

**Fig14: time terms' definition**



Summary of the rules:

1. Auto-calculated in simulation period: simulation end = time step range \* time step interval.
2. Auto-calculated in output specifications: last of output period = time step interval (from simulation period) \* last point (from output specifications).
3. First step (in subseries selection) = step (in subseries selection) = last step (in subseries selection).
4. Time step (in subseries selection) = time step interval \* frequency \* step (in subseries selection).
5. Last set (in subseries selection) = last point (in output specifications) / frequency.

These two following columns mean then the same things but the terms are different:

**Tab11: identical meanings of Mike 21**

Data creation (type 0, 1 or 2)	Simulation period
Number of time sets: 34	Time step range: 0-33
Time step: 12	Time step interval: 12

➤ Courant number

In Mike 21 grid cell size and time step are predetermined to ensure a low courant number is obtained. The grid spacing is linked with the current number as follows:

$$C_R = c \times \frac{\Delta t}{\Delta x}$$

, where  $c$  is the celerity,  $\Delta t$  the time step and  $\Delta x$  the grid spacing. For a tidal wave the celerity is:

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

, where  $g$  is gravity and  $h$  is the maximal water depth.

In the same way Mike 21 calculates the water level and flow in a number of discrete points in the computational grid. It also calculates them at a number of discrete time steps. And just as the grid point should be placed equidistant so should the time step, i.e. 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 Courant number is an expression of how many grid points the information moves in one time step.

Normally we can have a maximum Courant number in the model of up to 5. The maximum value, which can be used without having stability problems, does however depend on the bathymetry. For very smooth bathymetry, Mike 21 allows Courant numbers up to about 20.

Therefore, the grid spacing becomes a compromise between the purpose of the study, the time step and the Courant number.

- Initial surface

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.

- 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 type2 file as a Manning or Chezy number because the formula which links both depends on the height:

$C = M * h^{1/6}$
-------------------

Values in the range 20–40 are normally used with a suggested value of  $32 \text{ m}^{1/3}/\text{s}$  for the Manning number whereas the range is 30-50 for the Chezy number. It is better to choose the Chezy one not to increase the computational time.

If the bathymetry and the boundary conditions are the primary causes for a blow-up, the bed resistance and the eddy viscosity can help to damp out numerical instability.

- Boundary conditions

In this menu, a check of the open is recommended. If it is not the case, it is possible to change them or add some others by using *user defined*.

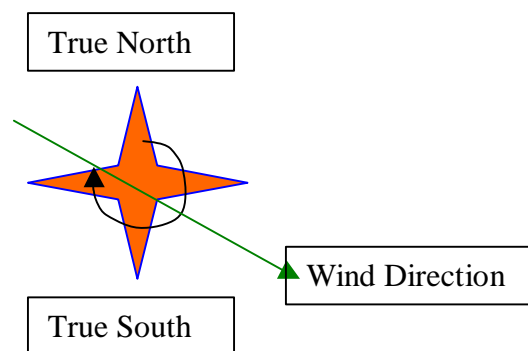
They are sure the most difficult things to get rid of. The numerical instability comes often from them.

- Wind conditions

Definition of wind direction:

The degrees have to be calculated like shown with the black arrow.

**Fig 15: wind orientation**



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. Be careful of the default value of the beginning hour because it is different from the other ones.
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. It is counseled to call the file startwd.

- Output specifications

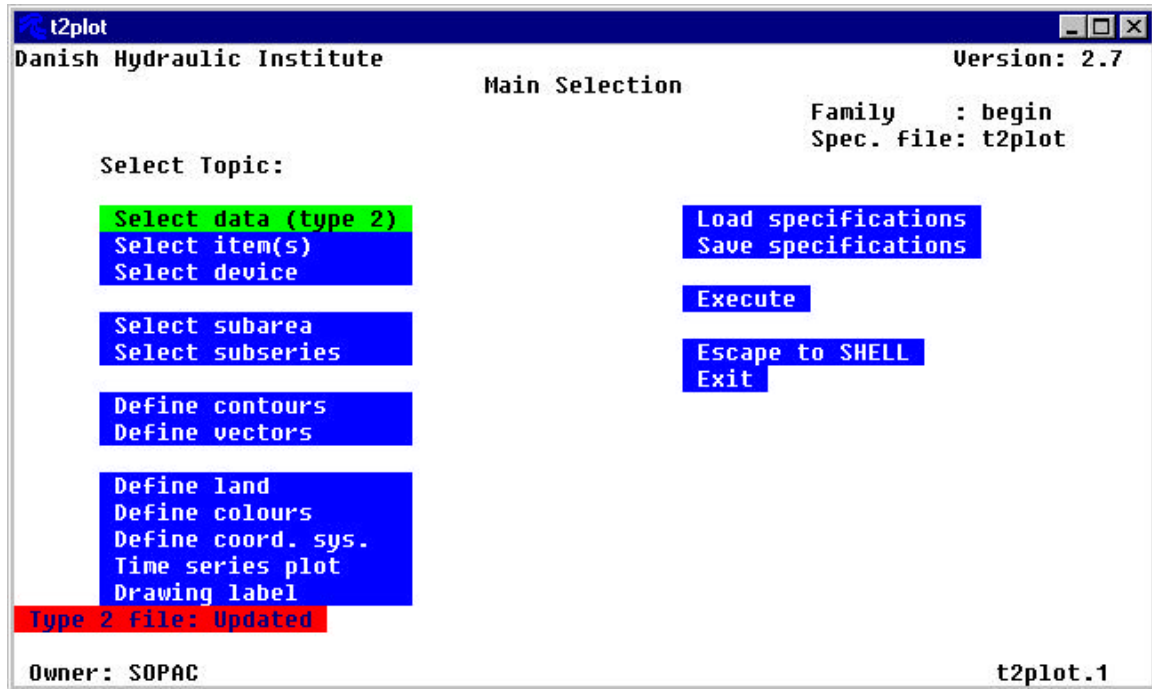
Here is chosen the output data that are going to be simulated in the post-processing.

The difference between them can come from the choice of the [last point](#) and from the [frequency](#).

It only remains to execute after having verified.

d) Post processing

Fig16: post processing window



(1) open

The type-2 file that has been executed thanks to the simulation is editable through “graphics-matrix series plot” in the main window. A type 0 file has first to be extracted before observing the results in “graphics-time series plot”.

(2) Running 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 subseries

The last available set is written by default but can be corrected.

To know how many steps there are in the simulation, calculate:

$$\text{Number of Steps} = \text{Floor} (1 + (\text{last set} - \text{first set})/\text{step})$$

- Contours definition

It is perhaps better with the isolines and the shading colors. Anyway it is necessary to click on the linear scale on show statistics and then on set defaults to have an appropriate scale.



## *B. Basic simulation*

### **1. Setting up of the bathymetry**

The first step and by far the most important task in a modeling process is 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.

