3D/2D modelling suite for integral water solutions

DELFT3D

Deltares systems

TRIANA

User Manual

Deltares

Enabling Delta Life

Delft3D-TRIANA

Tidal analysis of FLOW time-series and comparison with observed constants

User Manual

Hydro-Morphodynamics

Version: 3.00
Revision: 78359

19 April 2024

Delft3D-TRIANA, User Manual

Published and printed by:
Deltares
Boussinesqweg 1
2629 HV Delft
P.O. 177
2600 MH Delft
The Netherlands

telephone: +31 88 335 82 73
e-mail: Information
www: Deltares

For sales contact:
telephone: +31 88 335 81 88
e-mail: Sales
www: Sales & Support

For support contact:
telephone: +31 88 335 81 00
e-mail: Support
www: Sales & Support

Contents

List of Figures

1 A guide to this manual

1.1 Introduction

This User Manual concerns the tidal analysis module Delft3D-TRIANA for FLOW results. Delft3D FLOW is the hydrodynamic module of the Delft3D software suite. To make this manual more accessible we will briefly describe the contents of each chapter and appendix.

If this is your first time to start working with Delft3D-TRIANA we suggest you to read and practice the getting started of Chapter 3 and the tutorial of Chapter 5. These chapters explain the user interface options and guide you through your first usage of Delft3D-TRIANA.

Chapter 2: Introduction to Delft3D-TRIANA, provides specifications and background information of Delft3D-TRIANA.

Chapter 3: Getting started, explains the use of the overall menu program, which gives access to all Delft3D modules and to the pre-processing and post-processing tools, such as Delft3D-TRIANA.

Chapter 4: General operation of Delft3D-TRIANA, provides practical information on the input and output files, selection of parameters and the restrictions of the module.

Chapter 5: Tutorial, gives you some first hands-on experience in executing Delft3D-TRIANA and interpreting the results.

References, gives an overview of related Delft3D User Manuals.

The appendices contain example in- and output files of Delft3D-TRIANA.

1.2 Manual version and revisions

A manual applies to a certain release of the related numerical program. This manual applies to Delft3D-TRIANA version 3.05.00.

The manual version number and its release date are given in the page header. Revisions to (a part of) this manual will be indicated by a version number followed by the revision number separated by a dot. So, version 3.05.02 is the second revision of version 3.05 of that page, section or chapter. The version number is increased when the entire manual is upgraded.

1.3 Typographical conventions

Throughout this manual, the following conventions in text formats help you to distinguish between different types of text elements.

Example	**Description**
Module **Project**	Title of a window or a sub-window are in given in **bold**. Sub-windows are displayed in the **Module** window and cannot be moved. Windows can be moved independently from the **Module** window, such as the **Visualisation Area** window.

Example	Description
Save	Item from a menu, title of a push button or the name of a user interface input field. Upon selecting this item (click or in some cases double click with the left mouse button on it) a related action will be executed; in most cases it will result in displaying some other (sub-)window. In case of an input field you are supposed to enter input data of the required format and in the required domain.
<\tutorial\wave\swan-curvi> <siu.mdw>	Directory names, filenames, and path names are expressed between angle brackets, <>. For Linux environments a forward slash (/) is used instead of the backward slash (\) for Windows environments.
“27 08 1999”	Data to be typed by you into the input fields are displayed between double quotes. Selections of menu items, option boxes etc. are described as such: for instance ‘select *Save* and go to the next window’.
`delft3d-menu`	Commands to be typed by you are given in the font Courier New, 10 points.
➢	In this User manual, user actions are indicated with this arrow.
[m s^{-1}] [–]	Units are given between square brackets when used next to the formulae. Leaving them out might result in misinterpretation. Most units will be in SI notation. [m AD] stands for ’meter Above Datum’, which denotes a level relative to the vertical reference system in the model.

2 Introduction to Delft3D-TRIANA

In 1992 a WL | Delft Hydraulics funded validation study of the 3D numerical hydrodynamic model Delft3D-FLOW (Deltares, 2024) was carried out. Within this project, generic tools for the evaluation and interpretation of 2DH and 3D tidal flow computations have been developed.

One of these tools, Delft3D-TRIANA, performs offline tidal analyses of time-series generated by Delft3D-FLOW. These time-series can be water levels or velocities.

Apart from the actual tidal analysis, Delft3D-TRIANA also provides the opportunity to compare the computed tidal constants (amplitudes and phases) with a second, reference set of tidal constants. The latter must be supplied by you to Delft3D-TRIANA; in general this reference set will arise from observed water levels or velocities. Both the tidal constants that must be calculated (and/or compared with tidal constants obtained elsewhere, e.g. via a tidal analysis of observed water levels or velocities) and the locations where this must be done can be specified by you.

This tool thus enables a quick analysis and interpretation of Delft3D-FLOW computations in terms of tidal quantities. Especially during model calibration on the basis of tidal boundary conditions this tool can be of great help: mismatches of computed and observed amplitudes and/or phases can easily be translated into appropriate adjustments of one or more boundary conditions.

During the past years, Delft3D-TRIANA has been extensively used for the calibration of several large scale tidal flow models, such as:

- the Total Irish Sea model
- the Cumbrian and the Southern Coast model
- the Arabian Gulf model
- the South China Sea model, see Appendix F
- the Continental Shelf model
- the Mirfa far-field flow model
- the RYMAMO (Rhine-Meuse estuary) model

Delft3D-TRIANA proved to be an indispensable tool for the calibration of large scale tidal flow models. However, several short-comings of the first prototype version of Delft3D-TRIANA where encountered during these projects. Therefore, the program has been revised. Several minor bugs have been corrected, the structure of the input and output files has been changed and additional functionality has been added, resulting in Delft3D-TRIANA version 3.01.00.

3 Getting started

3.1 Overview of Delft3D

The Delft3D program suite is composed of a set of modules (components) each of which covers a certain range of aspects of a research or engineering problem. Each module can be executed independently or in combination with one or more other modules. The information exchange between modules is provided automatically by means of a so-called communication file; each module writes results required by an other module to this communication file and reads from this file the information required from other modules. Other, module-specific, files contain results of a computation and are used for visualisation and animation of results. The hydrodynamic module Delft3D-FLOW produces a time-series files that is part of the input for the analysis module Delft3D-TRIANA.

Delft3D is provided with a menu shell through which you can access the various modules. In this chapter we will guide you through some of the input screens to get the look-and-feel of the program. In Chapters 4 and 5 you will learn to define and run a TRIANA analysis.

3.2 Starting Delft3D

To start Delft3D:

◇ On an MS Windows platform: select Delft3D in the Applications menu or click on the Delft3D icon on the desktop.
◇ On Linux machines: type `delft3d-menu` on the command line.

The title window of Delft3D is displayed in Figure 3.1.

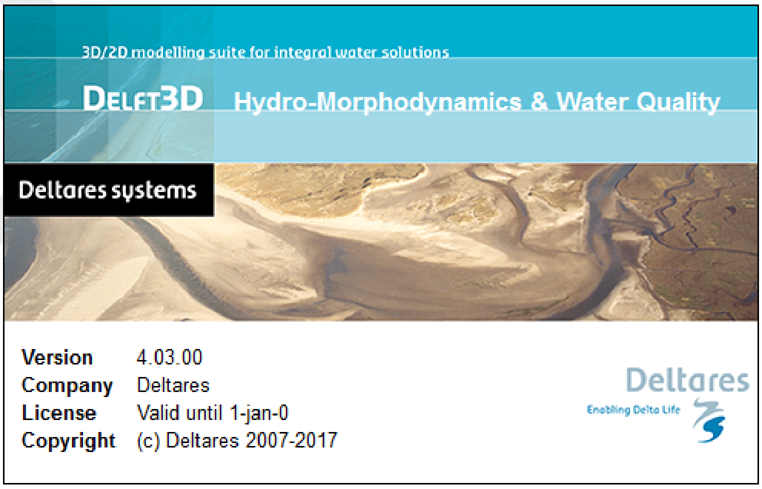


Figure 3.1: *Title window of Delft3D*

After a short while the main window of the Delft3D-MENU appears, Figure 3.2.

◇ Whether or not you may use specific Delft3D modules and features depends on the license file you have. For now, only concentrate on exiting Delft3D-MENU
◇ Click on *Exit*.

The window will be closed and you are back in the Windows Desk Top screen for PCs or on the command line for Linux workstations.

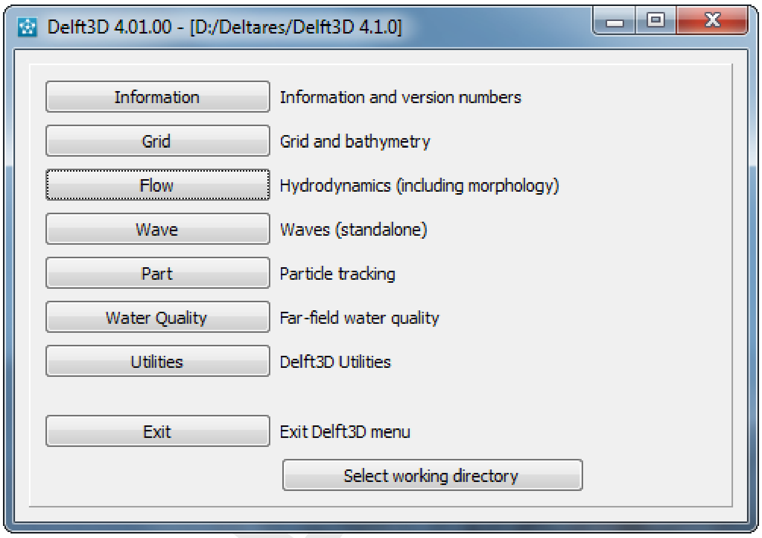


Figure 3.2: *Main window Delft3D-MENU*

Remark:

◇ In this and the following chapters several windows are shown to illustrate the presentation of Delft3D-MENU and Delft3D-TRIANA. These windows are grabbed from the PC-platform. For Linux workstations the content of the windows is the same, but the colours may be different. On the PC-platform you can set your preferred colours by using the Display Properties.

3.3 Getting into Delft3D-FLOW and Delft3D-TRIANA

To continue restart the menu program as indicated above.

◇ Select *Flow* in the main window, see Figure 3.2.

Next the selection window for **Hydrodynamics (including morphology)** is displayed for preparing a flow input or Master Definition Flow file (MDF-file), a wave input file (for a combined FLOW-WAVE simulation), to execute a computation in foreground or in batch, to inspect the report files with information on the execution and to visualise the results: Figure 3.3. Delft3D-TRIANA is part of the additional tools.

Before continuing with any of the selections of this **Hydrodynamics (including morphology)** window, you must select the directory in which you are going to prepare scenarios and execute computations:

◇ Click *Select working directory*.
◇ Next the **Select working directory** window, Figure 3.4, is displayed (your current directory may differ, depending on the location of your Delft3D installation).

◇ Browse to the <Tutorial> sub-directory of your Delft3D Home-directory.
◇ Enter <flow> directory.
◇ Enter the <triana> sub-directory and close the **Select working directory** window by clicking *OK*, see Figure 3.5.

◇ Next the **Hydrodynamics (including morphology)** window is re-displayed, but now the changed current working directory is displayed in the title bar, see Figure 3.6.

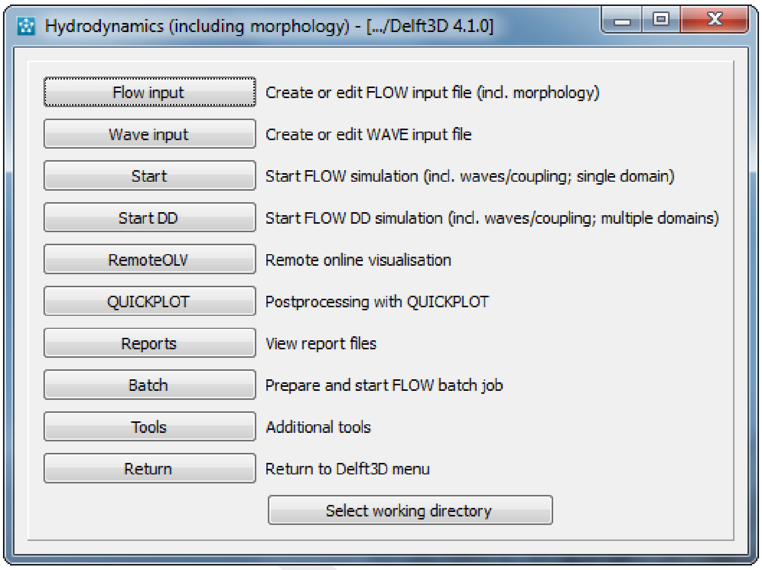


Figure 3.3: *Selection window for* ***Hydrodynamics (including morphology)***

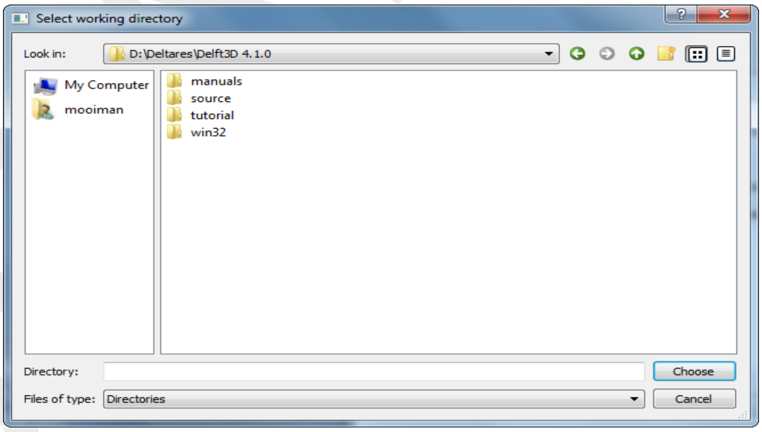


Figure 3.4: Select working directory *window*

In this guided tour through Delft3D-FLOW and Delft3D-TRIANA we limit ourselves to the point where you start Delft3D-TRIANA.

