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Benchmarking Hydraulic River Modelling Software Packages

Results – Test O (Tidally Influenced Outfall)

R&D Technical Report: W5-105/TR2 O

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Statement of use

This document provides the results and findings from undertaking the Environment Agency's Benchmarking Test O (Tidally Influenced Outfall) for hydraulic river modelling software. The results only relate to the ISIS, MIKE 11 and HEC-RAS software packages and inference to the likely performance to other software packages should not be made.

The findings are intended to be a supplementary resource for Defra and Agency staff, research contractors and consultants, academics and students for assessing the applicability of any one of these software packages for their own modelling requirements. This report should not be considered in isolation and should be read in conjunction with the other tests reports produced as part of this R&D project.

Keywords

Hydraulic Modelling, River Modelling, Benchmarking, Test Specifications, Tidal Outfall, Culvert

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EXECUTIVE SUMMARY

The undertaking of this test has proven to be possible with both the ISIS and MIKE 11 software packages; however, HEC-RAS has not been able to solve this test case.

The failure of HEC-RAS to solve this test case is due to the inability of the software package to consider an outfall that is operated by water level rules. A subsequent release of the software has the functionality to model the opening and closing of a sluice structure based on water level control which should provide the functionality required for this test. Hence, it is recommended that this should be benchmarked in due course.

Differences between the ISIS and MIKE 11 water level results, which have been up to 0.15m (approx.), have highlighted the variation in performance of the two software packages. Consequently, and without relevant calibration data, there is the scope to either over or under design engineering solutions.

The ISIS results at the downstream limit of the model have exhibited unexpected peaks in discharge at periods of high slack-water. It has not been possible to reach firm conclusions as to the validity or cause of this.

Both ISIS and MIKE 11 have the ability to include an artificial slot in the bed topography so as to improve model stability and convergence. It is recommended that further study be made as to the impact on accuracy the use of this feature may have on results.

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1 INTRODUCTION

1.1 Background

This report presents the results and findings from Test O (Tidally Influenced Outfall) of the Environment Agency of England and Wales (EA), Benchmarking and Scoping Study (2004). The study, which encompasses a series of tests, is intended to be an independent research investigation into the accuracy, capability and suitability of the following one-dimensional hydraulic river modelling software packages:

Software	Version		Developer
ISIS	User Interface:	2.0 (13/01/01)	Halcrow /
	Flow Engine:	5.0.1 (27/06/01)	Wallingford Software
MIKE11	User Interface:	Build 5-052 (2001b)	DHI Water and Environment
	Flow Engine:	5.0.5.5	
HEC-RAS	User Interface:	3.1.0 (Beta) (03/02)	US Corps of Engineers
	Pre-processor:	3.1.0 (Beta) (03/02)	
	Steady Flow Engine:	3.1.0 (Beta) (03/02)	
	Unsteady Flow Engine:	3.1.0 (Beta) (03/02)	
	Post-processor:	3.1.0 (Beta) (03/02)	

Each of the above software packages was tested in the previously undertaken benchmarking study (Crowder *et al*, 1997). They are currently on the EA's BIS-A list of software packages for one-dimensional hydraulic river modelling.

The test has been undertaken on behalf of the EA by the following team in accordance with the Benchmarking Test Specification - Test O (Tidally Influenced Outcall), (Crowder *et al,* 2004):

	Role	Affiliation
Mr Andrew Pepper	EA Project Manager	ATPEC River Engineering
Dr Richard Crowder	Study Project Manager/ Tester	Bullen Consultants Ltd
Dr Nigel Wright	Advisor	University of Nottingham
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Dr Andrew Sleigh	Advisor	University of Leeds
Dr Chris Tomlin	Advisor	Environment Agency
Dr Mohammad Dastorani	Tester/Reporter	University of Nottingham

1.2 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model flapped outfalls that are influenced by both tidal and fluvial boundary conditions; and

- present the particulars for developing and undertaking the tests (Model Build) with each of the software packages and the associated results so that others can repeat the test with their own software.

