Application of Mathematical Modelling in Coastal Engineering Investigations

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Abstract

Application of mathematical modelling in Coastal Engineering Investigations is discussed referring to examples from recently concluded studies in Sri Lanka. The paper demonstrates how well proven mathematical models in Coastal Engineering, such as, MIKE 21 and LITPACK, could be successfully applied to reproduce the natural conditions and altered conditions due to various man-made implementations in the coastal environment. The paper identifies various phenomena of interest to the Coastal Engineer, such as, wave propagation, hydrodynamics, sediment transport and advection-dispersion. The important processes to be considered in modelling these phenomena are also discussed. The selection of appropriate mathematical modelling tools, setting up of a model, and model calibration and verification processes are outlined.

The reliability of results produced by a mathematical model will increase to the extent to which it is verified against field measurements. Field data are also required in the setting up of models and establishing model boundary conditions. The field data often required in coastal engineering applications include, bathymetry, coastline geometry, wave data, current data, water levels, and sediment and water quality parameters. These data requirements in terms of details and coverage are also discussed.

Introduction

Coastal Engineering investigations are an essential prerequisite in projects which will lead to alteration of existing conditions within the coastal environment. Such projects may include implementation of a harbour, implementation of a coast protection scheme or construction of an outfall structure for effluent disposal. The coastal engineering investigations required in this connection should essentially concentrate on two main aspects: establishment of existing conditions within the project environment; and prediction of impacts due to proposed changes within the environment.

The methodology adopted in a particular coastal engineering investigation may involve exclusively either mathematical modelling or physical modelling or desk calculations or an appropriate combination of all these three approaches. Out of these investigation approaches, mathematical modelling has become increasingly popular over the last decade or so. The main reasons for this can be attributed to the advances made in theoretical description of physical processes, evolution of efficient numerical solution techniques and, most importantly, the development of high speed computers that can handle a large volume of numerical calculations at an unbelievably quick time. Today, more and more well proven mathematical models are becoming available to practicing coastal engineers as computer software packages with user-friendly interfaces.

Prior to the advances made in mathematical modelling, physical modelling was the only available choice in the investigation of complex coastal engineering problems. The main advantages of mathematical models over physical models are the ease and convenience with which structure layouts and bathymetric changes can be incorporated, the possibility of preserving different model set ups used for studying various solution options for future re-use and the absence of scale effects. These advantages make mathematical models highly versatile tools in coastal engineering applications. Any disadvantages in mathematical models arise out of the simplification of physical processes in the theoretical description and numerical discretisation and the inability to provide the user with a physical visualisation of the processes. However, the rapid advances made in theoretical developments and numerical solution techniques, and the ever increasing capability of software packages in providing real-time animations have gone a long way towards nullifying these disadvantages.

The establishment of natural conditions within a particular coastal environment often requires acquisition of various forms of data such as waves, currents, sea bed topographical data (bathymetry), etc. A sound interpretation of these data using good technical judgment will be necessary in establishing existing conditions. The conditions within a coastal environment may vary throughout the year due to varying influence of oceanographic factors such as tides, waves and currents, and meteorological factors such as wind and temperature. However, it is physically not possible to acquire relevant data covering a wide range of sea states. This is where properly set-up mathematical models become useful in establishing natural conditions under different simulation scenarios. Prior to applying a mathematical model it is necessary to verify the validity of its computations using field recordings. This process is known as the "model calibration". A well calibrated mathematical model can then be applied to predict altered conditions due to any man-made implementations.

Modelling Considerations

The primary consideration in a mathematical model application is the identification of physical phenomena of interest. Among the physical phenomena of interest to the coastal engineer are wave dynamics, tidal circulations, storm surges, sediment transport and advection-dispersion processes. The recognition of important processes will lead to the selection of appropriate modelling tools which can be used to simulate these processes. In this paper, the selection of appropriate mathematical modelling tools is described by making references to computational modules available within MIKE 21, two dimensional mathematical modelling system. MIKE 21, developed at Danish Hydraulic Institute (DHI), Denmark is a highly versatile software package, with a wide range of applications in coastal and estuarine waters. Lanka Hydraulic Institute Ltd. (LHI) has successfully applied MIKE 21 in a number of projects carried out locally and overseas.