Hence:

◇ Click on *Tools*.

The additional tools for Delft3D-FLOW are verifying the input file, nesting (NESTHD1 and NESTHD2), tidal analysis of FLOW time-series (TRIANA), tidal analysis and prediction of tides (TIDE), and some other selection programs (DATSEL, LINT and KUBINT), see Figure 3.7.

To run Delft3D-TRIANA (*TRIANA*) you must have FLOW results and the additional TRIANA input files.

3.4 Executing Delft3D-TRIANA

Before running Delft3D-TRIANA you have to prepare the input files. See Chapters 4 and 5.

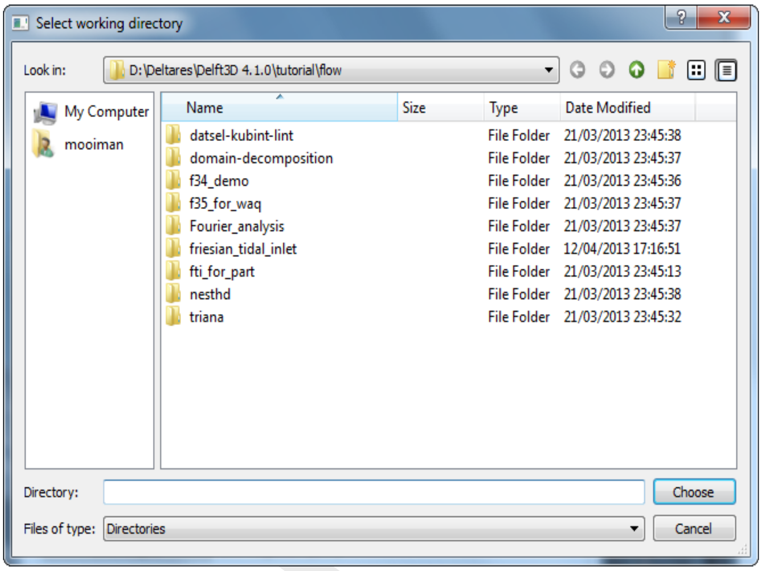


Figure 3.5: ***Select working directory*** *window to set the working directory to <flow/triana>*

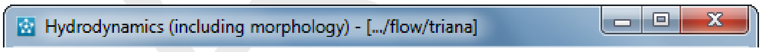


Figure 3.6: *Current working directory*

3.5 Exiting Delft3D

To return to the main **Hydrodynamics (including morphology)** selection window:

◇ Click *Return*.

You will be back in the **Hydrodynamics (including morphology)** window of the Delft3D-MENU program, Figure 3.3.

Ignore all other options and just:

◇ Click *Return* to return to the main window of Delft3D-MENU, Figure 3.2.
◇ Click *Exit*.

The window is closed and the control is returned to the desk top or the command line.

In this Getting Started session you have learned to access the Delft3D-TRIANA module as part of the Delft3D-FLOW module.

We encourage new users next to run the tutorial described in Chapter 5.

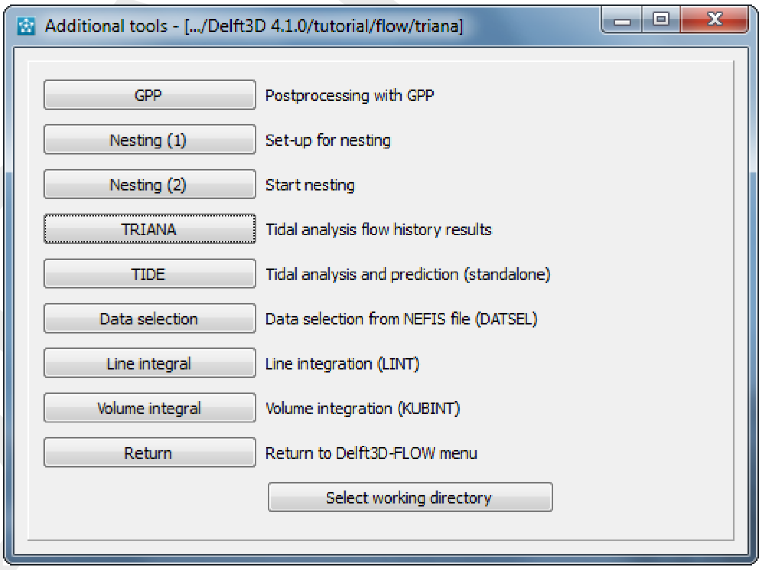


Figure 3.7: *Additional tools for the Delft3D-FLOW module*

4 General operation of Delft3D-TRIANA

In this chapter the structure of the input and output of Delft3D-TRIANA will be described, see section 4.1 and Section 4.2 respectively. Some remarks on usage and restrictions of the tool can be found in Section 4.3.

4.1 Delft3D-TRIANA input files

Delft3D-TRIANA requires 3 input files:

1 a *general input file* containing information on the tidal analysis and the stations where an analysis is required
2 a file with *observed* tidal constants
3 a file with the *time-series* of water levels and currents as generated by Delft3D-FLOW

The contents and structure of these files are described in Sections 4.1.1 to 4.1.3.

4.1.1 General input file

The general input file for Delft3D-TRIANA is a common ASCII file, organised as follows:

- First, the **time interval** $[T_{beg}, T_{end}]$ of the tidal analysis period must be given. The time points T_{beg} and T_{end} must be in Delft3D-FLOW format, i.e. they are in minutes with respect to the Reference date (ITDATE) of the Delft3D-FLOW computation. Delft3D-TRIANA checks whether the time interval matches that of the Delft3D-FLOW computation. In case of a mismatch in time frames, the time interval for the tidal analyses is adjusted.
- The analysis interval must be followed by a **list of the (main) tidal constituents** (one constituent per record of the input file). After this list, the number of main constituents used in the coupling relations must be given. This number must be followed by **records that contain the coupling relations between main and sub constituents**. For further information on these coupling relations you are referred to the Delft3D-TIDE User Manual (TIDE UM, 2013).
- Information on the **locations** where an analysis is required must be provided in the last records of the input file. Each record consists of a code, W for an analysis of computed water levels and V for an analysis on computed east and north velocities, followed by the Delft3D-FLOW M and N indices of the station and, in case of an analysis on velocities, a layer number. When, in case of a 3D-computation, an analysis on depth-averaged velocities is required, this layer number must equal 0.

An example of a general input file is shown in Appendix A.

4.1.2 File with the observed tidal constants

Delft3D-TRIANA compares sets of computed tidal constants with a second series of sets of tidal constants (usually these will be tidal constants derived from observed time-series). This file consists of an arbitrary number of blocks, separated from each other by means of a record starting with an asterisk. Each block consists of:

- A **code**, W, E or N, indicating the type of date, water level, east velocity or north velocity data.
- The Delft3D-FLOW **M and N indices** of the observation point. In case of velocity observations also the **layer number** must follow these indices. A layer number equal to 0 indicates depth-averaged current velocities.
- A set of **constituent names, amplitudes and phases**.

Remark:
- ◇ It is assumed that all tidal constants are given in [m] or [m/s]. Phases refer to the time zone in which the model has been defined.

An example of the observation file is shown in Appendix B.

4.1.3 Time-series input file

The Delft3D-FLOW time-series for which Delft3D-TRIANA derives tidal constants must be supplied by means of the NEFIS history files as produced by Delft3D-FLOW version 2.03 or higher.

4.2 Delft3D-TRIANA output files

Delft3D-TRIANA produces three output files:

1. a print file
2. a 'Table A'-file
3. a 'Table B'-file

The contents and structure of these files are described in the Sections 4.2.1 to 4.2.3.

4.2.1 Print file

The Delft3D-TRIANA print file gives an echo of the input, i.e. the general input file and the observation file. Furthermore, error and warning messages are printed in this file. Therefore, it is advised to inspect this file regularly.

An example of a Delft3D-TRIANA print file is shown in Appendix C.

4.2.2 Table-A file

In this file a table is written for **each tidal constituent** that was used in the tidal analysis of water levels or velocities (=selection on the basis of the tidal constituents leading to 'constituent-tables'). Each table, e.g. the M_2-table, contains a comparison of observed and computed M_2 tidal constants for all checkpoints. This comparison involves the following information:

- ◇ Comment record that gives the modality of the time-series: water levels, east-velocities or north-velocities.
- ◇ Delft3D-FLOW co-ordinate pair of the monitoring station and, in case of velocities, the layer number.
- ◇ Computed amplitudes (H_c) and phases (G_c).
- ◇ Observed amplitudes (H_o) and phases (G_o) (if available for that specific station).
- ◇ Amplitude and phase differences ($H_c - H_o$, $G_c - G_o$).
- ◇ Amplitude ratio (H_c/H_o).
- ◇ Vector difference between the computed amplitude and phase, and the observed amplitude and phase, if available.

The vector difference is defined as:

$$\sqrt{[H_c \cos(G_c) - H_o \cos(G_o)]^2 + [H_c \sin(G_c) - H_o \sin(G_o)]^2} \tag{4.1}$$

The table is followed by statistical information with regard to the 'agreement' of the computed and the observed tidal constants. This statistical information considers

◇ mean differences
◇ absolute mean differences
◇ root mean square differences.

These differences are evaluated for the

◇ amplitudes
◇ phases
◇ amplitude ratios

Finally, a summed vector difference is given:

$$\sum_{Obs} \sqrt{[H_c \cos(G_c) - H_o \cos(G_o)]^2 + [H_c \sin(G_c) - H_o \sin(G_o)]^2} \tag{4.2}$$

in which $\sum_{Obs}$ refers to a summation over the stations with observed amplitudes and phases.

An example of a 'Table A file' is given in Appendix D.

4.2.3 Table-B file

In this file a table is written for **each station** where a tidal analysis has been performed (= selection on the basis of the stations leading to 'station tables'). Each table contains a comparison of all observed and computed tidal constants for that station:

◇ General header information for that station, and a record giving the number of tidal constants compared (= number of rows) plus the number of columns.
◇ Per record the following information:
  - frequency of a tidal constituent
  - computed amplitude and phase of that specific tidal constituent
  - observed amplitude and phase of the tidal constituent (if available)
  - amplitude and phase differences of the computed and observed 'constituent' (if available)
  - amplitude factor of the specific tidal constituent (if available)
  - vector difference between computed and observed constants, if available
  - name of that specific tidal constituent

The vector difference is defined as:

$$\sqrt{[H_c \cos(G_c) - H_o \cos(G_o)]^2 + [H_c \sin(G_c) - H_o \sin(G_o)]^2} \tag{4.3}$$

Note that the structure of the B-tables is very similar to the output of Delft3D-TIDE.

Each table is followed by information on the residuals. Here the residuals must be understood as the difference of the Delft3D-FLOW time-series as supplied by you, and the 'predicted' time-series based on the calculated tidal constants. In Table B the standard deviation of the tidal analysis (= RMS-value of the residuals) is given as well as the upper and lower extremes of the residuals.

Finally, the summed vector difference is given.

$$\sum_{TC} \sqrt{[H_c \cos(G_c) - H_o \cos(G_o)]^2 + [H_c \sin(G_c) - H_o \sin(G_o)]^2} \tag{4.4}$$

in which $\sum_{TC}$ refers to summation over the tidal constituents with observed amplitudes and phases.

An example of a 'Table B file' can be found in Appendix E.

4.3 Comments and restrictions of the present implementation

In this section some comments and restrictions will be given on the present implementation of Delft3D-TRIANA. These comments are a result of the experience gained with the tool during its application.

- The analysis performed by Delft3D-TRIANA does **not** differ from a 'usual' tidal analysis as e.g. by Delft3D-TIDE. This means that the **suitability** (predictive value) of the results is determined by the set of constituents and the coupling relations used in the analysis. Moreover, for Delft3D-TRIANA as for Delft3D-TIDE care must be taken that the analysis period is sufficiently long for the resolution of the main constituents. In other words, the Rayleigh criterion must be satisfied, see e.g. the User Manual Delft3D-TIDE.
- When numerical model results are analysed, the constituents that are used in the analysis must be chosen on the basis of the constituents present in the model's **boundary conditions**, and their compound harmonics generated in the model.
- The coupling relations given in the general input file are applied for all stations where a tidal analysis is performed. In case of a large model area this can be inappropriate, or even highly undesirable. You then have to group the stations with similar coupling relations and execute Delft3D-TRIANA for each group.

5 Tutorial

5.1 Preparing input files

The Hong Kong model covers an area as shown in Figure 5.1. Inside this model area observed tidal constants are collected for 24 locations.