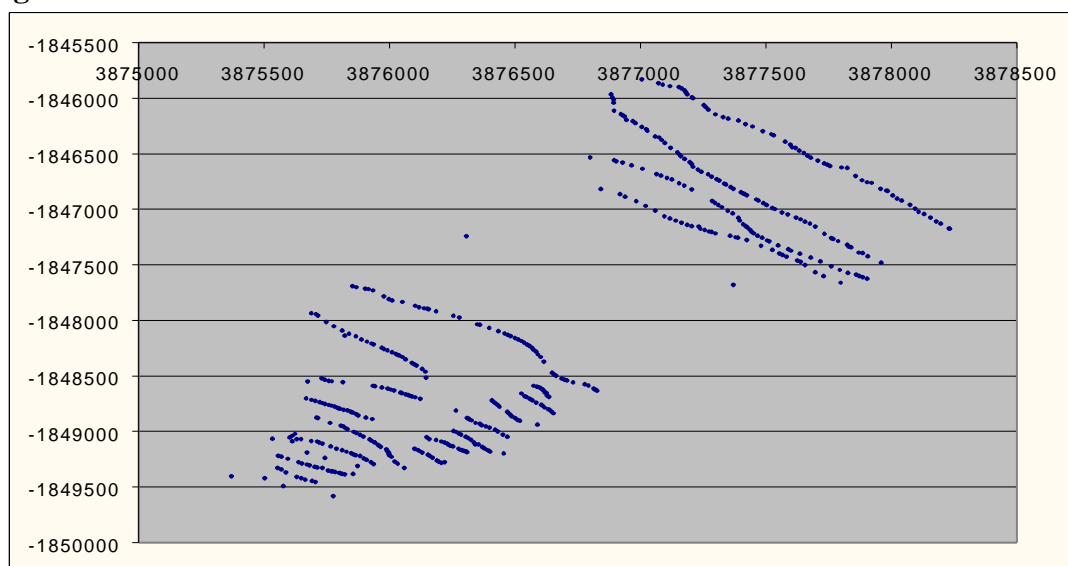
Data used for the compilation was sourced from the survey completed in 1996 by R. Smith and the one I made with Sekove and Isei in May 1999.

To decide where to place the open boundaries, some modeling guideline are followed in order to avoid many pitfalls in the modeling process:

1. In order to have a "well behaved" flow at the open boundary, the bathymetry has to be smoothed close to it and that is not a big problem in the case of Natadola with the reef boundaries.
2. Because of the way Mike 21 solves the equations, better results are normally obtained with flow parallel to one of the coordinate axes. Therefore the model should be placed so that the main flow direction is aligned with the grid.
3. In order to have a "well behaved" flow at the open boundary, the bathymetry is smoothed close to it.
4. Because of the way Mike 21 solves the equations, better results are normally obtained with flow parallel to one of the coordinate axes. Therefore the model should be placed so that the main flow direction is aligned with the grid.
5. The currentmeters and water level recorders must be in the grid to check if the model and the measurements in the field have the same values.

#### **a) Data reading**

**Fig17: lines of measurements in Natadola Harbor**



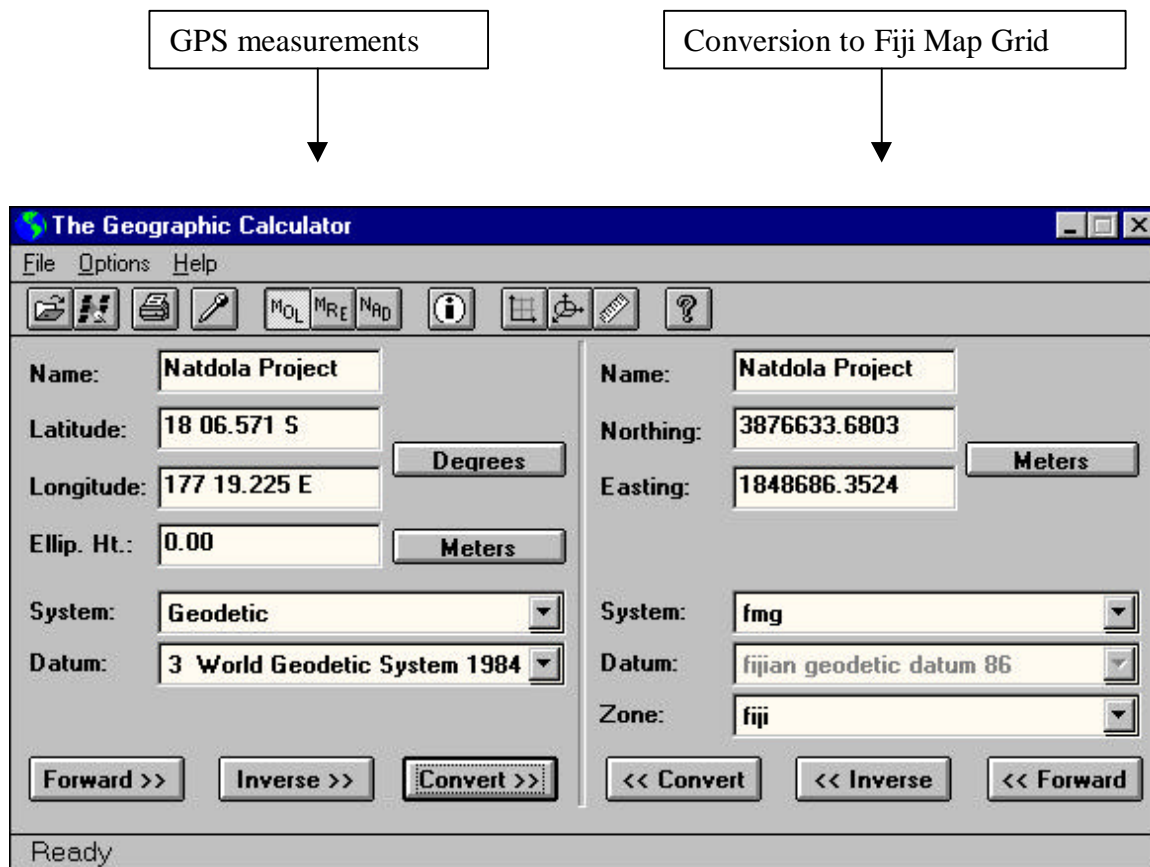
Seeing that the area where we measured the depth is very shallow, we only used a very small transducer which cursor could only draw the depth on a chart. As a consequence, a depth had to be manually attached to each GPS measurement afterwards. See annex 2. This step was particularly long especially because an interpolation was often necessary between several points owing to the steep relief of the bottom.

### b) Conversion

Because the tectonic plaque of Fiji is moving from 5cm/year, the measurements from 1996 could not be superposed to the ones from 1999.

Blue Marble Geographic Calculator is used to carry out the transformations from WGS84 to FMG (Fiji Map Grid). To avoid converting the five hundred measurements one by one, a file has been created with the extension “pts” but it is still a long task to find the right file format.

**Fig18: conversion under Geographical calculator**



### c) Corrections

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.

Even before the real interpolation I have added some measurements in the excel file. It was necessary for being able to choose the cell size of the interpolation.

### d) Interpolation

Several interpolations have been tried. The first one with AutoCAD was not easy and not efficient at all considering that I was not able to recognize the shore. Even so I went through several tools of AutoCAD, some of Quicksurf and eventually through a Fortran routine.

