FIFTH AUSTRALASIAN CONFERENCE

on

HYDRAULICS AND FLUID MECHANICS

at

University of Canterbury, Christchurch, New Zealand
1974 December 9 to December 13

ON THE DEVELOPMENT AND CALIBRATION OF A LARGE NUMERICAL HYDRODYNAMIC MODEL

by

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SUMMARY

Aspects of the development and calibration of a large two-dimensional hydrodynamic model are described. This numerical model is one of a sequence of models used to simulate water movement and water quality changes in bays and estuaries currently being applied to Westernport Bay near Melbourne.

The development of the model included adapting it to the available computer and modifying it to treat a bay with tidal mud flats. The criteria for selection of model time step and spatial grid size are then discussed. Model calibration is defined and each of the adjustments which may be made to bring model and field measurements into accord are described.

It is concluded that adaptation of one of the available hydrodynamic models to a particular computer and a given bay takes time and involves detailed consideration of both the physical and computational factors.

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1. INTRODUCTION

This paper describes aspects of the development and calibration of a large scale hydrodynamic model. This model forms part of a group of models used to simulate water quality changes in bays and estuaries, currently being applied to Westernport Bay near Melbourne (Figure 1.). These models give a relatively coarse scale representation of the whole bay and adjacent areas of Bass Strait. They have been developed under contract for the Westernport Bay Environmental Study, a multi-disciplinary investigation of the bay and its catchment sponsored by the Victorian Government and industries with an interest in the area. The Westernport Bay Environmental Study will operate the models to compare and evaluate alternative waste disposal schemes and may also test the effects of dredging and reclamation on currents, tides and water quality.

In recent years there has been a surge of interest in mathematical models of rivers estuaries and bays. Most of these models are transport models which require velocity data to be supplied. Hydrodynamic models, in which the velocity field is calculated at each instant from the hydrodynamic equations are less numerous. The hydrodynamic model developed by Leendertse (1967, Fischer 1970) at the Rand Institute has been remarkably sucessful in a number of applications and was chosen as the basis for the hydrodynamic section of our model.

The Leendertse scheme uses a finite difference formulation of depth integrated Navier-Stokes equations. The equations account for coriolis force, wind shear force, bed resistance and convective acceleration in addition to local acceleration. A two-dimensional model was chosen because early measurements had shown that the bay is unstratified with negligible fresh water inflows, while its plan form is complicated leading to highly non-uniform velocity distributions across the channels.

The basic information required as input to the model is:-

(i) Spatial grid intervals (Δs) and time interval (Δt).
(ii) A boundary array whose elements can take one of two values indicating whether the grid points corresponding to the elements are inside (water) or outside (land) the computational field.
(iii) A depth array whose elements contain the water depth at the position of the corresponding grid point.
(iv) Information for the calculation of the bed resistance coefficient.
(v) The latitude, enabling computation of coriolis forces.
(vi) Information allowing the tidal elevation or the velocity at the open water boundary at the bay's mouth to be prescribed.
(vii) Wind velocity data.

The output of the model consists of water levels and velocities at each intersection of the finite difference grid. In its present form the model operates on a 42 x 56 grid with Δs = 1 km. The time step Δt is 1.5 minutes. Using a CDC 6400 computer the ratio of computer time to real time is about 1.60 enabling a simulation of a 12.4 hour tidal cycle in as many minutes. The cost is less than $100 at present commercial rates.