The locations with their M, N indices are:

```
Chek Lap Kok        c     36      36
RO Chi Ma Wan      oc     43      26
S Chi Wan          oc     23      45
Chuanbi Jiao        c     10      45
Dangan Isl          c     53       8
Da Wan Shan         c     20      13
Gaolan Dao          c     11      15
H6                  c     13      18
H9                  c     21      13
H11                 c     53       7
Heng Men Haikou     c     12      39
SP Lamma Isl PS    oc     49      21
P Macau ColoanePS  oc     17      22
Macau Harbour       c     16      24
RO Quarry Bay      oc     62      20
Sha Jiao PS         c     11      45
T07                 c     36       8
S WLR T10           c     73      11
RO Tai O           oc     31      28
V S Tsing Yi PS     o     59      34
RO Waglan Isl      oc     62      11
Wailingding Dao     c     41      16
Wenwei Zhou         c     28       8
Yung Shue Wan       c     50      23
```

Together with other monitoring stations these 'tidal' stations are stored in the FLOW observation point file <∗.obs>. The 'observed' tidal constants are stored in the TRIANA observation file <triahkc4.obs>, see Appendix B.

The Hong Kong model is run from 14:00 on 18 July 1996 till 12:00 on 10 August 1996, i.e. almost 23 days. The Reference date was set to 18 July 1996. The run identification is <fou>.

To perform a tidal analysis for the required locations, the FLOW results will be analysed over a period from 00:00 on 26 July 1996 till 12:00 on 10 August 1996, i.e. 15 days and 12 hours. Since the FLOW simulation was a 'cold' start, the first 7 days are affected by spin-up effects, and thus ignored for the analysis.

The Rayleigh criterion defines which constituents can be resolved independently. Their frequencies must differ from one another by at least:

$$\Delta\omega = \frac{360^\circ}{T}$$

in which T is the duration of the observation in hours.

In our example $T = 15 \times 24 + 12 = 372$ and thus $\Delta\omega = 0.9677\ deg/h$.

In minutes relative to the Reference Date 18 July 1996 the analysis period is:

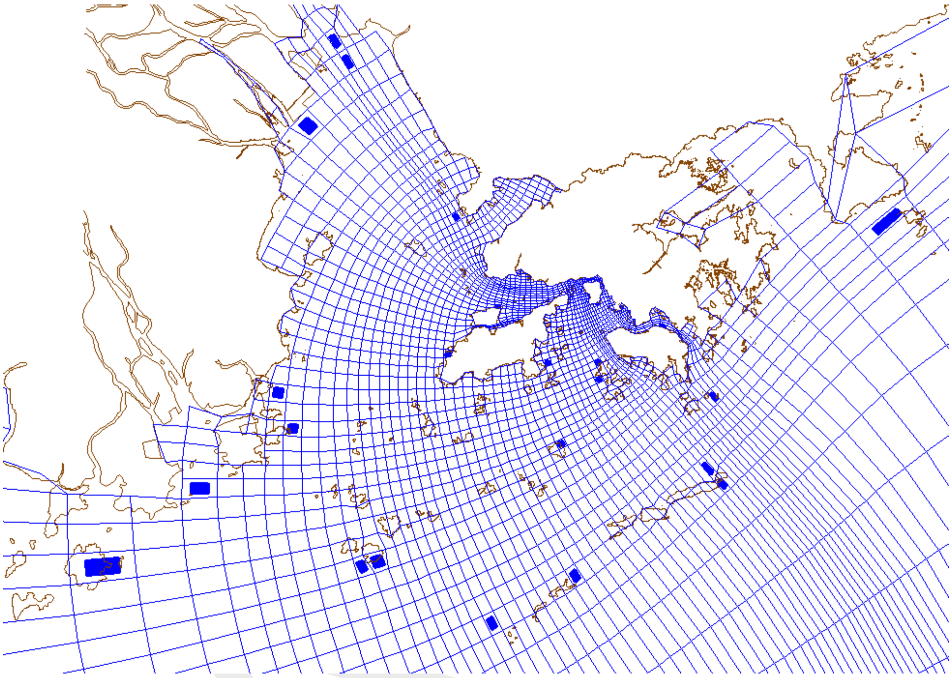


Figure 5.1: *Hong Kong model grid and locations with 'observed' tidal constants*

```
11520.0  (00:00 on 26 July 1996)
33840.0  (12:00 on 10 August 1996)
```

The main tidal constituents we want to resolve are:

```
K1
O1
M2
S2
N2
M4
MS4
```

Also the amplitudes of P_1 and K_2 are relevant. Since the analysis period is too short to extract these tidal constituents, we use coupling:

```
  K1     P1     0.320     -4.25
  S2     K2     0.291      0.00
```

The amplitude ratio 0.32 and phase difference 4.24 degrees between K_1 and P_1 is based upon the tidal constants from a long-term observation at Quarry Bay. Similar for S_2 and K_2.

The analysis period, the tidal constants and the 24 locations with their indices are stored in the TRIANA main input file <triahkc4.inp>, see Appendix A.

5.2 Executing Delft3D-TRIANA

The TRIANA input files <triahkc4.inp> and <triahkc4.obs>, together with the FLOW time-series file <trih-fou.dat> are stored in the FLOW-TRIANA Tutorial sub-directory of your Delft3D Home-directory, e.g. <c:\delft3d\tutorial\flow\triana>.

Follow the instructions in Sections 3.1 to 3.3 to get to the TRIANA directory and the FLOW **Additional tools** window. To start Delft3D-TRIANA:

◇ Click on *TRIANA.*

Next a command box opens in which you are asked to enter the filenames of input and output, see Figure 5.2. Press `Enter` when you have specified an item.

1 For the TRIANA input file enter “triahkc4.inp”.
2 For the TRIANA observation file enter “triahkc4.obs”.
3 For the TRIANA print file enter “tria-fou-ex.prt”.
4 For the TRIANA table A file enter “tria-fou-ex.tba”.
5 For the TRIANA table B file enter “tria-fou-ex.tbb”.
6 For the FLOW run identification enter “fou-ex”.

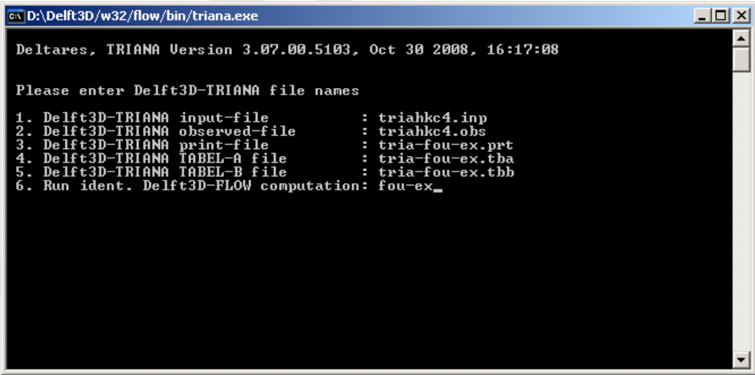


Figure 5.2: *Input and output filenames for Delft3D-TRIANA*

Next Delft3D-TRIANA runs, it makes the tidal analyses and compares computed and observed tidal constants.

5.3 Inspecting results

Part of the print file is presented in Appendix C. The first part is an echo of (part of) the <∗.inp> and <∗.obs> files. At the end of the print file warnings are written from the analysis. In this case: the Rayleigh criterion has been violated for M_2 and N_2, meaning that the observation period is too short to resolve M_2 and N_2 independently. The same as for P_1 and K_2 we have to couple N_2 (to M_2). See the Delft3D-TIDE User Manual (TIDE UM, 2013) for details on how to make a proper tidal analysis.

Appendix D contains the first part of the table A file. In this file the results are presented per tidal constituent. Appendix D shows the comparison between the computed and observed tidal constants for tidal constituents K_1, M_2 and S_2, for all locations.

Ideally, the phase difference $(G_c - G_o)$ is zero and the amplitude ratio (H_c/H_o) is 1.0.

If we look at the performance for K_1 at the first location, being Chep Lak Kok, we see that the phase difference equals -0.996 and the amplitude ratio is 0.910. Since the frequency of K_1 is 15.041 deg/h, the computed phase is accurate within 4 minutes; and the K_1-amplitude is computed with an accuracy of 9%.

The overall performance for K_1 can be seen at the end of the table. The RMS error for the amplitude ratio is 1.028 (3%) and the RMS error for the phase difference is 5.625 (about 20 minutes)

In table B the overall performance per location is evaluated. Appendix E contains part of the tutorial table B file. For Chep Lak Kok the standard deviation is less than 6 cm.

5.4 Calibrating your model using TRIANA

Delft3D-TRIANA performs a tidal analysis on computed time-series and compares the 'computed' tidal constants with 'measured' tidal constants.

From the deviations in terms of amplitude ratio and phase differences you get an evaluation of the performance of your model regarding the horizontal and/or vertical tide.

If you know that certain model input parameters are inaccurate or uncertain, you can adjust these parameters to obtain a better performance.

For instance: if in certain areas of your model the bathymetry data was outdated, not available or otherwise, you may change locally the bathymetry and re-run your model. Re-run TRIANA and evaluate the performance with the adjusted bathymetry.

In case the tidal forcing at the open boundaries are a candidate in the calibration process you can use the amplitude ratios and phase differences at internal points to adjust specific tidal constants at the boundary. In this case it is advised to also make co-tidal maps using the online Fourier analysis of Delft3D-FLOW, Deltares (2024). These maps will help you where to adjust a certain tidal constituent at the model boundary.

References

Deltares, 2024. *Delft3D-FLOW User Manual*. Deltares, 3.14 ed.

TIDE UM, 2013. *Delft3D-TIDE User Manual*. Deltares, 3.00 ed.

A Examples of a main input file

In this appendix the first example refers to the Delft3D-TRIANA input file used for the tutorial case described in Chapter 5.

File contents	TRIANA input file
Filetype	ASCII
File format	Free formatted
Filename	<*name*.inp>
Generated	Some offline program.

Record description:

Record	**Record description**
	Records starting with a '∗' will be ignored
1	Time interval in minutes after Reference date
Several	List of main tidal constituents
next	An integer number indicating the number of coupling relations (NCOUP).
NCOUP	Coupling relation between main and sub tidal constituents.
Several	List of locations for the analysis Each record: Code 'W' or 'V' (1 character); (M, N) indices (two integers), layer number (integer), name of the location

```
*  TRIANA-input file for the coarse HK model
*
*  Interval [Tmin,Tmax] for tidal analyses (in minutes)
*
   11520. 33840.
*
*  Tidal components for analysis
*
K1
O1
M2
S2
N2
M4
MS4
    2
  K1    P1    0.320    -4.25
  S2    K2    0.291     0.00
*
*  >> stations
*
W    36   36     Chek Lap Kok       c
W    43   26    *RO Chi Ma Wan     oc
W    23   45    *S Chi Wan         oc
W    10   45     Chuanbi Jiao       c
W    53    8     Dangan Isl         c
W    20   13     Da Wan Shan        c
```

```
W    11   15      Gaolan Dao         c
W    13   18      H6                 c
W    21   13      H9                 c
W    53    7      H11                c
W    12   39      Heng Men Haikou    c
W    49   21     *SP Lamma Isl PS   oc
W    17   22      P Macau ColoanePS oc
W    16   24      Macau Harbour      c
W    62   20      RO Quarry Bay     oc
W    11   45      Sha Jiao PS        c
W    36    8      T07                c
W    73   11     *S WLR T10          c
W    31   28      RO Tai O          oc
W    59   34     *V S Tsing Yi PS    o
W    62   11     *RO Waglan Isl     oc
W    41   16     *Wailingding Dao    c
W    28    8      Wenwei Zhou        c
W    50   23      Yung Shue Wan      c
```

The second example is not described in this manual. It demonstrates the use of velocity analysis together with the specification of layers, or depth averaged.

Remark:

◇ The set of constituents and couplings is purely fictive. Do not use this set for your own tidal analysis.

```
*  TRIANA.INP file
*
*  Interval [Tmin,Tmax] for tidal analyses
*
    5000. 150000.
*
*  Tidal constituents for analysis
*
 M2
 M4
 M6
 M8
   2
 M2      S2      0.5    -3.
 M4      S4      0.05   -2.
*
*  >> stations
*
  W   3   17      Station W1
  V   8   17   0  depth averaged velocities station W2
  V   8   17   1  velocities in layer 1 station W2
  W  11   17      Station W5
  V   8   17   2  velocities in layer 2 station W2
  V   8   17   3  velocities in non existent layer
  V   3   17   0  depth averaged velocities station W1
```

B Examples of an observation file

In this appendix the first example refers to the tutorial described in Chapter 5. It shows a part of the Delft3D-TRIANA input file with observed tidal constants.

File contents	TRIANA input file
Filetype	ASCII
File format	Free formatted
Filename	<*name*.obs>
Generated	Some offline program.