After having discovered AutoCAD, I have discovered MapInfo and VerticalMapper, which has more powerful interpolations and viewers than AutoCAD. But I had to make several manipulations for exporting the results to Mike 21.

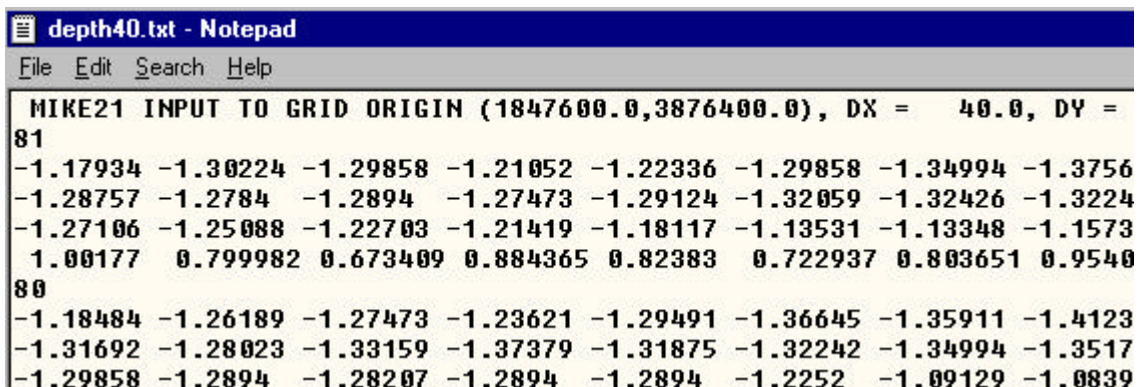
Summary:

1. List all the data in an Excel file. Sort them in order to keep only the ones that are part of the grid (rectangle).
2. Rotate the rectangle of values by multiplying by a matrix
3. Copy the values to MapInfo where the points have to be created, interpolated and then exported thanks to VerticalMapper to a file.

At this stage, the grid spacing was chosen. It has to be at least smaller than 40m because the thinnest passage in the channel is 80m wide, the highest possible to make the courant number decrease. That is why a 40m gridspacing has been chosen

The most important is the file format that mike 21 can read:

**Fig19: Mike 21 file format**



```
MIKE21 INPUT TO GRID ORIGIN (1847600.0,3876400.0), DX = 40.0, DY = 80.0
-1.17934 -1.30224 -1.29858 -1.21052 -1.22336 -1.29858 -1.34994 -1.3756
-1.28757 -1.2784 -1.2894 -1.27473 -1.29124 -1.32059 -1.32426 -1.3224
-1.27106 -1.25088 -1.22703 -1.21419 -1.18117 -1.13531 -1.13348 -1.1573
1.00177 0.799982 0.673409 0.884365 0.82383 0.722937 0.803651 0.9540
-1.18484 -1.26189 -1.27473 -1.23621 -1.29491 -1.36645 -1.35911 -1.4123
-1.31692 -1.28023 -1.33159 -1.37379 -1.31875 -1.32242 -1.34994 -1.3517
-1.29858 -1.2894 -1.28207 -1.2894 -1.2894 -1.2252 -1.09129 -1.0839
```

**e) Extracting the data to Mike 21**

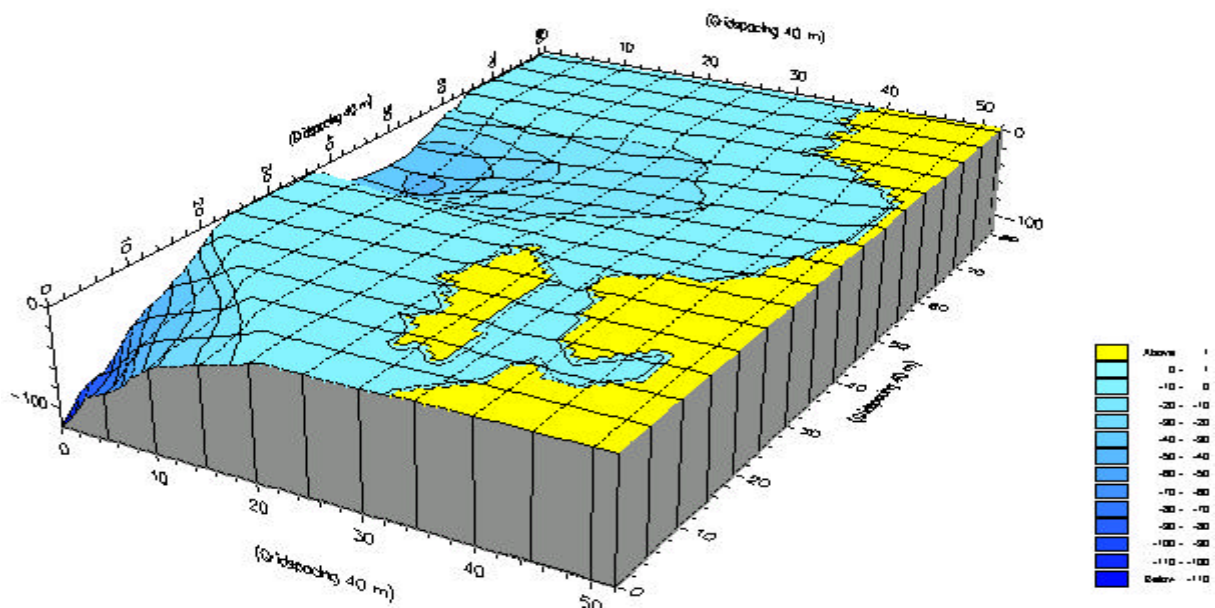
Thus, after having generated an interpolation grid, the next step consists in exporting it into Mike 21 after having converted the grid data into a Mike 21 format using a Fortran program.

**f) Smoothing the bathymetry**

There were still some adjustments to make before any simulation because some depth values were incoherent.

After almost two months of work I got the bathymetry.

**Fig20: final bathymetry**



## **2. Hydrodynamic simulation**

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 the channel with:

- The 12 hours period,
- The change of flux direction,
- Approximately the same amplitudes.

### **a) Time**

The measurements have been taken every ten seconds and during approximately six days for all them. So the simulation period and the time were naturally easy to choose. It is important because with different time steps or periods, some phenomena could have been missed.

But at the beginning, the simulated plot is too far from the measurement that there is no need to wait for a long computation. Then I chose a simulation period of one day.

The simulation period is from the 12<sup>th</sup> to the 18<sup>th</sup> of May 1999.

This produces a courant number of 8, which is a good indicator for model stability. Several hours have been necessary to complete the simulation.

### **b) Initial elevation**

At the beginning of the simulation, the tide is not at the mean level. So the initial elevation had to be found not to abort the computation.

By editing the type 0 file of the admiralty tide, the initial surface elevation was given as the same value as the surface elevation at the open boundary, i.e. 0.21m

### **c) 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 solutions is to removing the dry zones from the computational domain or “moving boundary technique”

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 to say 0.2 m for the drying depth and 0.3 m for the flooding depth fits perfectly to the situation.