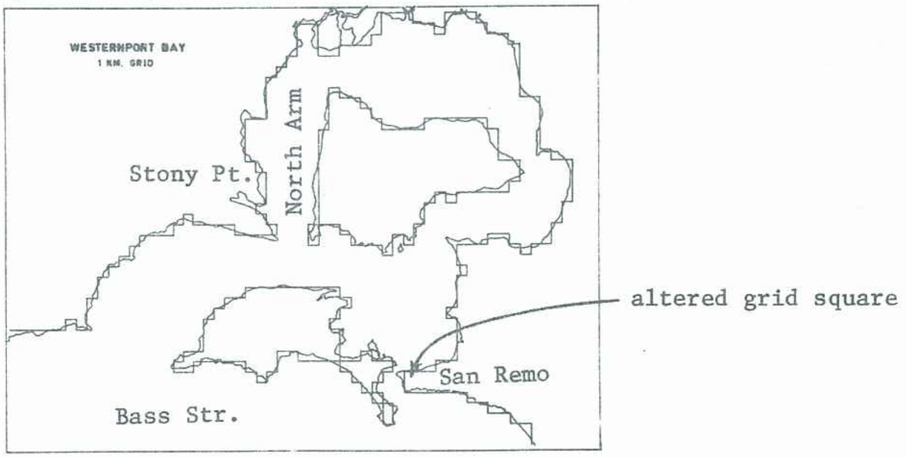

FIG. 1. Westernport Bay

2. DEVELOPMENT

The first page of the development was to take a published version of the model and adapt it to the requirements of the computer and the topography of Westernport Bay. The latter involved deleting a large section containing the diffusion equation since it was to be replaced with an entirely new pollutant transport model. The former requirement was the necessity to zero all arrays - one of the nasty products of non-standard computer control systems. The second stage of development involved the provision of some computational features.

It was decided during early running of the model that a "hotstart" capability would be extremely useful in development and even more so in production running of the model. Since the programme is basically a series of iterations, each of which represents a point in time, it is clear that if all of the information relevant to any one instant is stored, then the model can be "hot-started" from that point. In essence this is what our Hot-start does. Hot-starts are normally made from disc permanent files although the magnetic tape output used for plotting can also be used.

The Hot-start feature provides the user with great flexibility. Not only can the programme be re-started from an intermediate time, but new data can be fed in with the Hot-start. The user can for example, change wind data, tidal data or even depth data, (allowing for dredging); he can adjust print out, plots and so on. The most important feature of the Hotstart, of course, is that it saves a large amount of machine time. Leendertse has pointed out that on average the model takes a full tidal cycle to "settle down" after a dead start. Theoretically, using Hot-start only one dead start need ever be made, all subsequent runs "starting" after 12½ hours.

A second computational feature of the model is that it provides for a "compressed" output to magnetic tape. More than half of the grid points in our 42 x 56 grid are on land so that large amounts of useless data were being recorded prior to the introduction of this option. Two reference arrays, one 42 x 56 and the other 2 x 1050 (where 1050 is the number of wet points) allow a simple mapping of the useful data. Since the subsequent Pollutant Transport and Chemical Kinetics and Interaction Models of our overall model are very heavy users of the computer's central memory, this compression is used whenever output is required for these models.

A large proportion of development time of the Hydrodynamic Model has been spent on the section which simulates the drying and flooding of the mud flats. This simulation is considerably more complex than might be imagined. It required a thorough understanding of the computational structure of the model and the physical processes it simulates. The only literature available on the subject is that of Leendertse and this is very sketchy. Detailed investigations of several alternatives to the scheme outlined by Leendertse have been undertaken but in principle the one selected is quite similar to his.

The most important point within the drying calculation is to ensure that interference with continuity and momentum equations does not occur. Secondly, the representation must be as realistic as possible and the stability of the model must be preserved. The latter two points, "realism" and "stability" require a compromise in terms of detail; a compromise which may not be apparent.

Because the boundary of the field of computation is moving, "noise" is introduced into the nearby computations. Although this is quickly dissipated, it is necessary to ensure that it does not build up during subsequent iterations. We have followed Leendertse's scheme to achieve this condition: a "tight" check on boundaries is used at slightly longer time intervals than the checks used at every iteration, thus ensuring that momentum and continuity are preserved. This means that the majority of boundary movements will occur during the "tight" check. We currently operate this major check every fifth time step. The two checks to ensure that flows do not occur in negative volumes or through negative cross-sections. These checks are carried out at every iteration.

Our checks for flooding follow the same general procedure. Flooding checks occur at the same time interval as the major drying check, i.e. every fifth time step. At the time of writing, movie film of output was not yet available so that a search for the best interval for these checks could not easily be made. A thorough study of output to data has suggested that the five time step interval is satisfactory in that it produces no serious anomalies.

We have also included a heuristic device to shorten computation time. In its general form, the model will carry out these checks on every grid square in the water field regardless of the depth in that square. In our model, prior to undertaking this series of checks, we have included a test for depth. Thus, if a grid square exceeds a pre-set minimum depth, we skip all drying and flooding checks for that square. This precludes a large proportion of the water field from the somewhat length flooding/drying computations.