Record description:

Record	**Record description**
	Records starting with a '$*$' will be ignored
For each observation location	
1	Code 'W', 'E' or 'N' to indicate the type of data, water level, east or north velocity (1 character)
next	(M, N) indices of the observation point (2 integers), and in case of velocity observations also a layer number is required (1 integer). A layer number equal to 0 indicates depth-averaged current velocities
Several	List of constituent names, amplitudes and phases

```
* Tidal constants for stations within coarse HK model
*
* Station: CHEK LAP KOK
W
   36    36
O1           0.29     258.0
K1           0.40     310.0
M2           0.49     309.0
S2           0.13     337.0
*
* Station: CHI MA WAN
W
   43    26
O1         0.2933    250.71
P1         0.1144    293.51
K1         0.3653    299.17
N2         0.0875    253.96
M2         0.4151    269.43
S2         0.1661    299.89
K2         0.0471    297.71
M4         0.0350    340.44
MS4        0.0218     30.56
*
* Station: CHIWAN
W
    23    45
O1          0.315     261.0
P1          0.120     312.8
K1          0.396     310.9
N2          0.123     287.4
M2          0.573     302.9
```

```
S2           0.220     336.1
K2           0.071     337.2
M4           0.041      78.0
MS4          0.030     131.6
*
* Station: CHUANBI JIAO
W
    10    45
O1             .260     300.1
K1             .291     348.5
P1             .088     350.4
N2             .094     348.4
M2             .468     345.0
S2             .152      34.0
K2             .049      35.1
M4             .073     245.2
MS4            .042     325.0
*
* Station: Dangan Island
...
...
```

The second example is not described or used in this manual. It demonstrates the use of observed tidal constants for velocities.

```
* TRIANA.OBS-file
*
*  east velocities station  W1; depth averaged
E
    3  17       0
O1         .001     350.7
K1         .005     114.7
P1         .002     101.1
3MS2       .018     310.1
MNS2       .024      87.2
M2         .403     104.6
MU2        .019     182.0
N2         .064      84.8
NU2        .026      78.7
L2         .031     138.4
S2         .014     142.5
K2         .036     143.4
3MS4       .011     192.6
MN4        .004      83.8
M4         .023     109.7
3MN4       .004     201.7
MS4        .011     223.9
2MSN4      .003     120.0
*
* water levels station W5
W
    11      17
O1         .102     182.4
P1         .037     338.2
S1         .007     236.3
K1         .073     357.6
MU2        .075     194.5
M2         .829      68.7
L2         .020      26.7
M8         .018     180.1
*
*  water levels station W2
W
    8   17
```

```
O1        .103     186.7
P1        .036     346.2
S1        .011     272.4
K1        .072     359.7
N2        .117      58.5
NU2       .048      52.3
*
*  east velocities station W2; layer 1
E
    8  17      1
M2        .378     101.6
*
*  north velocities station W2; depth-averaged
N
    8   17     0
L2       .030      124.1
M2       .325      93.1
*
*  north velocities station W2; layer 1
N
    8   17     1
L2       .040      125.1
*  north velocities station W2;layer 2
N
    8   17     2
M2       .3820      90.4
```

C Example of a print file

In this appendix a part of the print output file from the tutorial is presented.

```
*
* Deltares, TRIANA Version 3.07.00.9446, Nov 11 2009, 12:13:01
*
* TRIANA File Report [I=Input,O=Output]
* ------ ---- ------  -------- --------
* TRIANA  Input    file                [I] : triahkc4.inp
* TRIANA  Observed file                [I] : triahkc4.obs
* TRIANA  Print    file                [O] : tria-fou-ex.prt
* TRIANA  Tabel-A  file                [O] : tria-fou-ex.tba
* TRIANA  Tabel-B  file                [O] : tria-fou-ex.tbb
* Run ident. \DFLOW\ computation  [I] : fou-ex
*
* TRIANA-file : tria-fou-ex.prt
*


 Observed water level constituents for station  36  36
 Name     Amplitude      Phase
                         (deg)
 O1            0.29    258.00
 K1            0.40    310.00
 M2            0.49    309.00
 S2            0.13    337.00


 Observed water level constituents for station  43  26
 Name     Amplitude      Phase
                         (deg)
 O1            0.29    250.71
 P1            0.11    293.51
 K1            0.37    299.17
 N2            0.09    253.96
 M2            0.42    269.43
 S2            0.17    299.89
 K2            0.05    297.71
 M4            0.04    340.44
 MS4           0.02     30.56


 Observed water level constituents for station  23  45
 Name     Amplitude      Phase
                         (deg)
 O1            0.31    261.00
 P1            0.12    312.80
 K1            0.40    310.90
 N2            0.12    287.40
 M2            0.57    302.90
 S2            0.22    336.10
 K2            0.07    337.20
 M4            0.04     78.00
 MS4           0.03    131.60


 Observed water level constituents for station  10  45
 Name     Amplitude      Phase
                         (deg)
 O1            0.26    300.10
 K1            0.29    348.50
 P1            0.09    350.40
 N2            0.09    348.40
 M2            0.47    345.00
```

```
 S2             0.15     34.00
 K2             0.05     35.10
 M4             0.07    245.20
 MS4            0.04    325.00


 Observed water level constituents for station  53   8
...
..
.

.
..
...
 Observed water level constituents for station  28   8
 Name     Amplitude     Phase
                        (deg)
 O1             0.30    255.00
 K1             0.30    302.00
 M2             0.30    275.00
 S2             0.10    305.00


 Observed water level constituents for station  50  23
 Name     Amplitude     Phase
                        (deg)
 O1             0.27    247.00
 K1             0.36    294.00
 M2             0.36    264.00
 S2             0.14    301.00


 Stations to analyse water levels
 Gridpoints (M,N)  :      M     N
                         36    36
                         43    26
                         23    45
                         10    45
                         53     8
                         20    13
                         11    15
                         13    18
                         21    13
                         53     7
                         12    39
                         49    21
                         17    22
                         16    24
                         62    20
                         11    45
                         36     8
                         73    11
                         31    28
                         59    34
                         62    11
                         41    16
                         28     8
                         50    23


 Time interval for analysis : [    11520.,    33840.] (in minutes since ITDATE)


 Set of tidal components for tidal analysis
     1  K1
     2  P1
```

```
    3  O1
    4  M2
    5  S2
    6  K2
    7  N2
    8  M4
    9  MS4

Astronomical coupling
Number of coupled groups  :      2
Sub components for main component K1
P1            0.32     -4.25
Sub components for main component S2
K2            0.29      0.00


 WARNING 1 RAYLEIGH CRITERION VIOLATED
          COMPONENTS M2       AND N2       ARE TOO CLOSE IN FREQUENCY
          ACTUAL  FREQUENCY DISTANCE (MAGNITUDE)         :     0.5444 DEGR./HOUR
          MINIMUM FREQUENCY DISTANCE (RAYLEIGH CRITERION):     0.9677 DEGR./HOUR
          PLEASE CHECK; CONSIDER COUPLING OR REMOVAL
 WARNING 1 RAYLEIGH CRITERION VIOLATED
          COMPONENTS N2       AND M2       ARE TOO CLOSE IN FREQUENCY
          ACTUAL  FREQUENCY DISTANCE (MAGNITUDE)         :     0.5444 DEGR./HOUR
          MINIMUM FREQUENCY DISTANCE (RAYLEIGH CRITERION):     0.9677 DEGR./HOUR
          PLEASE CHECK; CONSIDER COUPLING OR REMOVAL
```