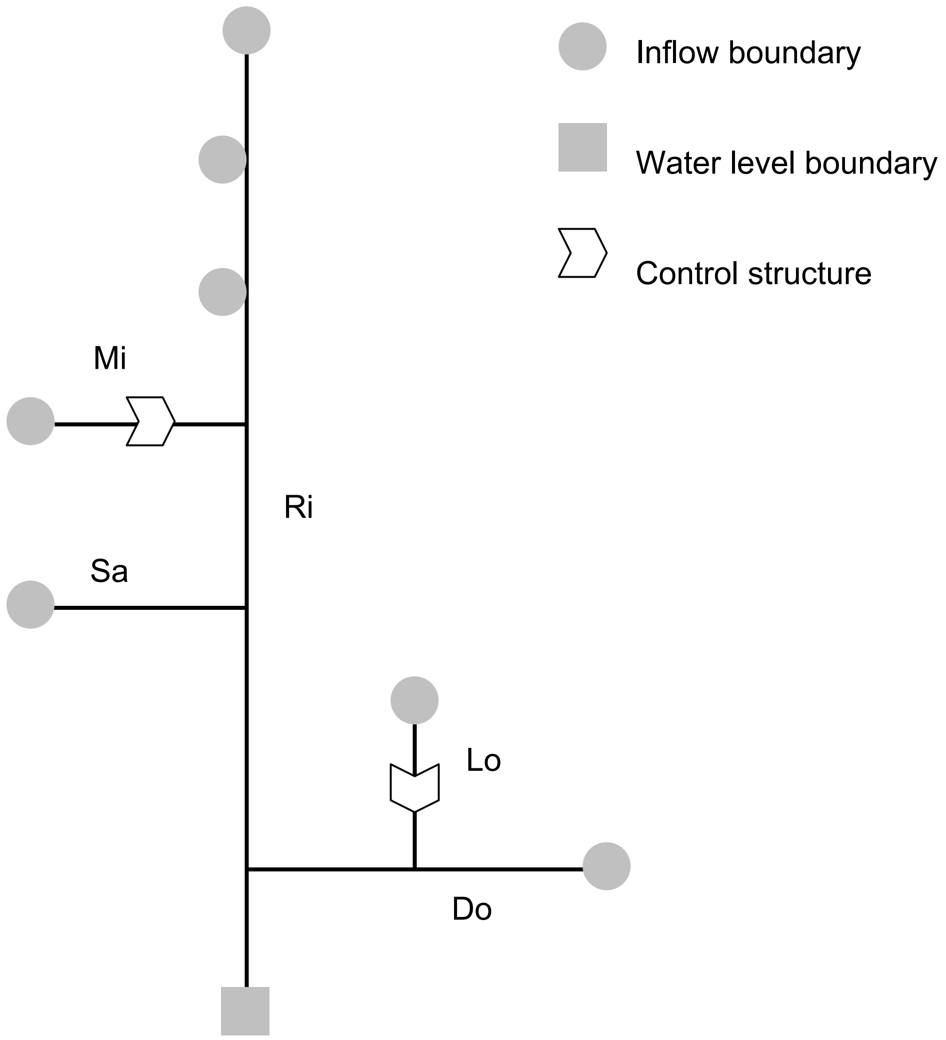
2 MODEL BUILD

2.1 Test Configuration

The test has been undertaken in accordance with the Benchmarking Test Specification - Test O (Crowder *et al*, 2004).

The test configuration is illustrated schematically in Figure 2.1. There is one main river designated Ri and three main tributaries designated Mi, Sa, and Do. Tributary Do has a further tributary designated Lo.

Figure 2.1: Schematic Illustration of Test Configuration



At the upstream boundary of the main channel and each of the tributaries, inflow hydrographs are defined to simulate the fluvial conditions. Additionally, two inflow hydrographs are defined to simulate flows from tributaries that are not modelled explicitly. A time dependent water level boundary is defined at the downstream limit of the model to simulate tidal conditions.

At each cross-section Manning's n values are used to define channel roughness. A range of Manning's n values is used to represent changes in roughness both within a cross-section and along the length of the model.