Having selected the appropriate modelling tools for simulating different phenomena of interest, the model that will be set up need to be first validated against field recordings. It is not possible to generalize the data requirements for a model validation. However, some guidelines on typical data requirements are identified and presented in Table 1.

Coastal Engineering Phenomena Being Investigated	**Typical Data Requirements for Model Set up and Validation**
Hydrodynamics	Bathymetric data Water Level Recordings : At model boundaries to establish boundary conditions (Alternatively, model boundaries may be located in the vicinity of stations with established tidal information). Within the model for calibration and verification. Typically should cover few spring-neap-spring tidal cycles. Current Data: Two dimensional currents recorded continuously over few spring-neap-spring tidal cycles. Drogue trackings to ascertain nearshore current patterns. Wind Data: Wind speed and direction simultaneously recorded with current and water level data. Wind statistics established from long term recordings. River Flows: Measurements taken across a flood-ebb tidal cycle, at spring/neap tide and at low/flood discharges in the river.
Wave propagation	Bathymetric data Offshore Wave Recordings: A large enough data base (typically few years) to establish representative wave statistics Nearshore Wave Data: over a very short duration to validate model computations
Sediment Transport	Bathymetric, Hydrodynamic and Wave Data Bed Sediment Characteristics: mean grain size, gradation, specific gravity, calcium content determined for a sufficient number of representative samples. Suspended Sediment Characteristics: Sediment concentration measurements over the water column.
Water Quality	Ambient Water Quality Parameters: A sufficient number of samples to ascertain parameters, such as, temperature, salinity, dissolved oxygen, BOD, COD, pH, nutrients (NO_2, NO_3, etc.), bacteria etc. Water Quality Characteristics of Effluent.

Table 1. Typical Data Requirements of Mathematical Models Used for Coastal Engineering Applications

Hydrodynamic Modelling

Hydrodynamic modelling is carried out basically to establish water surface elevations and velocity fields within the area of interest under different simulation scenarios. These simulation scenarios typically consist of different combinations of tidal forcing, wind fields, wave incidences, outfall/intake and river discharges.

The hydrodynamics within the continental shelf off the Sri Lankan coast is typically characterised by weak tidal flows with flow velocities in general less than 0.1 m/s. At times strong intermittent wind influences may enhance velocities beyond 0.25 m/s. The tidal range along the coast is also marginal with about 0.7 m during spring tide and 0.15 m during neap tide. In the very shallow seas close to the beach, strong shore parallel currents due to breaking waves with an angular approach may be generated. These currents are responsible for longshore transport of sediments and are commonly known as "littoral currents". The peak littoral currents are, in general, in the range 1.0 m/s. The existence of nearshore reefs detached from the coastline, at certain localities may give rise to strong currents due to overtopping water masses. Such currents around 0.7 m/s have been measured behind a nearshore reef at Dikkowita about 6 km north of Colombo.

A MIKE 21 based hydrodynamic model covering most of the west coast of Sri Lanka has been developed by LHI, which has been used as the primary basis for establishing local flow fields within any desired location (Fig.1). This model commonly known as the "West Coast Regional Hydrodynamic Model" extends from Galle in the south and beyond Kalpitiya in the north. This model has been well calibrated for tidal flows (Fig. 2) and to a lesser extent for wind driven flows (Ref. /1/). For the purpose of establishing representative tidal boundary conditions, a detailed analysis of tidal wave propagation pattern within the west coast was made.

The coastal engineering projects in which local flow fields were derived from the above mentioned "Regional Model" include, a feasibility study for a proposed industrial fishery harbour, north of Colombo at Dikkowita, a hydraulic study for layout optimization of an outfall improvement structure for the Dehiwala Canal and cooling water dispersion study for a proposed coal power plant at Kalpitiya. On site current, water level and wind recordings made during these studies as well as in previous studies were useful in improving the model calibration. Another hydrodynamic model covering part of the east coast has also been developed by LHI in connection with a proposed harbour at Oluvil.