### **d) 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.

### **e) Wind**

Like the eddy viscosity, there is no wind measurement available. Actually, there are only those listed in chapter II but it is not accurate enough because Natadola is such a windy area. During the one-week survey, the wind was blowing particularly strongly. Without any idea of the speed, it was noticed that the direction was almost always the same that is to say from south east like most of the time the trade winds in Fiji: according to the requirements of Mike 21 the direction has been fixed to 140 degrees.

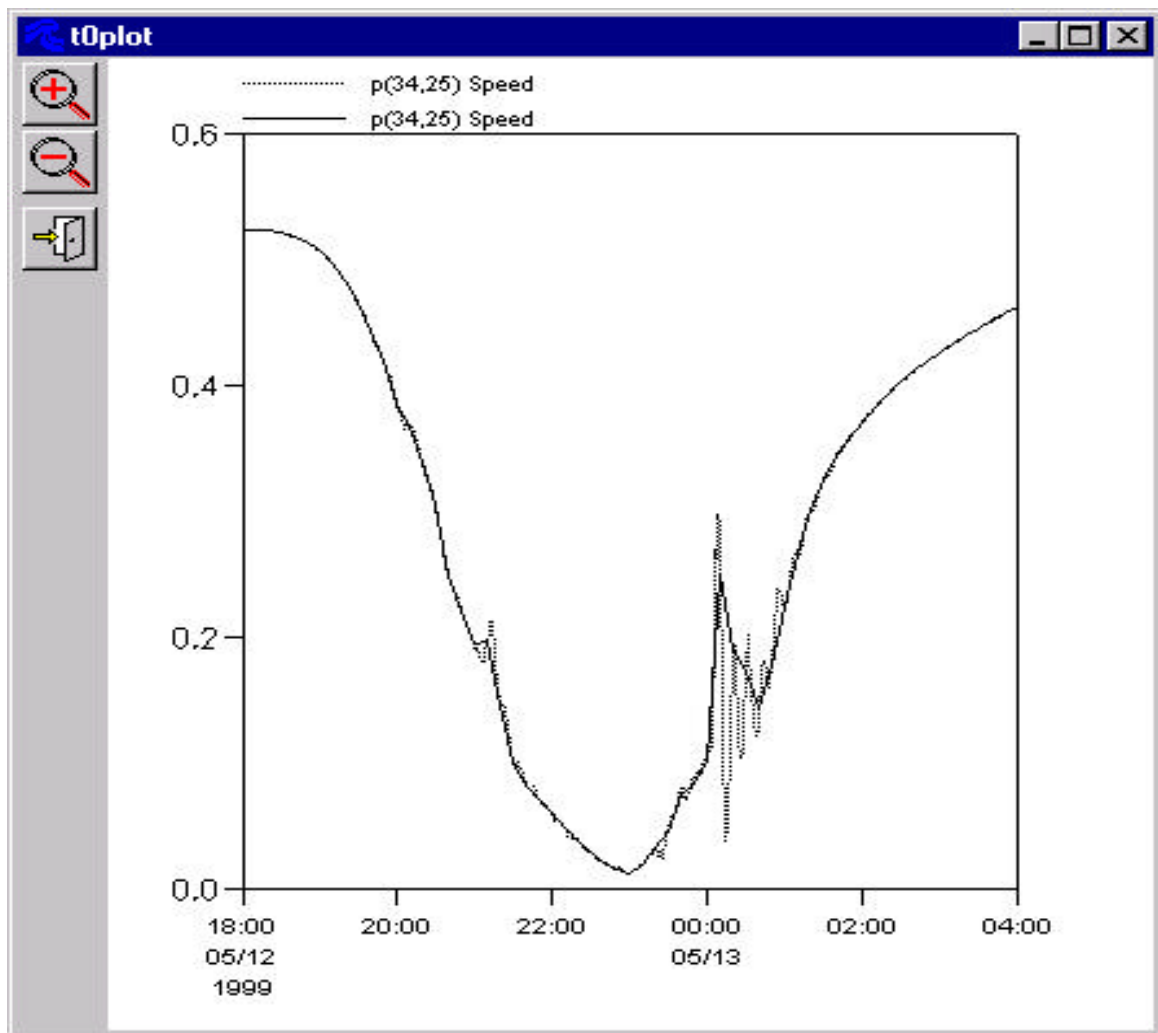
Then, the right speed had to be found by making it vary until finding the right plot.

These weather conditions made the measurements difficult but, except for extreme conditions, the simulations give a better idea of the risks of building a marina.

### 3. Plots and analyses

#### a) Importance of time frequency in output specifications

**Fig21: time frequency influence**

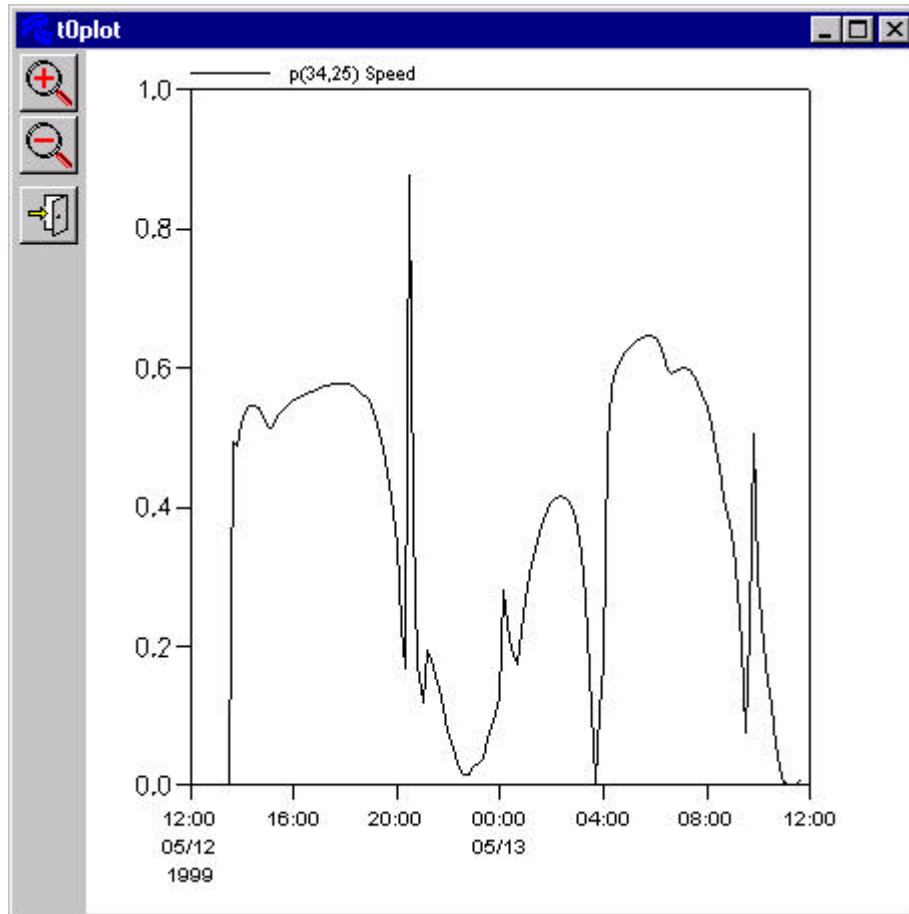


On this plot, we can notice the instability at low tide. Many changes appear at low tide because the flux is changing from direction. But they appear only on the plot with one measurement every minute. The ten-minute plot is not accurate enough at this period. Otherwise a computation every minute is not worth.