3. SELECTION OF GRID SIZE AND TIME STEP

The grid size and time step are selected by the user to suit his accuracy and cost requirements, subject to requirements of model stability. Initial runs made by Pollock (1973) used a very coarse 2½ km grid merely to get the model operating. Since many features of the bay are of this order of magnitude, a finer grid was essential to reproduce the dispersion caused by the transverse non-uniformity of velocity. A 1 km grid size has been used in the development work to give adequate reproduction of velocity distribution while enabling the data arrays used in the Hydrodynamic Model to be stored in the central memory of the computer.

Having selected the grid size, the time step cannot exceed a specified value or the model may become numerically unstable and it should not be too small or computation time will become too long and round off and other errors will accumulate. Leendertse has done considerable work on stability analysis of the linear parts of the model and has shown that such a model is unconditionally stable. This work has led to his suggesting the following criterion for selecting time step length, given a particular grid spacing

$$1 \leq \frac{\Delta t}{\Delta s} \sqrt{gh} \leq 2.5$$

where g is the acceleration of gravity and h is the depth. This criterion is based on the accuracy of the speed of long waves as predicted by the model.

For Westernport Bay, with an average depth of 15 metres, this suggests a time step in the range 1.35 minutes to 3.4 minutes for a 1 km grid. All of the early runs were made on a 3 minute time step, following this criterion. To ensure that this choice of time step had no effect on the results, four runs were made, each spanning two full tidal periods, with time steps of 1 minute, 1½ minutes, 3 minutes and 5 minutes. Figure 2 shows a plot of water level against time for a point in the North Arm for each of these runs.

It can be seen that the tidal range is little affected by the choice of time step in the range considered, but the tidal lag increases almost linearly as the time step increases from 1½ through 3 to 5 minutes. The velocity at this and other points also showed little variation of magnitude but some change in phase. Hence for studies of velocities and tide heights, the time step could be made 3 or 5 minutes, but for water quality studies it must be made smaller. This is because the model must reproduce the net circulation around French Island and Phillip Island and any net circulations within the major channels. These contribute significantly to the flushing of the bay despite being only a few percent of the peak tidal currents. For this reason a time step of 1½ minutes has been used in the model development.