In Fig. 3, a particular site specific application of hydrodynamic modelling at Dikkowita is shown (Ref. /1/). The area around Dikkowita is protected by two sandstone reefal systems. The outer reef, known as the *"Offshore Reef"*, exists about 1 km from the coast and is submerged at 2.5 to 3 m below mean sea level (MSL). The innermost of these two reefal systems, commonly known as the *"Secondary Reef"*, has got detached from its general existence along the coast over a certain stretch fronting Dikkowita. The maximum distance from the coast to this reef around Dikkowita is about 200m . The reef itself is variable in level consisting of exposed segments and submerged segments as much as 4 m below MSL. In the particular application shown in Fig. 3, wave overtopping currents behind the secondary reef are successfully simulated using an artificial combination of point sources and sinks. In mathematical modelling, such artificial implements are necessary when simulating complex processes.

Wave Propagation Modelling

Wave propagation modelling in the open ocean is carried out to establish nearshore wave fields for design of breakwater structures to withstand wave loads, to establish wave induced radiation stress fields for computing littoral currents and, in turn, sediment transport, and wave agitation within proposed harbour basin layouts. An essential prerequisite for wave propagation modelling is the establishment of directional wave field representative for the study area at a reasonable distance away from the coast. Such wave statistics are available from measurements and wave studies for a more or less continuous coastal stretch along the south western coast (Ref. /2/). Due to their predominantly different characteristics, it is necessary to obtain wave statistics in terms of sea and swell wave systems. Sea waves are those being developed locally under a wind field. Swell waves originate in the deep southern Indian Ocean off Sri Lanka, and have already travelled out of the generating fetches in reaching the Sri Lankan coasts.

Fig. 4 illustrates the propagation pattern of the pre-estimated 100 year return period wave at Dikkowita using a combination of MIKE 21's NSW (Nearshore Spectral Wave) and PMS (Parabolic Mild Slope) wave modules. Both these wave modules are based on an irregular, directional description of wave field considering shoaling, refraction, wave breaking and bed friction. The PMS model can additionally account for diffraction effects due to coastal structures and bathymetric features. The attenuation of wave height over the *"Offshore Reef"* and direct penetration of waves through a gap in this reef are clearly seen from this illustration. The MIKE 21 wave module system set up for this study was extensively calibrated using simultaneously recorded waves within and outside the reefal system (Ref. /3/).

Wave Disturbance Modelling

In the planning of a harbour, it is primarily important to ensure that wave conditions within the basin are within acceptable limits for safe loading and unloading of cargo and safe mooring of vessels. In order to determine wave conditions within a harbour basin it is necessary to consider complex influences of transmission, absorption, reflection of wave energy by harbour structures, in addition to other processes considered in wave propagation modelling.

MIKE 21's BW (Boussinesq Wave) model is a versatile tool that can be applied to compute wave heights within a harbour basin due to penetration of irregular directional waves. The model uses the numerical solution of Boussinesq Equations accounting for wave reflection properties of structures, in terms of a "porosity" and so called sponge layers, to absorb wave energy at natural beaches and at undesirable locations. A numerical wave generator may be placed outside the harbour entrance to generate waves. The model computation is supplemented with service programmes available within MIKE 21 for numerical wave generation, wave disturbance coefficient computation (the ratio of simulated and incoming wave heights) and computation of porosity characteristics to simulate a desired reflective property from a structure. MIKE 21 BW model simulated wave heights for the proposed Dikkowita Fishery Harbour layout for a particular wave incidence is shown in Fig. 5 (Ref. /4/).

Sediment Transport Modelling

Sediment Transport modelling is carried out in coastal engineering investigations in the preliminary phase to assist in the establishment of a sediment budget for an area of interest. For this purpose, LHI has successfully applied LITPACK, a one dimensional Coastal Processes Modelling System, also developed at Danish Hydraulic Institute. LITPACK model is capable of computing longshore current, longshore and cross shore sediment transport for a given bathymetric profile. The model usage may be extended for multiple profiles and multiple wave conditions to compute annual or seasonal sediment transport capacity and determine coastline and beach profile changes due to implementation of coastal and harbour structures.

MIKE 21 in itself is possessed of two dimensional sediment transport modules for computing sediment transport fields for pre-established hydrodynamic and wave fields. These computations can be used to obtain an indication of sediment by-pass capacity at a harbour entrance or an outlet stabilisation structure, or to identify eroding and accreting areas.