**b) Viscosity and wind**

- There must not be too high amplitude between the value of the viscosity (in  $\text{m}^2/\text{s}$ ) and the wind (in  $\text{m/s}$ ). The following example is the result of the computation with 21 for the viscosity and 32 for the wind speed.

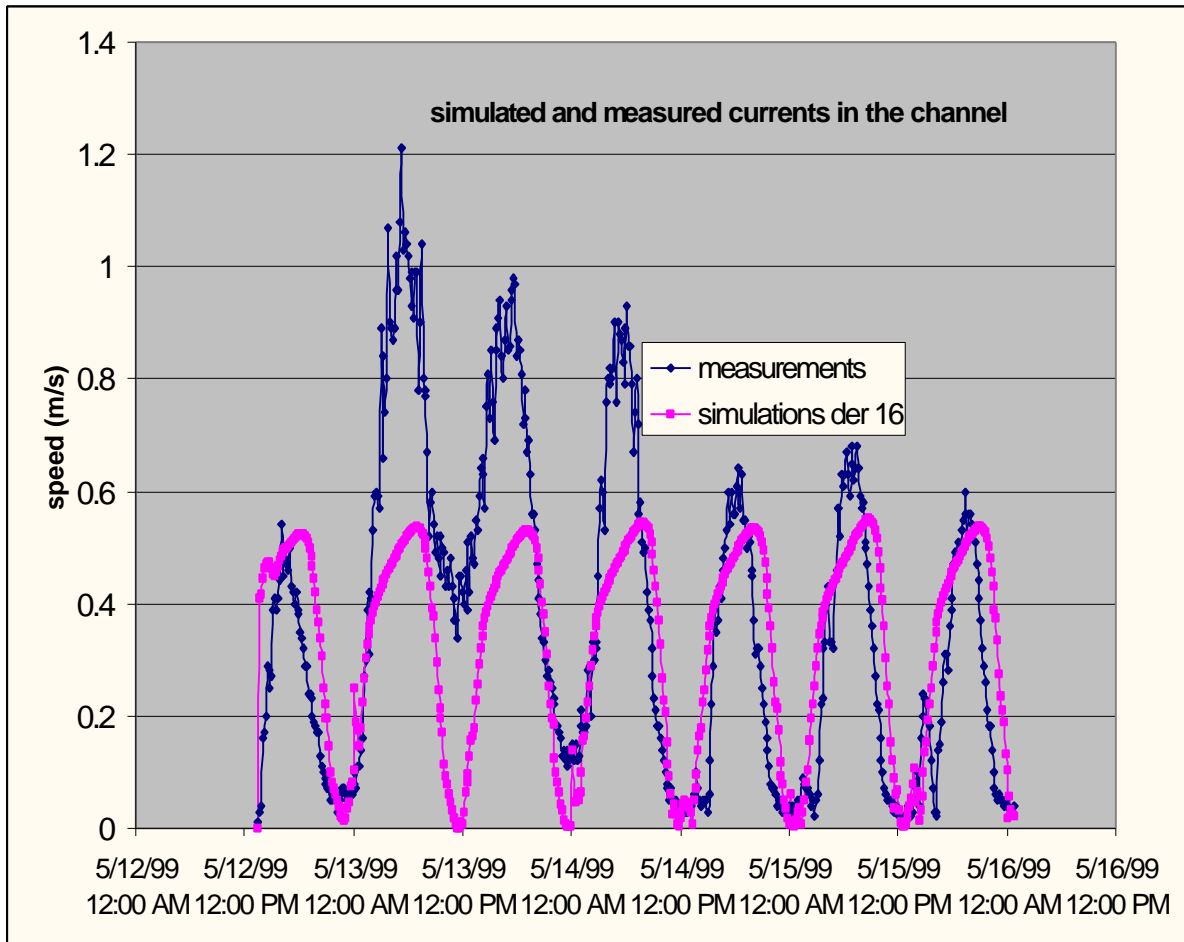
**Fig22: instability due to too high amplitude between the values of viscosity and wind**



- The higher the wind speed is, the faster the current, which is logical.
- The higher the viscosity is, the faster the current.
- It is not possible to increase the values of both until having the right plot because at one stage the reorientation of the flux is not observed any more. Then the maximum of amplitude accessible is 0.54 whereas the measurements in the field can reach 0.6.

## c) Right computation

Fig23: simulated and measured currents in the channel

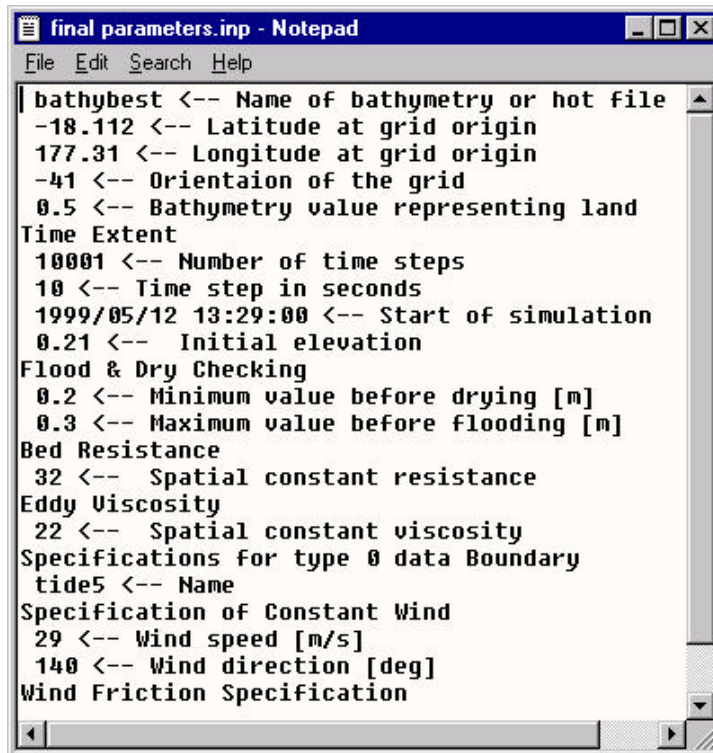


The plots have globally the same trend line except during two days. That can be explained by the very strong wind that has blown at this time of the one-week survey and the storm surge that happened only several days before in the area of Sigatoka. The lack of recording stops from assessing so. Otherwise, the wind was blowing approximately in the same way during the rest of the week that is to say around with the speed of 29 m/s and coming from 140 degrees according to the simulation.



The following figure lists the parameters used for the final computation.