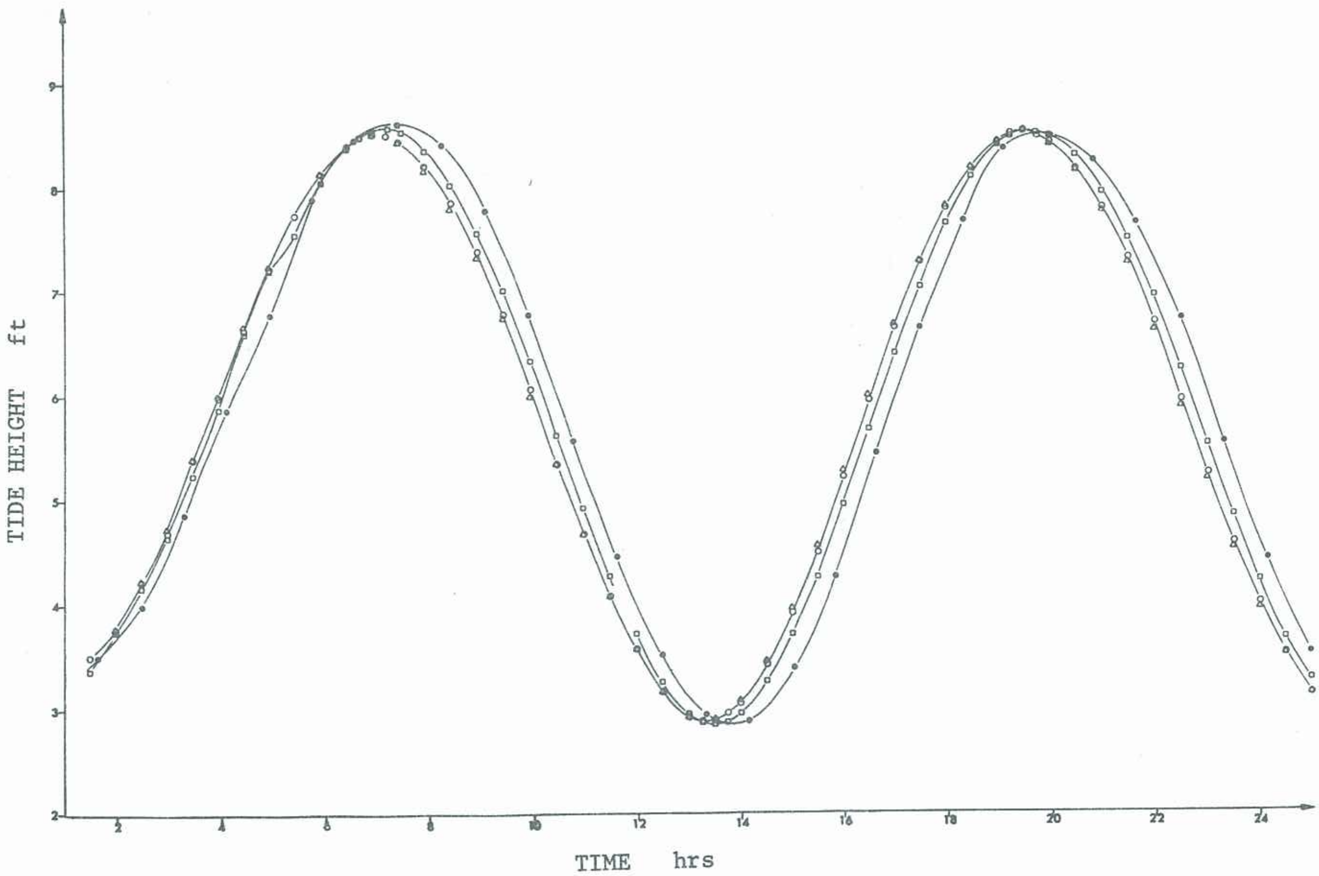

FIG. 2. Tide height of Stony Point as a function of time. Computational time step: . 5 min., 3 min., o 1½ min., Δ 1 min., (not drawn in).

4. CALIBRATION

4.1. General Consierations: Calibration is the process of adjusting the values of parameters used in formulating the model so as to reproduce known events in the model. These events should be related closely to the processes occurring so that the processes as well as their effects, are correctly reproduced. In the Hydrodynamic Model calibration comprises the following steps:

(i) Checking tidal lag and amplitudes against measured data.
(ii) Checking mass transport of water across selected sections against measured data.
(iii) Checking depth-integrated velocity distributions against measured data.
(iv) Checking the computed tide height and velocity fields for unexpected features and possible inconsistencies which are then checked in detail.
(v) Any departures of model and prototype are then checked in detail and if they appear to be due to errors in the model, the model is adjusted by altering the reistance coefficient
(vi) If there is no reason to suspect the resistance coefficient, or if the bottom or shoreline topography is particularly uneven, the depth data may be smoothed so that abrupt

changes in depth do not unduly influence the model results.

The parameters which may be altered are those which are not accurately defined by measurement or which are not reproduced in detail in the model. Data or parameters other than the resistance coefficient and topography may be inexact but should not be seriously in error. In particular the latitude should be known exactly and the use of a constant value over the model demonstrably does not introduce significant errors in the already small coriolis force. The ocean tide was not known exactly and required some adjustment, and the wind stress was not known exactly as a function of wind speed. These factors are now discussed in turn.

4.2 Resistance Coefficient: The model resistance coefficient was initially taken from the Moody diagram for the assumed roughness height of the bed of the bay. The roughness height and hence the resistance coefficient vary with the sediment diameter and the form and size of ripples or dunes on the bed. Direct observation of the bed over a significant part of the bay would be prohibitively expensive and time consuming; hence reasonable assumptions have had to be made. Failure of the model to reproduce the prototype reveals errors in these assumptions. If, following minor adjustments of the resistance coefficients, the model performs correctly for the given data set, it is assumed to be correct.

In order to test the sensitivity of the model to a variation of the resistance coefficient, a run was made in which the above values of the Chezy coefficient for each grid sequence were doubled. The variation in Chezy coefficient produced a substantial amplification of the "normal" tide and a significant reduction of the phase lag at the head of the bay. This tide had amplitudes typically greater than 1.5 and up to 1.8 times the ocean tide, approaching the condition of a frictionless wave for which the ratio is $1/\cos 2\pi t'/T \simeq 1.85$ for Westernport. In this expression $T = 12.4$ hours and t' is the time of travel of an infinitesimal long wave from the sea to the head of the bay.