Advection-Dispersion Modeling

Advection -dispersion of accidentally or intentionally released effluent matter is of particular importance to coastal engineers and enviornmental planners. These effuluent substances could be sewage, heated water, decaying matter such as coliform bacteria, orgain matter (BOD) , dissolved oxygen and non-toxic and toxic metalic substances. The dispersion in the near-field of effluent matter is governed by its own discharge characteristics such as mass, momentum and buoyancy fluxes, geometry and the ambient velocity of the receiving body. In the far-field, once the effluent substance is well diluted over the receiving water body, further dispersion is governed entirely by the ambient flow conditions. In general, there is however a transition region between these two zones of mixing.

Due to different forcing characteristics involved in the dispersion processes, the near-field and far-field modelling is typically carried out independant of each other. The nearfiled computations can be used to develop appropriate effluent discaharge boundary conditions for far-field modelling. In a recent application in a cooling water study for a proposed Coal Power Plant around Kalpitiya, LHI used mathematical modelling to account for both near and far field mixing. The nearfield modelling was carried out using a semi-empirical CORMIX3 model. The far field dispersion was computed using MIKE21's advection-dispersion module, MIKE 21 AD. A typical simulation result is shown in Fig. 6.

Water Quality Modelling

The large scale environmental pollution mainly resulting from industrial development has affected the coastal environment as well. Therefore, water quality modelling is increasingly becoming an attractive option for studying pollution levels in water bodies. To date, LHI has not engaged in complex water quality modelling except for simplified applications using MIKE 21 AD and CORMIX3 models. However, indications are that it will not be long before such model applications are carried out in Sri Lankan coastal waters.

The MIKE 21 model itself is equipped with three environmental modules that may be used for water quality studies. These are the Water Quality Module (WQ), the Eutrophication Module (EU) and the Heavy Metal Module (ME). MIKE 21 WQ, which is particularly applicable for coastal waters is used for advanced water quality studies considering dissolved oxygen (DO), organic matter (BOD), ammonia, nitrate and phosphorous.

Summary and Conclusions

The paper demonstrates how mathematical modelling can be successfully applied to simulate existing conditions and altered conditions due to implementation of various projects in the coastal environment. The main phenomena of interest to coastal engineers are identified and some guidelines on data requirements in modelling such phenomena are given. Selected simulation results from recent applications of MIKE 21 two dimensional mathematical modelling system in Sri Lankan coastal waters are also presented.

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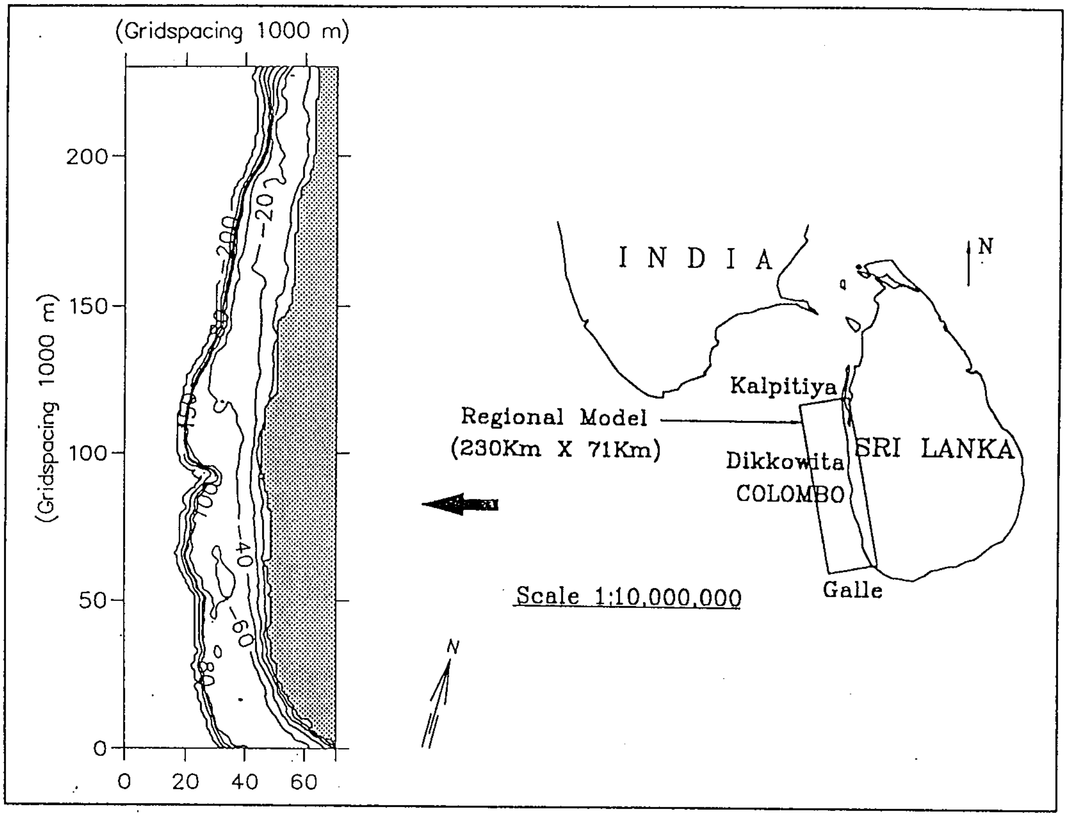