**Fig24: list of parameters of the simulation der16**



```
final parameters.inp - Notepad
File Edit Search Help
| bathybest <-- Name of bathymetry or hot file
-18.112 <-- Latitude at grid origin
177.31 <-- Longitude at grid origin
-41 <-- Orientation of the grid
0.5 <-- Bathymetry value representing land
Time Extent
10001 <-- Number of time steps
10 <-- Time step in seconds
1999/05/12 13:29:00 <-- Start of simulation
0.21 <-- Initial elevation
Flood & Dry Checking
0.2 <-- Minimum value before drying [m]
0.3 <-- Maximum value before flooding [m]
Bed Resistance
32 <-- Spatial constant resistance
Eddy Viscosity
22 <-- Spatial constant viscosity
Specifications for type 0 data Boundary
tide5 <-- Name
Specification of Constant Wind
29 <-- Wind speed [m/s]
140 <-- Wind direction [deg]
Wind Friction Specification
```

#### **d) Evapotranspiration and rainfalls**

Seeing that the evaporation and rainfall rates are almost the same in May, it has not been computed. That was interesting to compare with the results of October when there is a maximum of evaporation ( $5.9\text{E-}8$  m/s and only  $3.7\text{E-}8$  m/s of rainfall) and March when there is a maximum of rainfall ( $13.6\text{E-}8$  m/s and only  $5.3$  m/s of evaporation). But there is no effect on the simulation even in both extreme situations.

### *C. With the marina*

Unfortunately, no detailed design is provided on expected vessel size or channel dimensions, therefore simulation and comments are limited to general issues and potential impacts.

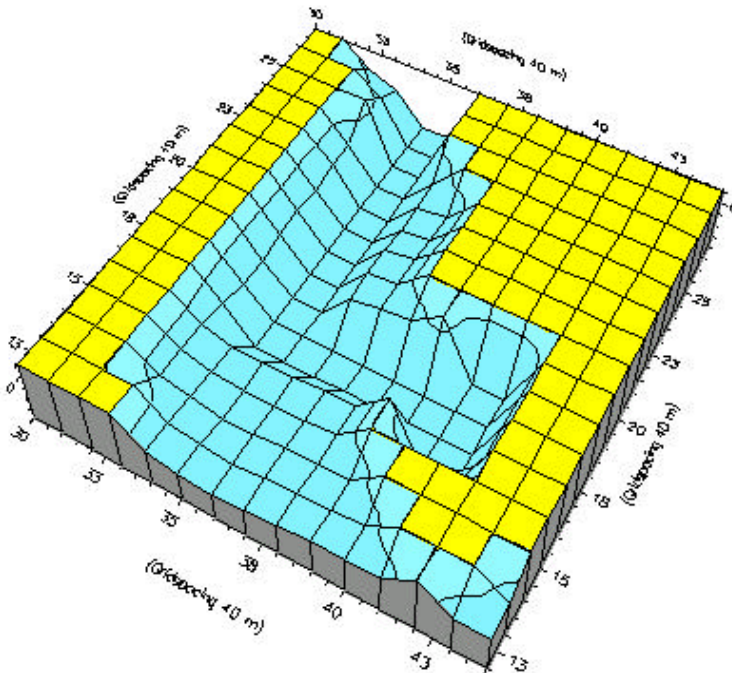
But, assuming a design vessel to be a yacht with a length of between 9 m and 15 m, the minimum water depth for these vessels is 2.7 m and 4.0 m respectively with 12-m yachts requiring a water depth of 3.3 m.

Based on existing marinas it is likely that the width of the access channel should be around 25 m (approximately five times the width of a 15-m vessel).

Should dredging through coral rock be a sound option, blasting may be required. In this instance a “box cut” section would be possible, although for ease of navigation a wider channel may be required. If dredging through sand side slopes is required, the angle of the slopes would depend on the grain size of the sediment but typically would be in the order of 6(H): 1(V).

#### **1. Bathymetry**

**Fig25: bathymetry with the marina and the dredged channel**



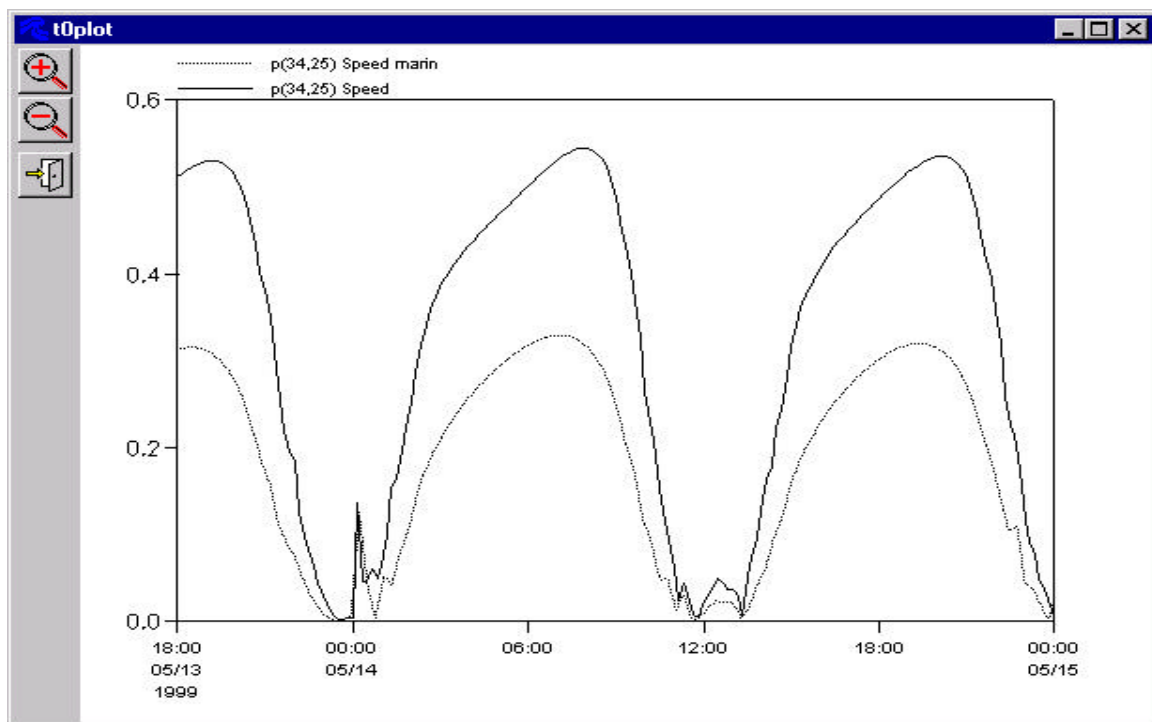
The channel and the marina have been virtually four meters deep as it is shown on fig3. As it is said at the beginning of the report, the purpose of the dredging is enabling two twelve-meter yachts to pass each other.

With a 40-meter gridspacing, the channel could be dredged with a width of either 40 meters or 80 meters. With no other information, the second choice has been chosen. But the bathymetry is very easy to modify with respect of the mike 21 guide.