D Example of a table A file

In this appendix a part of the Table-A output file from the tutorial is presented.

```
*
* Deltares, TRIANA Version 3.07.00.9446, Nov 11 2009, 12:13:01
*
* TRIANA File Report [I=Input,O=Output]
* ------ ---- ------  -------- --------
* TRIANA  Input    file                [I] : triahkc4.inp
* TRIANA  Observed file                [I] : triahkc4.obs
* TRIANA  Print    file                [O] : tria-fou-ex.prt
* TRIANA  Tabel-A  file                [O] : tria-fou-ex.tba
* TRIANA  Tabel-B  file                [O] : tria-fou-ex.tbb
* Run ident. \DFLOW\ computation  [I] : fou-ex
*
* TRIANA-file : tria-fou-ex.prt
*
*==============================================================================================================
* Tidal component    : K1
* ITDATE             : 1996/07/18 00:00:00
* Analysed period    :     11520.,     33840.( in minutes w.r.t. ITDATE)
* Time zone          : Model time
* Units              : m          for ampl.  degrees for phase
* Explanation        : Hc = computed ampl.  Gc = computed phase
*                      Ho = observed ampl.  Go = observed phase
*                      VD = vector difference
*                      M  = m-coordinate station; N = n-coordinate  station
*                      999.99 = not computed due to lack of observations
*
*   M    N    L          X          Y        Hc       Gc        Ho       Go     Hc-Ho     Gc-Go
*--------------------------------------------------------------------------------------------------------------
*                                       >> water levels <<
W001
   24   12
   36   36        811663.2   820560.9    0.371  306.711    0.400  310.000   -0.029    -3.289
   43   26        820280.2   810920.9    0.362  299.272    0.365  299.170   -0.003     0.102
   23   45        804525.1   835920.6    0.371  311.857    0.396  310.900   -0.025     0.957
   10   45        783764.6   866165.8    0.376  327.379    0.291  348.500    0.085   -21.121
   53    8        847813.6   792720.2    0.352  298.937    0.348  300.700    0.004    -1.763
   20   13        788360.1   775841.5    0.360  300.026    0.368  302.800   -0.008    -2.774
   11   15        743756.9   775794.2    0.356  301.542    0.400  319.000   -0.044   -17.458
   13   18        760521.1   789294.9    0.361  302.128    0.346  305.100    0.015    -2.972
   21   13        791076.4   776696.6    0.361  299.970    0.365  300.100   -0.004    -0.130
   53    7        850206.1   789995.4    0.347  298.484    0.355  299.500   -0.008    -1.016
   12   39        779129.9   851544.2    0.380  328.951    0.282  343.400    0.098   -14.449
   49   21        829049.0   807985.4    0.360  298.345    0.309  303.800    0.051    -5.455
   17   22        776489.6   799545.4    0.364  303.335    0.312  311.900    0.052    -8.565
   16   24        774007.5   805668.9    0.367  305.458    0.370  307.000   -0.003    -1.542
   62   20        840040.4   817237.8    0.355  298.349    0.357  299.720   -0.003    -1.371
   11   45        785944.8   862653.2    0.382  327.650    0.390  327.200   -0.008     0.450
   36    8        824958.8   774211.9    0.355  299.120    0.357  300.700   -0.002    -1.580
   73   11        878559.9   835186.2    0.342  298.069    0.343  299.500   -0.001    -1.431
   31   28        803093.8   812442.0    0.369  302.533    0.394  302.990   -0.025    -0.457
   59   34        828875.2   820952.4    0.364  299.664    0.360  296.000    0.004     3.664
   62   11        848819.3   805095.5    0.349  298.045    0.348  298.470    0.001    -0.425
   41   16        822607.9   796924.9    0.359  298.987    0.350  301.000    0.009    -2.013
   28    8        810730.1   766048.9    0.355  299.358    0.300  302.000    0.055    -2.642
   50   23        828898.2   810986.6    0.362  299.233    0.360  294.000    0.002     5.233
*
* Number of stations used    :        24
* Statistics for amplitudes
* Mean            Hc-Ho      :     0.009
* Absolute Mean |Hc-Ho|      :     0.022
* R.m.s. error    Hc-Ho      :     0.035
```

```
* Mean            Hc/Ho      :     1.035
* R.m.s. error    Hc/Ho      :     1.041
* Statistics for phases
* Mean            Gc-Go      :    -3.335
* Absolute Mean |Gc-Go|      :     4.202
* R.m.s. error    Gc-Go      :     6.942
* Summed vector difference  :     0.869
*===========================================================================================
* Tidal component    : P1
* ITDATE             : 1996/07/18 00:00:00
* Analysed period    :      11520.,     33840.( in minutes w.r.t. ITDATE)
* Time zone          : Model time
* Units              : m         for ampl.  degrees for phase
* Explanation        : Hc = computed ampl.  Gc = computed phase
*                      Ho = observed ampl.  Go = observed phase
*                      VD = vector difference
*                      M  = m-coordinate station; N = n-coordinate  station
*                      999.99 = not computed due to lack of observations
*
*   M    N    L           X          Y        Hc       Gc        Ho       Go     Hc-Ho    Gc-Go
*-------------------------------------------------------------------------------------------
*                                        >> water levels <<
W002
   24   12
   36   36        811663.2   820560.9    0.119  302.461  999.999  999.999  999.999  999.999
   43   26        820280.2   810920.9    0.116  295.022    0.114  293.510    0.002    1.512
   23   45        804525.1   835920.6    0.119  307.607    0.120  312.800   -0.001   -5.193
   10   45        783764.6   866165.8    0.120  323.129    0.088  350.400    0.032  -27.271
   53    8        847813.6   792720.2    0.113  294.687    0.100  293.200    0.013    1.487
   20   13        788360.1   775841.5    0.115  295.776    0.105  295.300    0.010    0.476
   11   15        743756.9   775794.2    0.114  297.292  999.999  999.999  999.999  999.999
   13   18        760521.1   789294.9    0.116  297.878    0.109  300.800    0.007   -2.922
   21   13        791076.4   776696.6    0.115  295.720    0.115  295.900    0.000   -0.180
   53    7        850206.1   789995.4    0.111  294.234    0.112  295.200   -0.001   -0.966
   12   39        779129.9   851544.2    0.122  324.701    0.085  345.300    0.037  -20.599
   49   21        829049.0   807985.4    0.115  294.095    0.097  296.800    0.018   -2.705
   17   22        776489.6   799545.4    0.117  299.085    0.098  304.900    0.019   -5.815
   16   24        774007.5   805668.9    0.117  301.208  999.999  999.999  999.999  999.999
   62   20        840040.4   817237.8    0.114  294.099    0.114  294.370    0.000   -0.271
   11   45        785944.8   862653.2    0.122  323.400    0.111  319.700    0.011    3.700
   36    8        824958.8   774211.9    0.114  294.870    0.116  296.800   -0.003   -1.930
   73   11        878559.9   835186.2    0.109  293.819    0.110  295.400    0.000   -1.581
   31   28        803093.8   812442.0    0.118  298.283    0.121  297.270   -0.003    1.013
   59   34        828875.2   820952.4    0.116  295.414  999.999  999.999  999.999  999.999
   62   11        848819.3   805095.5    0.112  293.795    0.100  291.020    0.012    2.775
   41   16        822607.9   796924.9    0.115  294.737  999.999  999.999  999.999  999.999
   28    8        810730.1   766048.9    0.114  295.108  999.999  999.999  999.999  999.999
   50   23        828898.2   810986.6    0.116  294.983  999.999  999.999  999.999  999.999
*
* Number of stations used    :        17
* Statistics for amplitudes
* Mean            Hc-Ho      :     0.009
* Absolute Mean |Hc-Ho|      :     0.010
* R.m.s. error    Hc-Ho      :     0.015
* Mean            Hc/Ho      :     1.096
* R.m.s. error    Hc/Ho      :     1.103
* Statistics for phases
* Mean            Gc-Go      :    -3.440
* Absolute Mean |Gc-Go|      :     4.729
* R.m.s. error    Gc-Go      :     8.674
* Summed vector difference  :     0.238
*===========================================================================================
* Tidal component    : O1
* ITDATE             : 1996/07/18 00:00:00
* Analysed period    :      11520.,     33840.( in minutes w.r.t. ITDATE)
* Time zone          : Model time
```

```
* Units              : m         for ampl.  degrees for phase
* Explanation        : Hc = computed ampl.  Gc = computed phase
*                      Ho = observed ampl.  Go = observed phase
*                      VD = vector difference
*                      M  = m-coordinate station; N = n-coordinate  station
*                      999.99 = not computed due to lack of observations
*
*   M    N    L          X          Y       Hc       Gc       Ho       Go    Hc-Ho    Gc-Go
*-----------------------------------------------------------------------------------------------
*                                      >> water levels <<
W003
   24   12
   36   36       811663.2   820560.9    0.320  258.065    0.290  258.000    0.030    0.065
   43   26       820280.2   810920.9    0.301  250.368    0.293  250.710    0.008   -0.342
   23   45       804525.1   835920.6    0.328  262.929    0.315  261.000    0.013    1.929
   10   45       783764.6   866165.8    0.356  279.343    0.260  300.100    0.096  -20.757
   53    8       847813.6   792720.2    0.288  249.862    0.289  251.100   -0.001   -1.238
   20   13       788360.1   775841.5    0.305  252.603    0.306  253.900   -0.001   -1.297
   11   15       743756.9   775794.2    0.309  255.095    0.300  270.000    0.009  -14.905
   13   18       760521.1   789294.9    0.312  254.374    0.320  255.500   -0.008   -1.126
   21   13       791076.4   776696.6    0.304  252.397    0.302  254.600    0.002   -2.203
   53    7       850206.1   789995.4    0.284  249.514    0.279  250.300    0.005   -0.786
   12   39       779129.9   851544.2    0.364  281.192    0.247  295.500    0.117  -14.308
   49   21       829049.0   807985.4    0.298  249.426    0.293  248.400    0.005    1.026
   17   22       776489.6   799545.4    0.310  254.702    0.304  256.600    0.006   -1.898
   16   24       774007.5   805668.9    0.314  256.958    0.310  257.000    0.004   -0.042
   62   20       840040.4   817237.8    0.292  248.653    0.289  250.760    0.003   -2.107
   11   45       785944.8   862653.2    0.364  279.848    0.354  282.800    0.010   -2.952
   36    8       824958.8   774211.9    0.293  251.065    0.289  248.900    0.004    2.165
   73   11       878559.9   835186.2    0.277  247.641    0.279  246.900   -0.002    0.741
   31   28       803093.8   812442.0    0.314  254.371    0.315  253.520   -0.001    0.851
   59   34       828875.2   820952.4    0.304  250.274    0.290  253.000    0.014   -2.726
   62   11       848819.3   805095.5    0.285  248.395    0.285  250.440    0.000   -2.045
   41   16       822607.9   796924.9    0.298  249.959    0.300  252.000   -0.002   -2.041
   28    8       810730.1   766048.9    0.294  251.706    0.300  255.000   -0.006   -3.294
   50   23       828898.2   810986.6    0.301  250.374    0.270  247.000    0.031    3.374
*
* Number of stations used   :        24
* Statistics for amplitudes
* Mean           Hc-Ho      :     0.014
* Absolute Mean |Hc-Ho|     :     0.016
* R.m.s. error   Hc-Ho      :     0.033
* Mean           Hc/Ho      :     1.053
* R.m.s. error   Hc/Ho      :     1.059
* Statistics for phases
* Mean           Gc-Go      :    -2.663
* Absolute Mean |Gc-Go|     :     3.509
* R.m.s. error   Gc-Go      :     6.236
* Summed vector difference  :     0.630
*===============================================================================================
* Tidal component    : M2
* ITDATE             : 1996/07/18 00:00:00
* Analysed period    :     11520.,    33840.( in minutes w.r.t. ITDATE)
* Time zone          : Model time
* Units              : m         for ampl.  degrees for phase
* Explanation        : Hc = computed ampl.  Gc = computed phase
*                      Ho = observed ampl.  Go = observed phase
*                      VD = vector difference
*                      M  = m-coordinate station; N = n-coordinate  station
*                      999.99 = not computed due to lack of observations
*
*   M    N    L          X          Y       Hc       Gc       Ho       Go    Hc-Ho    Gc-Go
*-----------------------------------------------------------------------------------------------
*                                      >> water levels <<
W004
   24   12
```

```
   36   36        811663.2   820560.9    0.548  287.100     0.490  309.000    0.058  -21.900
   43   26        820280.2   810920.9    0.443  267.458     0.415  269.430    0.028   -1.972
   23   45        804525.1   835920.6    0.616  298.370     0.573  302.900    0.043   -4.530
   10   45        783764.6   866165.8    0.764  325.602     0.468  345.000    0.296  -19.398
   53    8        847813.6   792720.2    0.384  262.697     0.340  264.600    0.044   -1.903
   20   13        788360.1   775841.5    0.428  268.926     0.409  271.900    0.019   -2.974
   11   15        743756.9   775794.2    0.438  272.459     0.500  309.000   -0.062  -36.541
   13   18        760521.1   789294.9    0.455  273.564     0.441  276.900    0.014   -3.336
   21   13        791076.4   776696.6    0.426  268.781     0.413  272.600    0.013   -3.819
   53    7        850206.1   789995.4    0.366  261.042     0.354  267.100    0.012   -6.058
   12   39        779129.9   851544.2    0.729  327.127     0.403  336.000    0.326   -8.873
   49   21        829049.0   807985.4    0.432  264.874     0.406  260.200    0.026    4.674
   17   22        776489.6   799545.4    0.475  277.895     0.455  280.700    0.020   -2.805
   16   24        774007.5   805668.9    0.489  282.698     0.470  288.000    0.019   -5.302
   62   20        840040.4   817237.8    0.414  263.203     0.390  268.370    0.024   -5.167
   11   45        785944.8   862653.2    0.762  324.846     0.631  334.000    0.131   -9.154
   36    8        824958.8   774211.9    0.391  264.929     0.378  266.500    0.013   -1.571
   73   11        878559.9   835186.2    0.356  256.211     0.333  257.200    0.023   -0.989
   31   28        803093.8   812442.0    0.538  281.132     0.514  285.080    0.024   -3.948
   59   34        828875.2   820952.4    0.461  268.839     0.420  271.000    0.041   -2.161
   62   11        848819.3   805095.5    0.381  260.192     0.346  264.580    0.035   -4.388
   41   16        822607.9   796924.9    0.423  265.409     0.410  272.000    0.013   -6.591
   28    8        810730.1   766048.9    0.396  266.262     0.300  275.000    0.096   -8.738
   50   23        828898.2   810986.6    0.436  266.885     0.360  264.000    0.076    2.885
*
* Number of stations used   :        24
* Statistics for amplitudes
* Mean           Hc-Ho      :     0.056
* Absolute Mean |Hc-Ho|     :     0.061
* R.m.s. error   Hc-Ho      :     0.101
* Mean           Hc/Ho      :     1.133
* R.m.s. error   Hc/Ho      :     1.149
* Statistics for phases
* Mean           Gc-Go      :    -6.440
* Absolute Mean |Gc-Go|     :     7.070
* R.m.s. error   Gc-Go      :    10.623
* Summed vector difference  :     2.217
*=====================================================================================================
* Tidal component    : S2
* ITDATE             : 1996/07/18 00:00:00
* Analysed period    :     11520.,    33840.( in minutes w.r.t. ITDATE)
* Time zone          : Model time
* Units              : m         for ampl.  degrees for phase
* Explanation        : Hc = computed ampl.  Gc = computed phase
*                      Ho = observed ampl.  Go = observed phase
*                      VD = vector difference
*                      M  = m-coordinate station; N = n-coordinate  station
*                      999.99 = not computed due to lack of observations
*
*   M    N    L          X          Y        Hc       Gc        Ho       Go    Hc-Ho    Gc-Go
*-----------------------------------------------------------------------------------------------------
*                                     >> water levels <<
W005
   24   12
   36   36        811663.2   820560.9    0.180  321.711     0.130  337.000    0.050  -15.289
   43   26        820280.2   810920.9    0.162  298.084     0.166  299.890   -0.004   -1.806
   23   45        804525.1   835920.6    0.188  337.966     0.220  336.100   -0.032    1.866
   10   45        783764.6   866165.8    0.212   17.342     0.152   34.000    0.060  -16.658
   53    8        847813.6   792720.2    0.143  292.251     0.155  291.600   -0.012    0.651
   20   13        788360.1   775841.5    0.153  301.692     0.190  301.500   -0.037    0.192
   11   15        743756.9   775794.2    0.153  307.943     0.200  348.000   -0.047  -40.057
   13   18        760521.1   789294.9    0.162  307.927     0.158  319.300    0.004  -11.373
   21   13        791076.4   776696.6    0.152  301.332     0.158  305.000   -0.006   -3.668
   53    7        850206.1   789995.4    0.137  290.149     0.125  293.800    0.012   -3.651
   12   39        779129.9   851544.2    0.201   19.795     0.146   22.300    0.055   -2.505
   49   21        829049.0   807985.4    0.159  295.397     0.165  292.700   -0.006    2.697
```

```
   17   22        776489.6   799545.4    0.168  310.652    0.183  315.400   -0.015   -4.748
   16   24        774007.5   805668.9    0.170  315.585    0.190  321.000   -0.020   -5.415
   62   20        840040.4   817237.8    0.154  292.664    0.156  297.180   -0.002   -4.516
   11   45        785944.8   862653.2    0.211   14.906    0.256   10.400   -0.045    4.506
   36    8        824958.8   774211.9    0.142  295.367    0.159  300.100   -0.017   -4.733
   73   11        878559.9   835186.2    0.138  284.537    0.147  289.700   -0.008   -5.163
   31   28        803093.8   812442.0    0.181  313.882    0.205  317.060   -0.024   -3.178
   59   34        828875.2   820952.4    0.166  300.038    0.170  296.000   -0.004    4.038
   62   11        848819.3   805095.5    0.144  289.638    0.139  292.920    0.004   -3.282
   41   16        822607.9   796924.9    0.156  296.426    0.160  299.000   -0.004   -2.574
   28    8        810730.1   766048.9    0.142  297.338    0.100  305.000    0.042   -7.662
   50   23        828898.2   810986.6    0.159  297.073    0.140  301.000    0.019   -3.927
*
* Number of stations used   :        24
* Statistics for amplitudes
* Mean           Hc-Ho      :    -0.002
* Absolute Mean |Hc-Ho|     :     0.022
* R.m.s. error   Hc-Ho      :     0.029
* Mean           Hc/Ho      :     1.016
* R.m.s. error   Hc/Ho      :     1.034
* Statistics for phases
* Mean           Gc-Go      :    -5.261
* Absolute Mean |Gc-Go|     :     6.423
* R.m.s. error   Gc-Go      :    10.312
* Summed vector difference  :     0.752
*==========================================================================================
...
...
```