Fig. 1 West Coast Regional Hydrodynamic Model

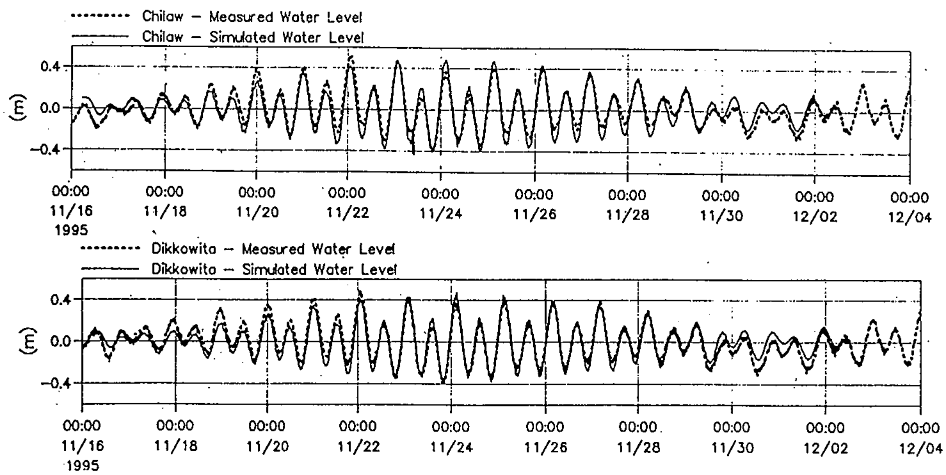

Fig. 2 The Calibration of West Coast Regional Hydrodynamic Model for Tidal Flows

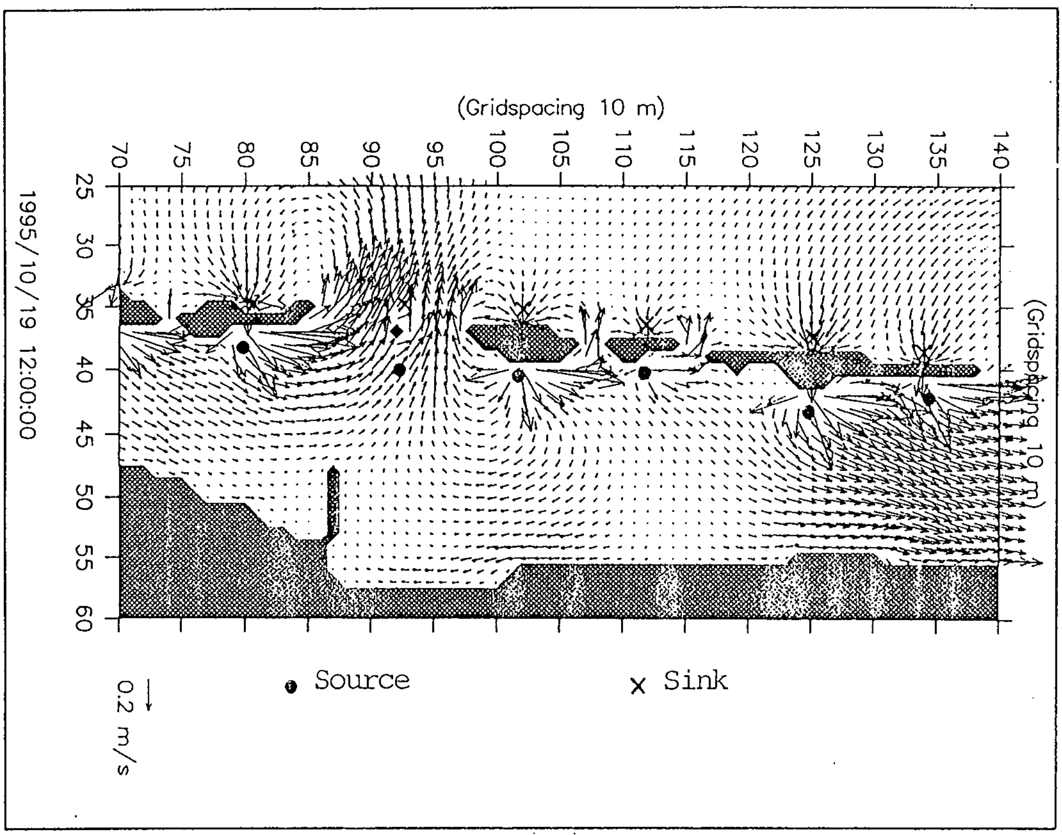

Fig. 3 Simulation of Wave Overtopping Currents Behind the Secondary Reef at Dikkowita