4.3 Geometry: Westernport Bay contains a number of significant features which cannot be modelled with sufficient accuracy using a 1 km grid. The most important of these is the Eastern Entrance at San Remo which was initially made 1 km wide. The volume flows on flood and ebb are small, but their difference - the net flow - is relatively large. An attempt was made to improve the calculation of net flow by replacing an additional land grid square with one set at the datum level, but as may be seen there was no improvement and other adjustments have had to be made.

	Ebb flow m^3x10^6	Flood flow m^3x10^6	Net flow m^3x10^6
Before adjustment	46.2	42.5	3.7
After adjustment	74.0	68.5	5.5
Field measurement	62.2	36.5	25.7

The mud flat regions of the North Arm of the bay contain a large number of channels of varying magnitude. Of these, only the very largest can be modelled at the 1 km scale and even then, somewhat artifically. This difficulty was recognised at the inception of this modelling application and has been accepted as one of the intrinsic difficulties of a finite difference scheme with limited computer core storage.

4.4 Other Factors: The ocean tide is imposed upon the seaward boundary of the model as a sinusoidally varying water level, equal at all points on the boundary. This boundary condition assumes (i) that there is no longshore slope in the watersurface, and hence that longshore currents are weak, (ii) that there is no tidal variation outside the bay in its neighbourhood, (iii) that the mean sea level is known and (iv) that the tidal amplitude is known outside the bay.

Taking these points in turn, float tests have shown that there are longshore currents but that they are weak.

Assumptions (1) and (ii) are supported by the tidal data for Waratah Bay 85 km east of Flinders in Westernport Bay and Port Phillip Heads 55 km west of Flinders. The phase of the M2 tide for these stations is Waratah Bay 326°, Flinders 326.16°, Port Phillip Heads 328°, showing that the tide is almost exactly in phase at all three stations along the coast.

To satisfy assumptions (iii) and (iv) in the absence of offshore tidal measurements the model was at first run with the ocean tide set equal to the tide at Flinders. It was observed that the mean sea levels differed negligibly and that the tidal amplitude at the ocean boundary was 0.972 of that at Flinders. The model was then operated with the ocean tide set equal to 0.972 of the M2 tide obtained from tide gaugings at Flinders.

At the time of writing comprehensive wind data were not available hence the wind stress-velocity relationships in the literature had to be used without a quantitative check. These relationships are not suspect but local wind patterns and topographic influences might modify the wind and its stress on the water surface. Rather than conduct a field study into the wind stress pattern it is proposed to calibrate the model by adopting the single value of the stress coefficient which gives the best reproduction of tides and currents under strong wind action, assuming the wind to act uniformly over the surface of the bay.

5. RUNNING EXPERIENCE

Since May 1973 the model has been run on an almost daily basis. The bulk of these runs has been developmental but a great deal of information and experience have been gained. The complicated nature of the programme of a two dimensional hydrodynamic model has required newcomers to spend at least 6 weeks in familiarising themselves with its structure, and the development and calibration work described have taken 1½ man years.

When a large number of runs is being made then the "one in a million" computational chance may easily occur. The programme as published does not test whether grid cross-sectional areas are exactly zero - a most unlikely event. Unfortunately in the course of many runs this event did occur and division by zero brings many computers to a sudden halt!

Almost every run is of some value. Early runs were made with the water levels of all grid squares set to high tide level. Following a published suggestion by Leendertse (1972) that low tide starts are preferable because of the lower energy content of the bay, data changes were made. An error was made which resulted in a run being computed with low tide levels on all grid squares within the bay and a high tide level set at the ocean boundary. The results were interesting but as yet no confirmation from field data has been possible. The run did indicate the remarkable stability of the model: after some very large surges back and forth, in the space of about four hours of real time the model had settled down to reasonable behaviour. The surfes travelled at the correct speeds despite the large magnitude, and behaved "reasonably".

6. CONCLUSIONS

While numerical hydrodynamic models for bays of complex planform are available in the literature, the modification and càlibration of a model for a particular bay cannot be done on a "black box" basis. Both the physical and computational aspects of the model must be considered in detail.

The model initially developed by Leendertse has been adapted to Westernport Bay and calibration against field data is close to completion. Simple adjustments to model parameters have enabled the predictions of the model to be brought into agreement with the available field data.

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