E Example of a table B file

In this appendix a part of the Table-B output file from the tutorial is presented.

```
*
* Deltares, TRIANA Version 3.07.00.9446, Nov 11 2009, 12:13:01
*
* TRIANA File Report [I=Input,O=Output]
* ------ ---- ------  -------- --------
* TRIANA  Input    file               [I] : triahkc4.inp
* TRIANA  Observed file               [I] : triahkc4.obs
* TRIANA  Print    file               [O] : tria-fou-ex.prt
* TRIANA  Tabel-A  file               [O] : tria-fou-ex.tba
* TRIANA  Tabel-B  file               [O] : tria-fou-ex.tbb
* Run ident. \DFLOW\ computation  [I] : fou-ex
*
* TRIANA-file : tria-fou-ex.prt
*
*=====================================================================================
* Water levels
* Station          : Chek Lap Kok          c
* (M,N)            : (   36,   36)
* ITDATE           : 1996/07/18 00:00:00
* Analysed period :      11520.,     33840.( in minutes w.r.t. ITDATE)
* Time zone        : Model time
* Units            : m          for ampl.  degrees for phase
* Explanation      : Hc = computed ampl.  Gc = computed phase
*                    Ho = observed ampl.  Go = observed phase
*                    Vd = vector difference (m)
*                    999.999 = not computed due to lack of  observations
*
* Freq        Hc        Gc        Ho        Go     Hc-Ho     Gc-Go     Hc/Ho        VD  Comp
*-------------------------------------------------------------------------------------
W001
   10     9
 0.00  1.35335  999.999  999.999  999.999  999.999  999.999  999.999  999.999  A0
15.04    0.371  306.711    0.400  310.000   -0.029   -3.289    0.929    0.036  K1
14.96    0.119  302.461  999.999  999.999  999.999  999.999  999.999  999.999  P1
13.94    0.320  258.065    0.290  258.000    0.030    0.065    1.105    0.030  O1
28.98    0.548  287.100    0.490  309.000    0.058  -21.900    1.118    0.205  M2
30.00    0.180  321.711    0.130  337.000    0.050  -15.289    1.381    0.064  S2
30.08    0.052  321.711  999.999  999.999  999.999  999.999  999.999  999.999  K2
28.44    0.074  276.809  999.999  999.999  999.999  999.999  999.999  999.999  N2
57.97    0.036   42.076  999.999  999.999  999.999  999.999  999.999  999.999  M4
58.98    0.027  100.089  999.999  999.999  999.999  999.999  999.999  999.999  MS4
*
* Standard deviation of tidal analysis :      0.052
* Lower extreme for residuals          :     -0.143
* Upper extreme for residuals          :      0.158
* Summed vector difference             :      0.336
*=====================================================================================
* Water levels
* Station          : RO Chi Ma Wan      oc
* (M,N)            : (   43,   26)
* ITDATE           : 1996/07/18 00:00:00
* Analysed period :      11520.,     33840.( in minutes w.r.t. ITDATE)
* Time zone        : Model time
* Units            : m          for ampl.  degrees for phase
* Explanation      : Hc = computed ampl.  Gc = computed phase
*                    Ho = observed ampl.  Go = observed phase
*                    Vd = vector difference (m)
*                    999.999 = not computed due to lack of  observations
*
* Freq        Hc        Gc        Ho        Go     Hc-Ho     Gc-Go     Hc/Ho        VD  Comp
*-------------------------------------------------------------------------------------
```

```
W002
   10    9
  0.00  1.26852  999.999  999.999  999.999  999.999  999.999  999.999  999.999  A0
 15.04    0.362  299.272    0.365  299.170   -0.003    0.102    0.992    0.003  K1
 14.96    0.116  295.022    0.114  293.510    0.002    1.512    1.013    0.003  P1
 13.94    0.301  250.368    0.293  250.710    0.008   -0.342    1.026    0.008  O1
 28.98    0.443  267.458    0.415  269.430    0.028   -1.972    1.067    0.032  M2
 30.00    0.162  298.084    0.166  299.890   -0.004   -1.806    0.974    0.007  S2
 30.08    0.047  298.084    0.047  297.710    0.000    0.374    0.999    0.000  K2
 28.44    0.078  251.509    0.087  253.960   -0.009   -2.451    0.893    0.010  N2
 57.97    0.040    3.778    0.035  340.440    0.005   23.338    1.148    0.016  M4
 58.98    0.026   63.743    0.022   30.560    0.005   33.183    1.212    0.014  MS4
*
* Standard deviation of tidal analysis :      0.030
* Lower extreme for residuals         :     -0.085
* Upper extreme for residuals         :      0.070
* Summed vector difference            :      0.094
*=====================================================================================
* Water levels
* Station         : S Chi Wan         oc
* (M,N)           : (  23,  45)
* ITDATE          : 1996/07/18 00:00:00
* Analysed period :     11520.,    33840.( in minutes w.r.t. ITDATE)
* Time zone       : Model time
* Units           : m         for ampl.  degrees for phase
* Explanation     : Hc = computed ampl.  Gc = computed phase
*                   Ho = observed ampl.  Go = observed phase
*                   Vd = vector difference (m)
*                   999.999 = not computed due to lack of  observations
*
* Freq       Hc       Gc       Ho       Go    Hc-Ho    Gc-Go    Hc/Ho       VD  Comp
*-------------------------------------------------------------------------------------
W003
   10    9
  0.00  1.38148  999.999  999.999  999.999  999.999  999.999  999.999  999.999  A0
 15.04    0.371  311.857    0.396  310.900   -0.025    0.957    0.938    0.025  K1
 14.96    0.119  307.607    0.120  312.800   -0.001   -5.193    0.990    0.011  P1
 13.94    0.328  262.929    0.315  261.000    0.013    1.929    1.040    0.017  O1
 28.98    0.616  298.370    0.573  302.900    0.043   -4.530    1.075    0.064  M2
 30.00    0.188  337.966    0.220  336.100   -0.032    1.866    0.856    0.032  S2
 30.08    0.055  337.966    0.071  337.200   -0.016    0.766    0.772    0.016  K2
 28.44    0.072  292.131    0.123  287.400   -0.051    4.731    0.585    0.052  N2
 57.97    0.028   68.363    0.041   78.000   -0.013   -9.637    0.677    0.014  M4
 58.98    0.024  121.088    0.030  131.600   -0.006  -10.512    0.802    0.008  MS4
*
* Standard deviation of tidal analysis :      0.054
* Lower extreme for residuals         :     -0.178
* Upper extreme for residuals         :      0.169
* Summed vector difference            :      0.239
*=====================================================================================
* Water levels
* Station         : Chuanbi Jiao       c
* (M,N)           : (  10,  45)
* ITDATE          : 1996/07/18 00:00:00
* Analysed period :     11520.,    33840.( in minutes w.r.t. ITDATE)
* Time zone       : Model time
* Units           : m         for ampl.  degrees for phase
* Explanation     : Hc = computed ampl.  Gc = computed phase
*                   Ho = observed ampl.  Go = observed phase
*                   Vd = vector difference (m)
*                   999.999 = not computed due to lack of  observations
*
* Freq       Hc       Gc       Ho       Go    Hc-Ho    Gc-Go    Hc/Ho       VD  Comp
*-------------------------------------------------------------------------------------
W004
   10    9
```

```
  0.00  1.44519  999.999  999.999  999.999  999.999  999.999  999.999  999.999  A0
 15.04    0.376  327.379    0.291  348.500    0.085  -21.121    1.293    0.148  K1
 14.96    0.120  323.129    0.088  350.400    0.032  -27.271    1.369    0.058  P1
 13.94    0.356  279.343    0.260  300.100    0.096  -20.757    1.368    0.145  O1
 28.98    0.764  325.602    0.468  345.000    0.296  -19.398    1.632    0.358  M2
 30.00    0.212   17.342    0.152   34.000    0.060  -16.658    1.395    0.079  S2
 30.08    0.062   17.342    0.049   35.100    0.013  -17.758    1.259    0.021  K2
 28.44    0.063  342.094    0.094  348.400   -0.031   -6.306    0.667    0.032  N2
 57.97    0.092  211.999    0.073  245.200    0.019  -33.201    1.257    0.050  M4
 58.98    0.051  275.671    0.042  325.000    0.009  -49.329    1.213    0.040  MS4
*
* Standard deviation of tidal analysis :      0.107
* Lower extreme for residuals          :     -0.315
* Upper extreme for residuals          :      0.298
* Summed vector difference             :      0.933
*=====================================================================================
* Water levels
* Station          : Dangan Isl         c
* (M,N)            : (  53,   8)
* ITDATE           : 1996/07/18 00:00:00
* Analysed period :     11520.,    33840.( in minutes w.r.t. ITDATE)
* Time zone        : Model time
* Units            : m         for ampl.  degrees for phase
* Explanation      : Hc = computed ampl.  Gc = computed phase
*                    Ho = observed ampl.  Go = observed phase
*                    Vd = vector difference (m)
*                    999.999 = not computed due to lack of  observations
*
* Freq       Hc       Gc       Ho       Go    Hc-Ho    Gc-Go    Hc/Ho       VD  Comp
*-------------------------------------------------------------------------------------
W005
   10    9
  0.00  1.23210  999.999  999.999  999.999  999.999  999.999  999.999  999.999  A0
 15.04    0.352  298.937    0.348  300.700    0.004   -1.763    1.011    0.011  K1
 14.96    0.113  294.687    0.100  293.200    0.013    1.487    1.126    0.013  P1
 13.94    0.288  249.862    0.289  251.100   -0.001   -1.238    0.996    0.006  O1
 28.98    0.384  262.697    0.340  264.600    0.044   -1.903    1.129    0.045  M2
 30.00    0.143  292.251    0.155  291.600   -0.012    0.651    0.921    0.012  S2
 30.08    0.042  292.251    0.043  299.600   -0.001   -7.349    0.967    0.006  K2
 28.44    0.073  246.523    0.073  251.900    0.000   -5.377    0.993    0.007  N2
 57.97    0.036  338.755    0.043  301.000   -0.007   37.755    0.826    0.026  M4
 58.98    0.024   44.921    0.025  203.400   -0.001 -158.479    0.977    0.049  MS4
*
* Standard deviation of tidal analysis :      0.012
* Lower extreme for residuals          :     -0.033
* Upper extreme for residuals          :      0.028
* Summed vector difference             :      0.176
. . .
. . .
```

F Article about tidal analysis

Tidal Model validation of the Seas of South East Asia using Altimeter Data and Adjoint Modelling

H. Gerritsen 1, E.J.O. Schrama 2, H.F.P. van den Boogaard 1

1) WL | DELFT HYDRAULICS, P.O. Box 177, 2600 MH DELFT, The Netherlands
2) Delft Institute for Earth-Orientated Space Research (DEOS), Delft, The Netherlands.

ABSTRACT

Focusing on depth-integrated numerical modelling of barotropic tides in the South China Sea and the seas of the Indonesian Archipelago, the tidal representation of a limited area tidal model was analysed and validated in two steps. First, TOPEX-POSEIDON altimeter data at track cross over points was introduced as offshore tidal information to complement the common four-constituent in-situ tidal data. The altimeter data provided five additional tidal constituents for the modelling, and indicated the need for adjustment of the open ocean tidal forcing of the South China Sea. Subsequently this led to a significantly improved tidal representation in the deeper parts of the model. Using the new model representation as starting point, the adjoint technique was used to perform a sensitivity analysis on the model, focusing on the shallower parts, to improve and validate these in a quantitative and objective way. The parameters considered represent the specification of the tidal components at the open boundaries, the depth in the shallow regions and the bed friction coefficient. The tidal behaviour was again found to depend strongly on the tidal specification at the open boundaries, while subsequently it showed much less sensitivity to the depth and bed friction used. It is concluded that the use of tidal information from altimetry, together with model calibration using an adjoint modelling technique, leads to quantitative insight in model behaviour and provides a structured approach to model validation.

KEYWORDS

Barotropic tidal models, Tidal modelling, Altimeter data, Adjoint modelling, Model calibration

1 Introduction

The South China Sea and the seas of the Indonesian Archipelago essentially consist of a series of interconnected basins, each with specific characteristic length and depth scales, separated by sills. Not only is the geometry of the region extremely intricate, but the two main diurnal and the two main semi-diurnal tides are all important. Phase plots for the diurnal and semi-diurnal tides show propagation from both the Pacific and Indian Oceans. The observed behaviour of these seas, Fig. 1, has been well documented by Wyrtki (1961). Since his report, there have been other substantial observational studies. The overall description provided by Wyrtki remains substantially true, however.

Altimeter-based data such as that recorded on the TOPEX-POSEIDON (T/P) satellite provides spatial coverage where no tidal station data are available, notably far offshore and in the deep waters of the South China Sea proper. It may complement or may replace data representing more local effects. In this study, the T/P satellite altimeter data essentially complements the well-defined near-coast in-situ tidal measurement data sets that are used. In total, 25 'cross-over' points between the ascending tracks and the descending tracks of the T/P data are used, retrieved from eight years of data, while 71 in-situ tide gauge based data sets were selected as being both of good quality and relatively free of highly local influences.

The adjoint method is used as a calibration technique to adjust uncertain model parameters to best achieve global agreement with observations. Briefly, the method seeks to determine the value of parameters used in the model such that some objective function or Goodness-of-Fit criterion is minimized. This is done subject to the governing equations of the model, which are handled in the minimization as constraints using Lagrange multipliers. The key is that the combination of adjoint and forward model provides an efficient computation of the cost function gradient. This gradient is then used in gradient descent techniques for actual, iterative minimization of the cost function. The advantage of the method over more traditional calibration methods is that it enables a large number of parameters to be adjusted simultaneously. Thus while traditional calibration may realistically allow say five to ten parameters to be adjusted in the model used here, the use of the adjoint method enables many more relevant parameters to be adjusted jointly (in this study 120 or more) and much more efficiently. Care is needed to ensure that the model is not 'over fitted' to the available data.

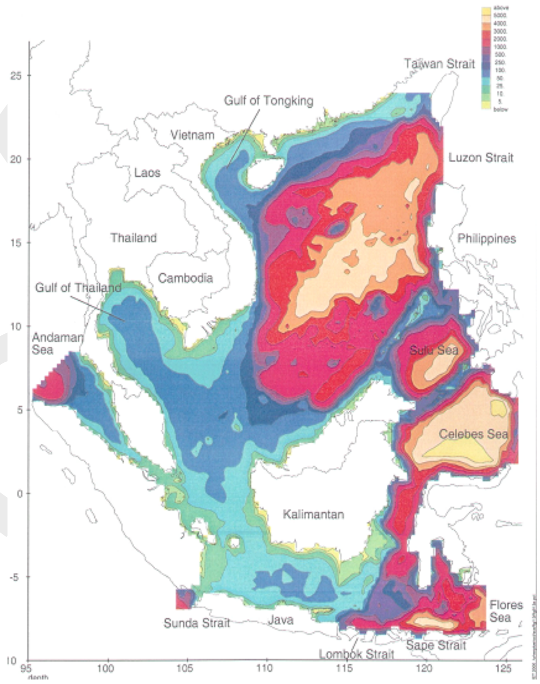


Fig. 1. Map of the seas of South East Asia with (model) bathymetry; red (dark) indicates depths > 1000m.