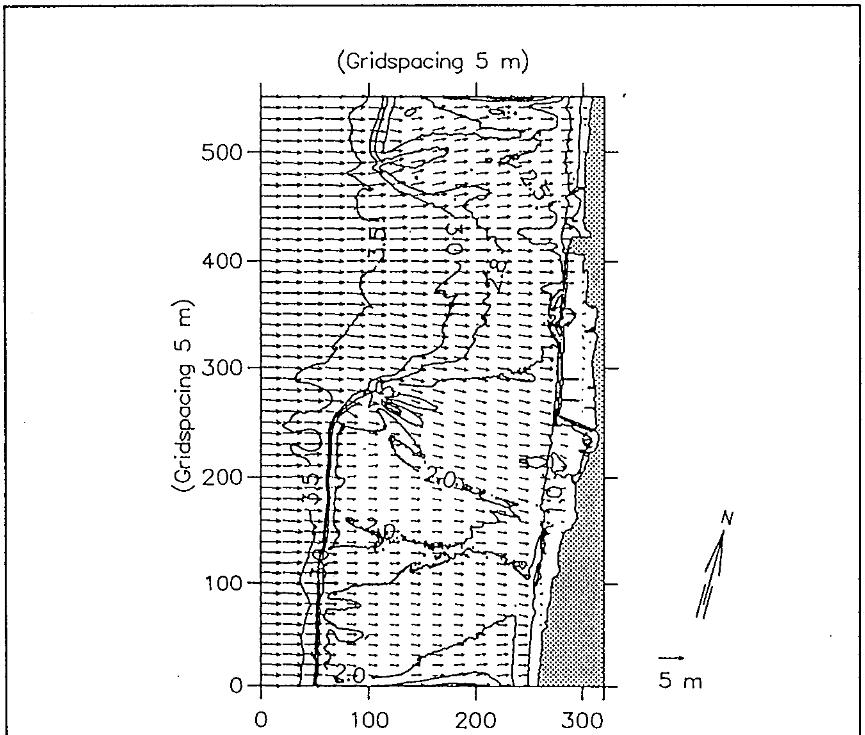

Fig. 4 Simulation of 100 year Return Period Wave at Dikkowita

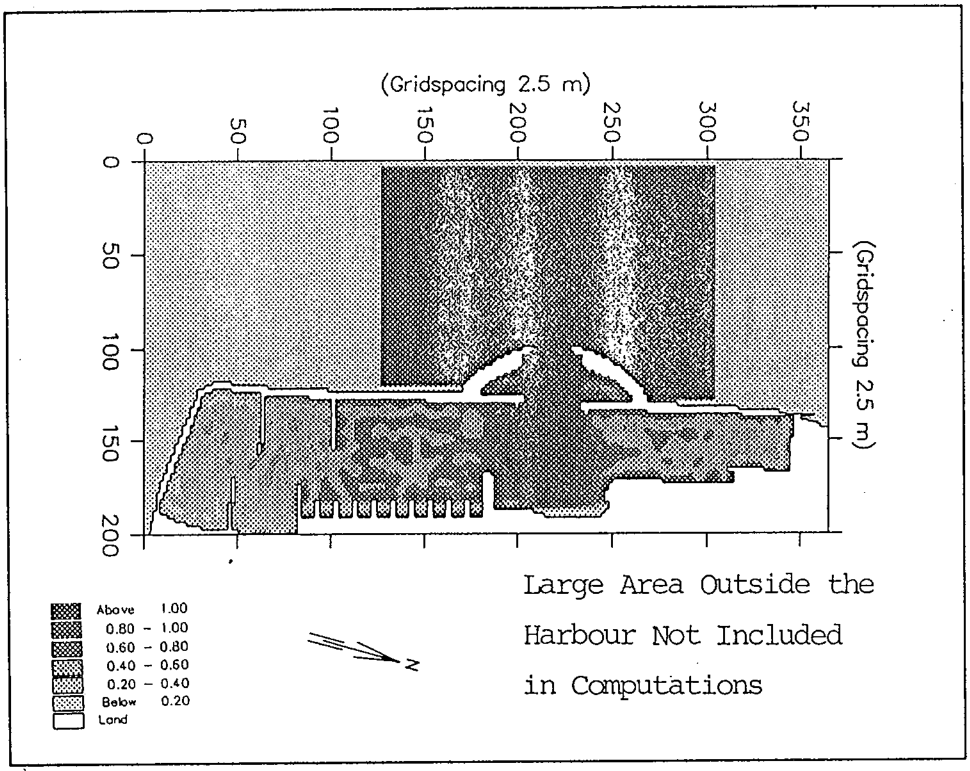

Fig. 5 Simulated Significant Wave Heights Exceeded 1 Week per