## 2. Results

If after the construction of the marina, a current meter were placed at the same place in the channel where we put it in May (position 34-25 in the grid), the plots could become the following ones:

**Fig26: comparison of the current at the passage with or without dredged channel**



The dotted line corresponds to the simulation with the marina and the dredged channel. We can see that in any direction, the speed of the current is always lower. There is still this period at low tide when the flux enters the channel.

It is easy to notice that the flow rate entering the bay is staying approximately constant with or without marina:

$$\text{speed}_{\text{marina}} * \text{horizontal surface} * \text{depth}_{\text{marina}} = \text{speed}_{\text{normal}} * \text{horizontal surface} * \text{depth}_{\text{normal}}$$

Indeed,

$$\text{speed}_{\text{marina}} / \text{speed}_{\text{normal}} = \text{depth}_{\text{normal}} / \text{depth}_{\text{marina}} = 2.15 / 4 = 0.54 = \text{trend line}$$

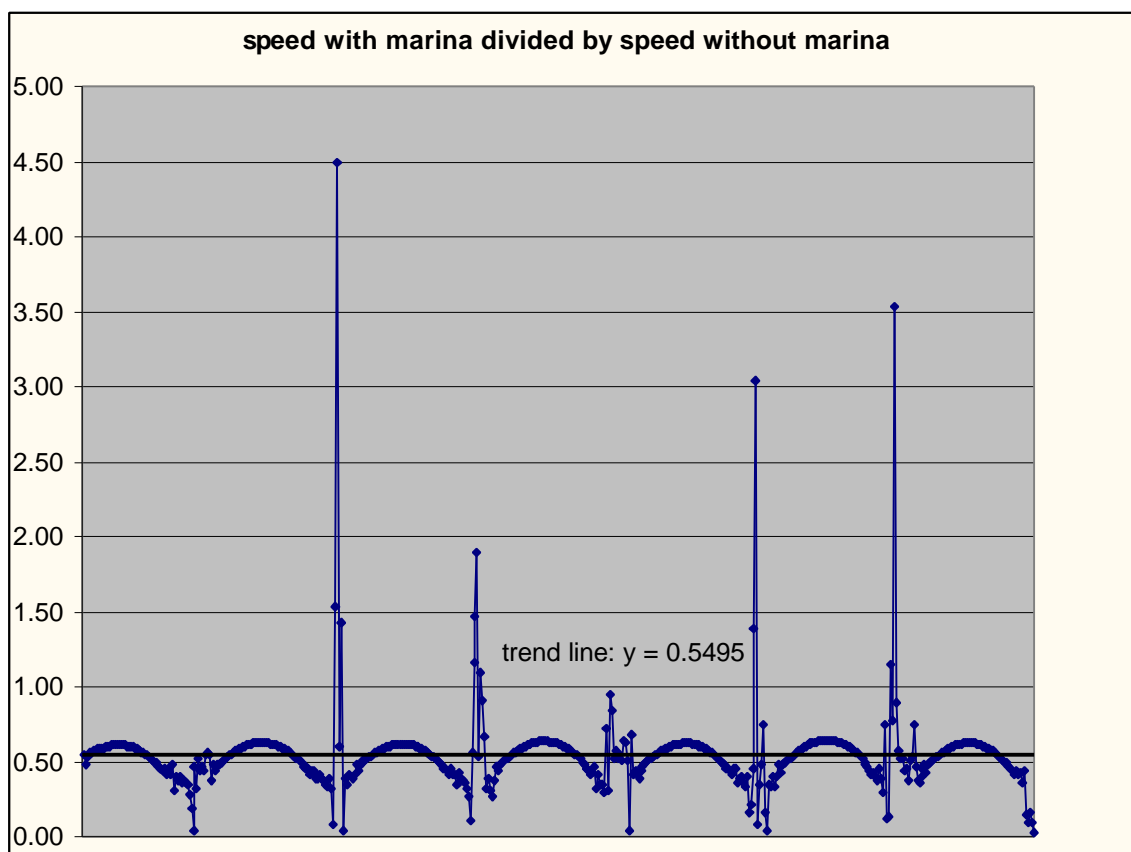
Actually:

$$\text{depth}_{\text{normal}} = \text{depth}_{\text{average}} + \text{tide elevation} = \text{depth}_{\text{average}} + \sum \text{amplitude} * \sin(\omega * t + \theta)$$

$$\text{depth}_{\text{marina}} = \text{depth}_{\text{average}} + \text{tide elevation} = \text{depth}_{\text{average}} + \sum \text{amplitude} * \sin(\omega * t + \theta)$$

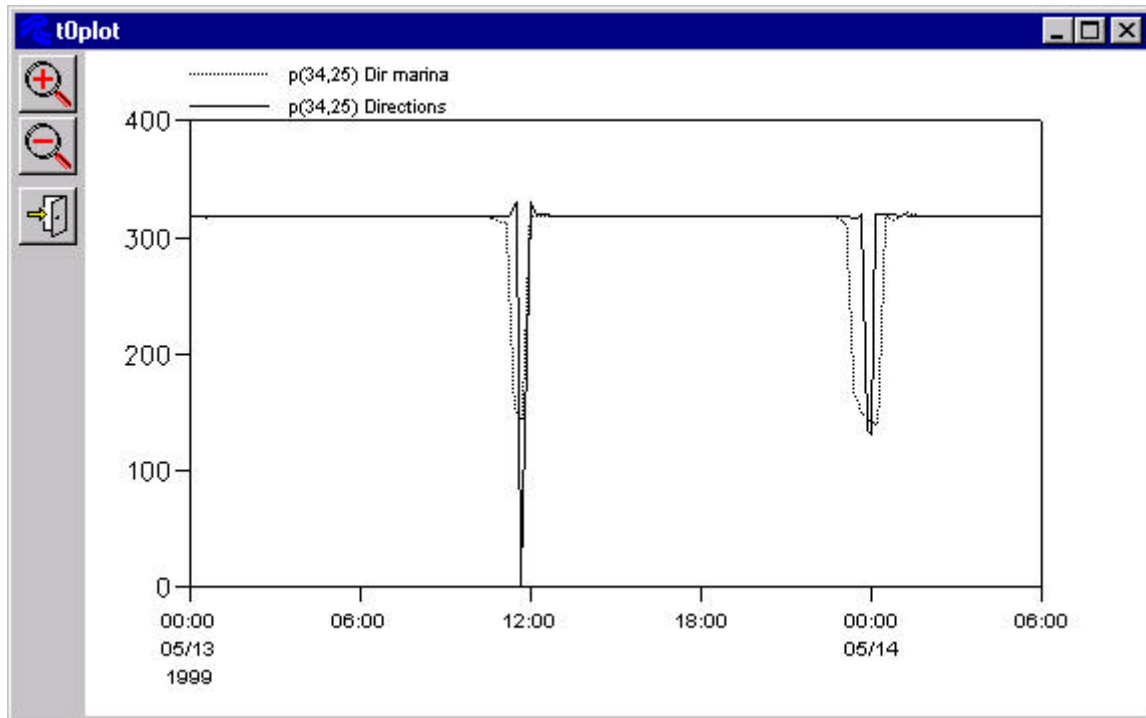
, Hence the periodicity of the plot.