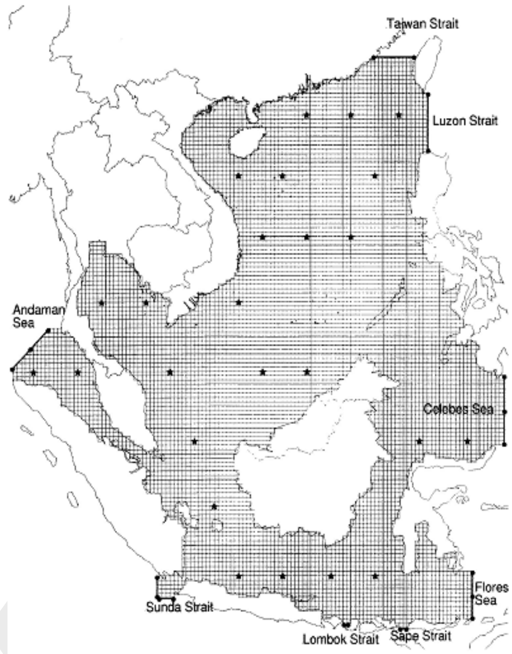


Fig. 2. The 1/4° by 1/4° Arakawa C-grid. The asterisks indicate the locations of the T/P altimeter cross-overs.

2 THE INITIAL TIDAL MODEL

Starting point of the study is a given tidal model application, defined as a barotropic depth-integrated time stepping model with variable Coriolis parameter on a 0.25^0 by 0.25^0 spherical, staggered Arakawa C-grid, advancing with a time step of 5 minutes, see Fig. 2. Its configuration is essentially that of Khanh (1998). While the topography of the basins of the Indonesian Archipelago is often extremely steep, at the resolution of the model all slopes are significantly less than unity and the use of the hydrostatic approximation is justifiable. The application uses the DELFT3D generic shallow water flow modelling system including tide generating forces (WL | Delft Hydraulics, 1999). Bed friction is parameterized using a Manning friction coefficient of 0.026, with local values 0.015 on the Vietnamese shelf and a value 0.500 across the archipelagos separating the Sulu and South China Seas, and the Sulu and Celebes Seas, to parameterise the effect of partly unresolved islands and underwater ridges. Khanh's tidal model was based on representation of the 4 tidal constituents O_1, K_1, M_2 and S_2, which were prescribed at the eight open ocean boundaries, see Fig. 2. Published amplitudes and phases of these four constituents from the Admiralty Tide Tables had been used to validate the model representation. Model simulations covered a period of one month, allowing for a full decomposition of the modelled local tidal series in the tidal constants of interest. The quality of the tidal model representation of Khanh's model (1998) is defined using summed vector differences at a number of selected representative tidal stations, with special interest in the Vietnamese coastal zone:

$$J = \sum_1 \sum_2 \sqrt{[H_c \cos(f_c) - H_o \cos(f_o)]^2 + [H_c \sin(f_c) - H_o \sin(f_o)]^2} \qquad \text{(F.1)}$$

where H_c, H_o, f_c, f_o are the computed and observed astronomical amplitude and phase of a given tidal constituent. $\sum_1$ refers to a summation over the stations, $\sum_2$ refers to summation over the four main tidal constituents O_1, K_1, M_2, S_2.

In quantitative sense the quality of the tidal model representation is given in Table 1:

	M2	S2	O1	K1	Summed
Group A (11 stations)	15.5	5.5	17.3	20.0	58.3
Group C (34 stations)	22.6	10.0	8.1	12.6	53.3

Table 1: Group-averaged vector differences in cm per tidal constituent, showing the initial quality of the tidal model, based on comparison of tidal data at 11+34 selected coastal stations in the area

Here, Group A is a set of 11 Vietnamese coastal stations, and Group C is a set of 34 stations in the shallow Java Sea and other shelf areas, see Fig. 3.

3 ALTIMETRY TIDAL DATA

For over a decade now, TOPEX and POSEIDON satellites have provided continuous and systematic data streams of altimetry data, which can be used to reliably extract tidal constituents at the 7 km pulse interval along the ascending and descending ground tracks, see e.g. Schrama and Ray (1994). For this study, high quality tidal constants were extracted for the nine primary constituents O1, K1, M2, S2 , Q1, P1, 2N2, N2, and K2 from a systematic database maintained by one of the authors which contained about eight years of data at the time (Schrama et al, 2000). Considering the cross-over positions of ascending and descending tracks, and applying local along-track averaging to smooth out possible baroclinic effects, sets of tidal constants at 25 positions in the area of interest were established which can directly be used for validation of a barotropic tidal model (Fig. 2). The benefit of the altimeter data to the modelling is twofold. Firstly, the information given by the behaviour of the additional five constituents can be used to estimate and validate oceanic tidal forcing in terms of those tidal contributions, and so essentially extend the tidal physics represented by the model. Secondly, the difference at the cross-over points between the modelled and observed large-scale tidal behaviour - which is practically linear over the South China Sea - gives information for systematic adjustment of the model parameters.

From the altimetry based tidal data over this deep water body, it is immediately observed that the open ocean tidal forcing through Luzon Strait is the determining parameter for the large scale tidal behaviour in the South China Sea. Based on evaluation for the earlier data sets A and C plus 10 well-chosen altimetry cross-over points (Group B), manual adjustment of mainly the open ocean tidal forcing through Luzon Strait boundary led to significant improvement of the tidal model for the four main constituents, see Table 2. The parameter adjustments improved the representation at the cross-over points (Group B) by 37%, those on the Vietnamese shelf part (Group A) by 22%, but gave only limited improvement for the other shelf stations (Group C, 8%), mainly stations in the Java Sea and its approaches.

	M2		S2		O1		K1		Summed		Improvement
Dataset:	after	before	after	before	after	before	after	before	after	before	
Group A (11 st.)	10.0	15.5	5.5	5.5	14.5	17.3	15.5	20.0	45.5	58.3	22%
Group B (10 st.)	8.0	11.0	4.0	4.0	2.0	5.0	5.0	10.0	19.0	30.0	37%
Group C (34 st.)	19.1	22.6	10.0	10.0	7.6	8.1	12.4	12.6	49.1	53.3	8%

Table 2: Group-averaged vector differences in cm per tidal constituent, showing the improvement during the sensitivity analysis and adjustment as a result of including altimetry data, based on comparison of tidal data at $11 + 10 + 34$ selected coastal stations in the area

Clearly, a more structured quantified calibration of the model is required, addressing a wider parameter variation. Given the complexity of the area with its many characteristic length scales, basin depths and sills, and resulting tidal resonance patterns, such a huge calibration effort is difficult to achieve with manual adjustment of model parameters. For this reason we have chosen for the adjoint modelling scheme to adjust boundary conditions, bathymetry and bed friction in order to accomplish automatic calibration.

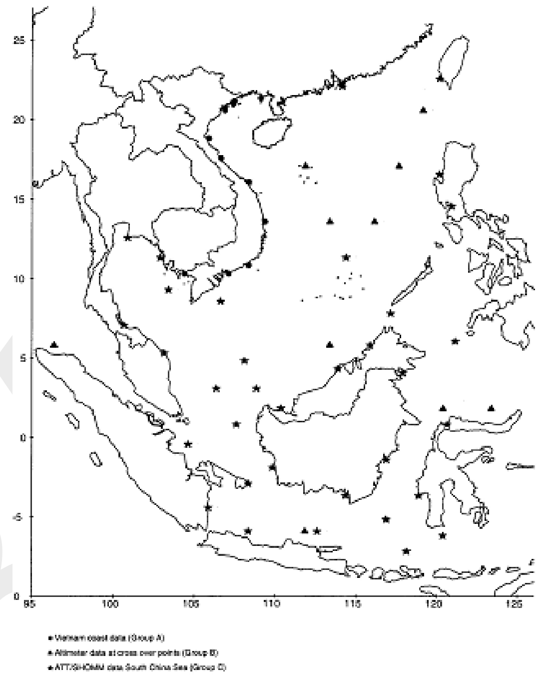


Fig. 3. Distribution of the in-situ stations and cross-over points used for the validation with altimeter data.

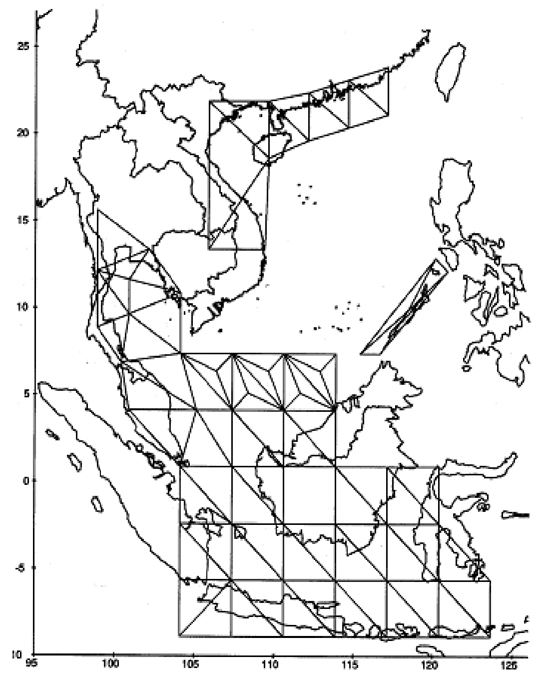


Fig. 4. Triangles used in the adjoint modelling calibration of the depth and bed friction coefficient, focussing on the shallow shelf regions.

4 THE ADJOINT CALIBRATION APPROACH

UNCERTAIN PARAMETERS IN THE TIDAL MODEL

There are only a few groups of uncertain parameters in a depth-integrated barotropic tidal model application: bathymetry, bed friction (both are sensitive mainly in the shelf parts) and the open ocean tidal forcing prescribed at the open boundaries. Due to the scale of and the physical realism of the model we ignored effects such as horizontal viscosity. The problem of parameter variation of depths and bed friction coefficients is simplified by first constructing a triangular net over the area, with higher detail in areas where much spatial variation or effect is expected. Multiplication factors of depth and/or bed friction parameter in the nodes are then defined as the parameters that need to be estimated. This provides a useful reduction of the number of parameters compared to considering values at individual grid points, and ensures spatial continuity of the resulting adjustment, see Fig. 4. Values of the depth and friction coefficient at non-internal points of the triangles in Fig. 4 were not adjusted, to avoid discontinuities with the remaining parts of the model domain.

FORMULATION OF THE COST FUNCTION

The adjoint modelling technique has been described by Panchang and O'Brien (1990), Das and Lardner (1992) and others. It involves minimizing some cost function, e.g.

$$J\left(\vec{p}\right) = \sum_{\vec{r},t} \left(\frac{h^t_{\vec{r}}(\vec{p}) - \hat{h}^t_{\vec{r}}}{\sigma^t_{\vec{r}}} \right)^2 \tag{F.2}$$

subject to constraints in the form of equations for horizontal momentum and continuity. Here $J\left(\overrightarrow{p}\right)$ is the functional to be minimized, $\overrightarrow{p}$ is the property (parameters describing adjustment in open boundary tidal elevation, depths or bed friction coefficients) with which $J\left(\overrightarrow{p}\right)$ is being minimized, $h^t_{\overrightarrow{r}}\left(\overrightarrow{p}\right)$and $\widehat{h^t_{\overrightarrow{r}}}$ are the model predicted tidal elevation and the observed tidal elevation respectively, $\sigma^t_{\overrightarrow{r}}$is the inverse weighting given to a particular station. The weight is a measure for the associated uncertainty in the data. The summation is done over all stations and all time steps. Contrary to the vector difference Eq F.1, the present cost function Eq. F.2 is formulated in the time domain, i.e. summation over the simulation period. This period of optimization of the model performance is again one month, 1st July 2000 to 1st August 2000, characterized by both strong diurnal and strong semi-diurnal spring-neap effects. Tidal analysis and prediction then provides the relation between the time series and the tidal amplitudes and phases of interest. The minimization of F.2, involves 71 selected in-situ tidal stations plus 25 T/P cross-overs. All T/P data refer to cross-overs at least 75 km from the coast, to avoid contamination of the processing due to land-sea transitions. The data available for model validation are divided into a calibration set (53 stations) and one to be used for validation (43 stations), both showing a very good spatial distribution, see Fig. 5. The 25 T/P data sets are equally well distributed over the calibration set (12) as in the validation set (13).

OCEAN TIDAL FORCING

As no detailed tidal observations are available along the open ocean boundaries, minimum weighting, effectively zero, is given to earlier values at the open boundaries during the adjoint simulations. At each tidal observation station the spread σ was taken as proportional to the tidal range. For the case of analysing the sensitivity of the tides in the Java Sea to the prescribed ocean tidal forcing at the Celebes Sea and Flores Sea, the total degrees of freedom or dimension of p is $4 \times 2 \times 2 \times 2 = 32$ (the four main tidal constituents O_1, K_1, M_2, S_2, each with amplitude and phase, and two support points for each of the two open sea boundaries, see Fig. 2). Adjustments for the related constituents follow from those of K_1 and S_2, respectively. The less important tidal components Q_1, $2N_2$, and N_2 were left unchanged. With their much smaller volume fluxes, the influence on the tidal behaviour in the Java Sea of the three openings to the Indian Ocean may be expected to be very small.