Year (Proposed Fishery Harbour at Dikkowita)

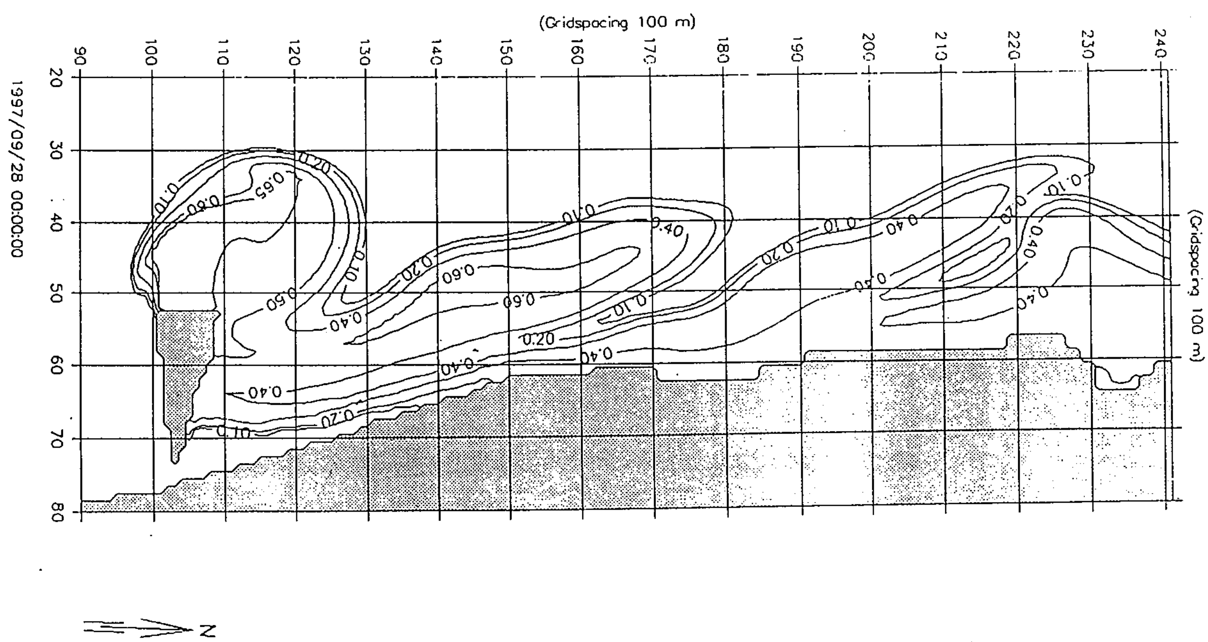

Fig. 6 Simulated Excess Water Temperature Contours (900 MW Power Plant Capacity - Tide + 2 m/s Southern Wind Driven Flow)