**Fig27: factor between the speeds of current with or without marina**



But it has to be noticed that the period while the flux is entering the bay that is to say at the level of the peaks is longer with the new marina.

**Fig28: direction of the current with or without marina**

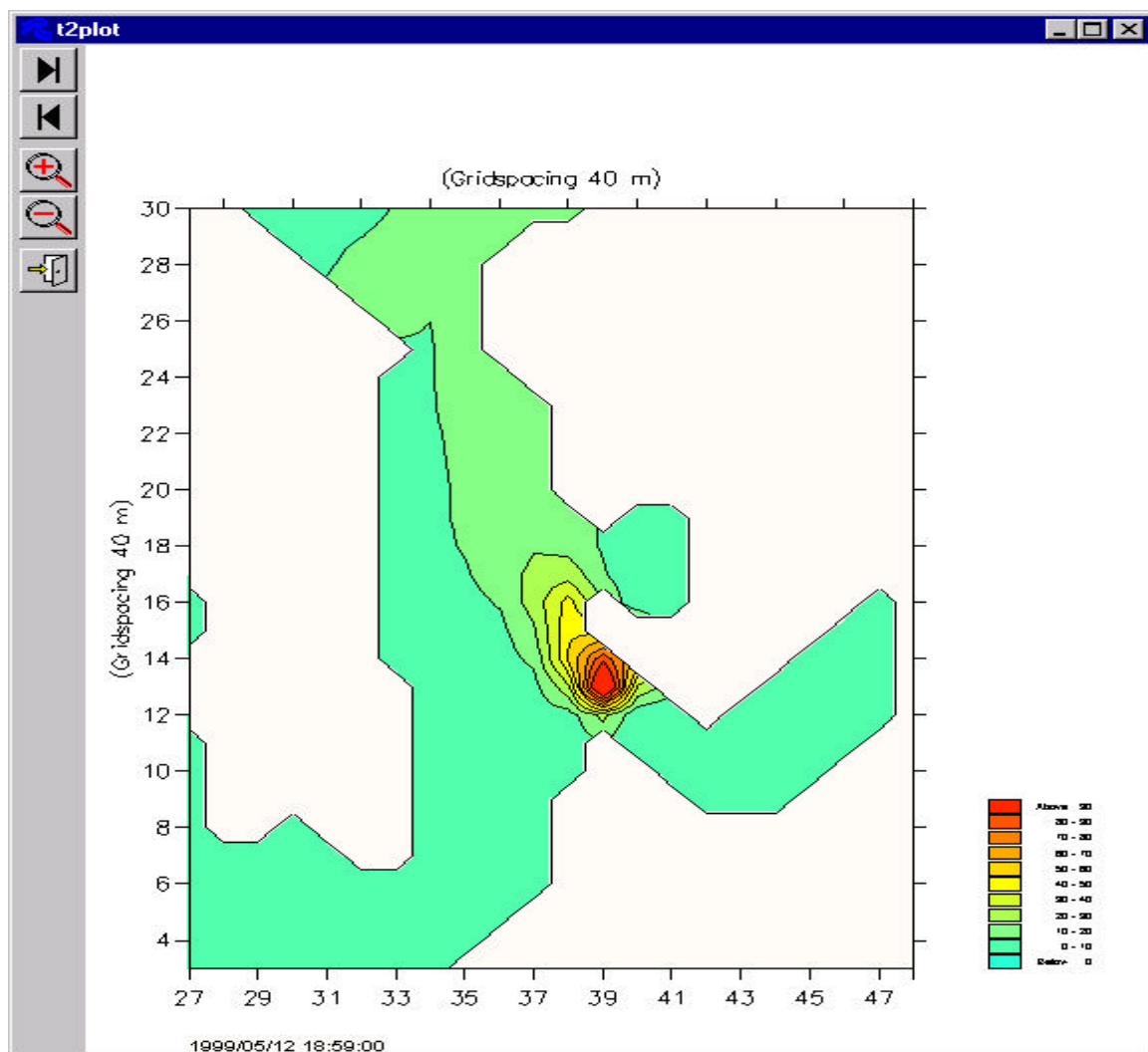


### D. Mud transport simulation

Seeing that there is a swamp behind the village, it was very interesting to know where the mud could travel. The marina would not apparently change anything but that could be the case of the dredged channel.

That for, a mud transport simulation was run. The concentration at the entry of the swamp is 100 kg/cm<sup>3</sup>. The following picture shows how the mud spreads between the channel and the main land. After six hours we can see that almost no mud can be found in the marina.

**Fig29: mud spreading in the passage after six hours**



### *E. Software assessment*

This software is very unfriendly for many reasons. The most tricky one is the definition of the terms: especially for the time, the same specification can be named two or three times differently.

The equation number 51 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 Natadola it is very acceptable because even if the maximal depth is 120m, this area of the grid is not very important because over the reef.

The issue is more a question of courant number. To avoid instabilities, the courant number has to be the lowest possible that is to say the gridspacing ( $\Delta x$ ) the highest. As a consequence the gridspacing could not be lower than 40 meters. But Natadola has very short passages. At these spots, the current speed is given for  $40 \times 40 = m^2$ !

## IV. Recommendations

Seeing that no detailed design is provided on expected vessel size or channel dimensions, further simulations has to be carried out. But there is only to modify the bathymetry according to the project plan and then make the simulations run with exactly the same parameters listed before.

How will the environmental impacts of each phase be monitored? The simulation can be run for each phase of the construction to decide what to build first among the bridge, the marina or the dredging.

The marina seems to be feasible with the dimensions supposed before. It has to be checked but apparently other dimensions would not change the results of the survey.

Further simulations based on the ones detailed in this report must yet be run before building anything in Natadola Harbor. Indeed, a review of all processes has to be carried out:

1. A seiching (own oscillations) study has to be done because Natadola Harbor has such a regular shape in which some wavelengths could propagate.
2. No waves data are available but a simulation of the impact of the waves is necessary.
3. An analysis of the sediment transport characteristics is compulsory because the beach can be damaged.

To that purpose, local weather data are essential. For instance, the wind is particularly strong there; the closest station where the tide characteristics are known is at least one hundred kilometers away.



CONCLUSION
------------

A hydrodynamic model has been set up through Mike 21. It is covering the area of Natadola Harbor with a 40-meter gridspacing. It has been calibrated with the speed and the direction of the current in the channel. The corresponding plots correlate well with the measurements in the field.

An unexpected phenomenon has been identified at the level of the passage: if it was thought that the flux comes always from the channel to the bay, it has been noticed and then checked with the simulation that there is a current entering the channel at low tide.

And it does not seem to be damaging for the marina. Even if there is still no detailed design available for the marina and the dredged channel, no coastal process seems to be endangered by the new project. A mud transport simulation shows that even the mud from the swamp behind the village would not invade the marina.

Being in charge of this hydrodynamic part of the environmental impact assessment was such a great pleasure. Especially in the field in Natadola, coastal engineering is a beautiful work.