BATHYMETRY AND BED FRICTION DISSIPATION

The second and third groups of parameters *p* are the multiplicative adjustments in depth and bed friction values at the nodes, respectively, restricted to the shelf areas (depths less than 200 *m*) plus the region of the islands and sills between the South China Sea and the Sulu Sea, see the discussion in Section 2. For depths exceeding 200 *m*, the sensitivity of the model performance to depth variation obviously is limited. A quadratic penalty function is introduced into the expression Eq. F.2 for $J(p)$, when calibrating these two quantities, to restrict maximum variations to about 10% of the pre-existing model value and so avoid physically unrealistically large variations.

5 APPLICATION TO THE SOUTH-EAST ASIAN WATERS

PRACTICAL EVALUATION CRITERION

For the evaluation of simulation results a weighted standard deviation has been applied

$$SD_{weigthed} = \sqrt{\frac{\sum_{m,n,t}\left(\frac{h^t_{m,n}(\vec{p}) - \hat{h}^t_{m,n}}{\sigma_{m,n}}\right)^2}{\sum_{m,n,t}\left(\frac{1}{\sigma_{m,n}}\right)^2}} \tag{F.3}$$

which is closely related to the functional J(p) Eq.F.2.

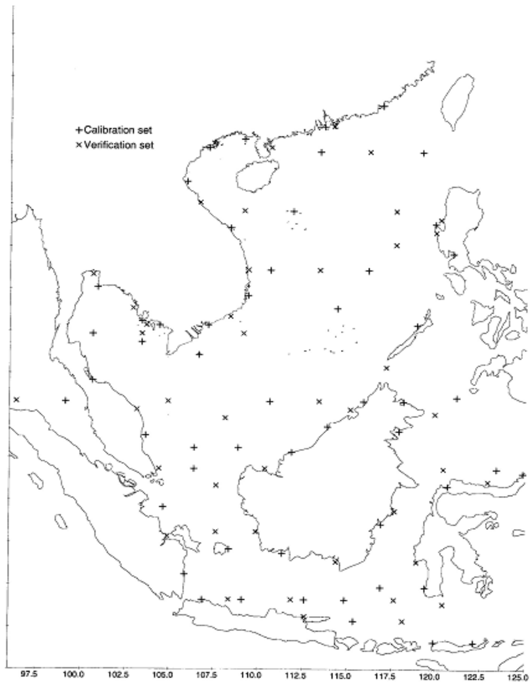


Fig. 5. Distribution of the 53 calibration and 43 validation stations / cross-over positions used in the adjoint modelling calibration.

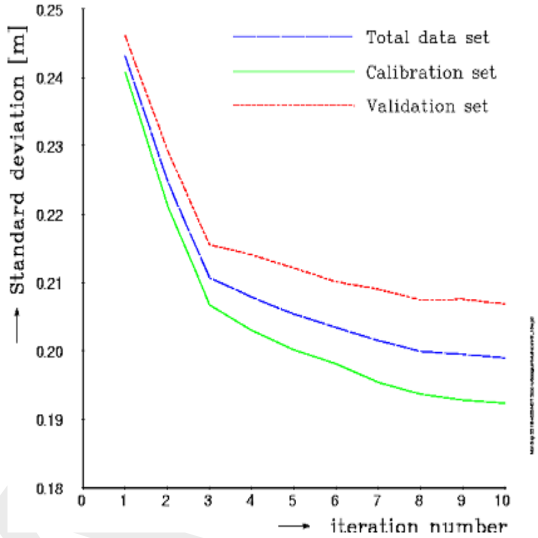


Fig. 6 Decrease in the weighted standard deviation evaluation norm with iteration for the adjustment of the tidal prescription along the Celebes Sea and Flores Sea open boundaries. The sharp decrease with the useful, first few iterations contrasts with the flat response later where noise dominates.

ANALYSIS OF SENSITIVITIES

Using the adjoint modelling approach as the parameter estimation technique, six successive simulations of systematic parameter variations have been made, to optimise the relevant parameters selected along the criteria discussed in the previous paragraphs. A description is presented in Table 3, including the result based on the weighted criterion Eq. (F.3).

Case	Sensitivities analyzed	p	N_{iter}	Initial value of $SD_{weighted}$ (cm)	Final value of $SD_{weighted}$ (cm)
0	Reference simulation; the model state including the adjustment using newly introduced altimetry data	–	–	–	24.4
1	Amplitudes and phases of O_1, K_1, M_2 and S_2 along the Celebes and Flores Seas open boundaries.	32	4	24.4	20.8
2	Starting from 1, amplitudes and phases of O_1, K_1, M_2 and S_2 along the three small southern open boundaries openings to the Indian Ocean	56	6	20.77	20.65
3	Amplitudes and phases as in 1, but now for all the model's open boundary sections	120	6	24.4	19.8
4	Starting from 3, depth at pre-defined shelf and sill subdomains; no penalty on maximum variation	44	4	19.8	19.0
5	Starting from 3, depth at pre-defined shelf and sill subdomains; Penalty: maximum variation = 10%	47	8	19.8	19.6
6	Starting from 3, bed friction at pre-defined shelf and sill subdomains; Penalty: maximum variation = 10%	46	1	19.84	19.82

Table 3: List of the sensitivity calculations in the order in which the analysed variables were updated; evaluation using weighted standard deviation, Eq. F.3. Here, p and N_{iter} are the number of uncertain parameters and significant iterations, respectively.

MINIMIZATION PROCEDURE

The procedure to minimize $J(p)$ is an iterative one since it is based on gradient descent techniques. Fig. 6 shows the rate of decrease in $J(p)$ with iteration number for the case of the variation of the ocean tidal forcing at the Celebes and Flores Sea open boundaries for both the calibration and validation data sets and the total set. Typical of the rate of decrease in $J(p)$, this figure shows a dramatic decrease in $J(p)$ for the first few iterations followed by a negligible response. This behaviour indicates that the first few correction steps are significant but that general noise in the system is obtained after about 10 steps. This is true for all cases investigated. Given moreover the consistent behaviour in both validation and calibration data sets, it is concluded that the minimization of $J(p)$ has indeed produced a meaningful improvement in the model performance.

6 DISCUSSION OF RESULTS

In the adjoint calibration of the order of 250 parameters were adjusted. Overall, corrections of the order of 20% in criterion Eq. F.3 were obtained during the calibration. This is additional to the model enhancement using altimetry information - with main focus on the South China Sea -, see Section 3. The present improvement represents the influence of the increased availability of calibration data but above all the use of much better and structured quality control on data and model parameters by means of application of adjoint modelling. The major improvement in case 1 shows that the decrease in $J(p)$ essentially comes from the improvement in the boundary specification at the Celebes Sea and Flores Sea open boundaries. Given that improvement, either the sensitivity to depth and friction coefficient variations has practically disappeared, or the initial guess was already quite adequate. Some of the calibration which would normally be taken by adjusting one quantity may be taken by adjusting another quantity earlier. Calculation of the function representing the gradient of $J(p)$ with respect to the depth, which is a measure for the sensitivity to depth variation, shows that where as the gradient was extremely strong in the Java and Flores Seas before calibration of the open boundaries it was slight after this calibration. A similar but weaker decrease in sensitivity occurred with respect to the bed friction coefficient in the Java and Flores Seas after calibration of the open boundaries.

The improvements obtained by the above two-step validation using quantitative, objective criteria and a formalised technique, are often striking when comparing the well-known time series of water level in individual stations before and after the validation study. The least acceptable representation of the tidal behaviour throughout the entire basin is in the Sulu Sea basin. Although this basin improved during calibration, its modelling clearly suffers from a lack of available tidal data, see Fig. 5, and the complicated forcing from surrounding seas across partly sub-surface ridges with its mix of diurnal and semi-diurnal tides.

7 Conclusions

The present study has shown that for large and complicated coastal ocean regions with strong variations in depths such as the Indonesian waters and the South China Sea, altimetry data provide unique tidal information to significantly improve and validate a numerical tidal model. Similarly, adjoint modelling techniques provide a powerful structured and quantitative means for sensitivity analysis, joint variation of hundreds of parameters and model calibration, which goes much beyond the common calibration techniques in use in hydraulic engineering.

Acknowledgements
The study presented here was funded by the Netherlands Remote Sensing Board under Contract Nr. 2.1/DE-09, and co-funded by WL | Delft Hydraulics' R&D programme and the Delft Institute of Earth-Oriented Space Research (DEOS).

The Netherlands National Institute for Coastal and Marine Management/ RIKZ, kindly supplied the RIKZ-WAQAD adjoint modelling package. Special thanks are due to T. van der Kaaij and D. Verploegh for realising most of the computer programming that was required.

References

Das, S. K. and R.W. Lardner, 1992: Variational Parameter Estimation for a Two-Dimensional Numerical Tidal Model. *Int. J. Num. Meth. Fluids*, 15, 313-327.

Khanh, T. G., 1998: *Sensitivity Analyis of the South China Sea Model.* Thesis sub. for M. Sc. Hydroinformatics. International Institute for for Infrastructural Hydraulic and Environmental Engineering / WL | Delft Hydraulics, Delft, 75pp.

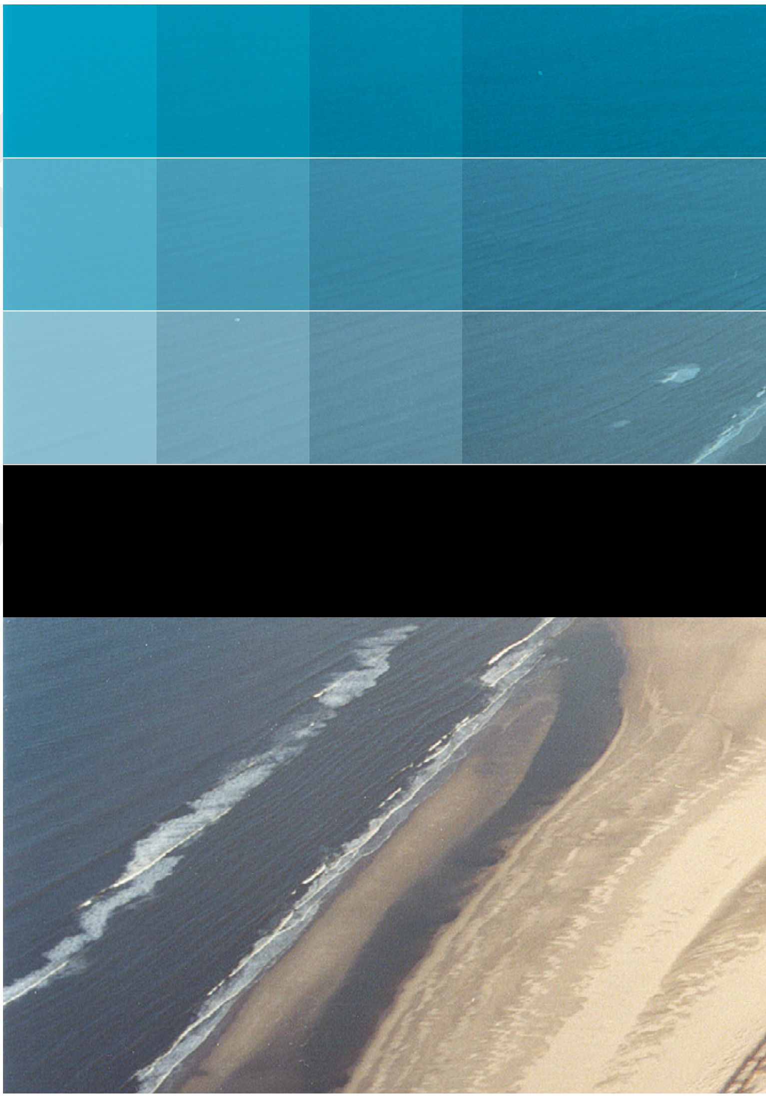
Panchang, V. G. and J. J. O'Brien, 1990: On the Determination of Hydraulic Model Parameters Using the Adjoint State Formulation. *Modelling Marine Systems*, A. M. Davies, Ed., CRC Press Inc., 1, 5-18.

Schrama E. and R. Ray, 1994: A preliminary tidal analysis of TOPEX/POSEIDON altimetry. *J. Geophys. Res. Oceans*, 99, No. C12, 24,799 - 24,808.

Schrama E., R. Scharroo & M. Naeije, 2000 *Radar Altimeter Database System (RADS): Towards a generic multi-purpose altimeter database system*. Netherlands Remote Sensing Board (BCRS) report

WL | Delft Hydraulics, 1999: *Delft3D-Flow modelling software.* WL | Delft Hydraulics, Delft, The Netherlands, 307pp.

Wyrtki, K., 1961: *Scientific Results of Investigations of the South China Sea and the Gulf of Thailand.* NAGA Report, Vol. 2. Univ. California, Scripps Inst. Oceanogr., La Jolla. 155-163, 194-195.



Deltares systems

PO Box 177
2600 MH Delft
Rotterdamseweg 185
2629 HD Delft
The Netherlands

+31 (0)88 335 81 88
sales@deltaressystems.nl
www.deltaressystems.nl