Two tidally influenced outfalls are defined within the model. One is located on tributary Mi immediately upstream of the junction with the main river, Ri. The other is located on tributary Lo immediately upstream of the junction with tributary Do.

The tidal outfalls enable tide locking when the downstream water level is higher than the upstream water level. The dimensions of the outfalls are summarised in Table 2.1.

Table 2.1: Outfall Dimensions

Dimension	Outfall in Mi tributary	Outfall in Lo tributary
Throat invert level	1.000 mAOD	2.400 mAOD
Throat soffit level	2.800 mAOD	4.365 mAOD
Upstream sill level	1.100 mAOD	2.500 mAOD
Downstream sill level	1.000 mAOD	2.400 mAOD
Bore area	5.089 m^2	4.198 m^2

2.2 Building the Model in ISIS

The ISIS model was constructed according to the test configuration. Any variations from this are outlined below.

The total number of the physical cross-sections, as defined by the dataset, was 105. To improve model stability 73 cross-sections (see Table 2.2) were inserted using the ISIS interface. The option provided in the software was used to interpolate cross-sections.

Table 2.2: Number of Interpolated Cross-Sections in ISIS Model

Reach	Interpolated cross-sections
Main river Ri	47
Tributary M	13
Tributary Sa	7
Tributary Do	6
Tributary Lo	-

Factors in the selection of locations for interpolated cross-sections were the distance between the physical cross-sections and warning messages (mainly "poor convergence") during model runs.

In ISIS, two tidal outfalls are defined within the model. One is located on tributary Mi immediately upstream of the junction with the main river, Ri, the other being located on tributary Lo immediately upstream of the junction with tributary Do. The tidal outfalls are to enable tide locking when the downstream water level is higher than the upstream water level.

In ISIS the OUTFALL unit in FLAPPED mode has been used to represent the outfall. This unit has the ability to model flow under various flow conditions as described below.

Mode 1	Dry sill
Mode 2	Flap shut
Mode 3	Free weir flow through culvert
Mode 4	Drowned weir flow through culvert
Mode 5	Orifice flow

Apart from the data in Table 2.1 default values of coefficients were used. It is believed that ISIS uses the equations as described in Bos (1989) for the flow though the structure.

The equations used in each mode are given in the ISIS manual in the section on orifices.

ISIS has two options for interpolating a time series boundary condition – linear and spline. In order to allow a fair comparison with MIKE 11, which only has the linear option, the same option was used in ISIS, however, as a sensitivity test ISIS was also run with the spline option.

It should be noted that it is also possible to model this situation with a VERTICAL SLUICE unit as a RULES unit, but this option was not adopted for this test.

2.3 Building the Model in MIKE 11

The model was set up as in the test specification. It was necessary to split reaches Ri and Do in the network editor in order to incorporate the junctions. Within the MIKE11 network editor, the “user-defined length” option was used to ensure that the correct chainage was used by the software. Further interpolated cross-sections were not used, but the parameter DXMAX was set to 2000m for the upstream reach of Ri.

In MIKE 11, a flapped outfall can be represented by the culvert structure with the “valve” operation.

The modelling of a culvert requires an upstream and downstream river cross-section, which must be within the defined “maximum dx distance” for the branch in question. When the user adds a culvert at a particular chainage the culvert attributes, head loss factors and geometry need to be defined.

The culvert dimensions include setting the upstream and downstream invert levels, the culvert length, and the Manning’s n value. The values used were those that defined the same or similar parameters for the outfall in the test specification.

MIKE 11 can consider three options for the outfall: a) no valve regulation, b) valve regulation to allow only positive flow, or c) valve regulation to allow only negative flow. For this study the culvert was defined to have a closed (i.e. no open free surface) cross-section and valve regulation with positive flow.

In order to define the culvert in MIKE 11 data are required that are not included in the test specification. The culvert length was taken to be 1.0m. The cross-section was taken to be rectangular with the height given by the definition of soffit and invert levels and the width chosen to give the required area.

Head loss factors are set for in-flow, out-flow, free-overflow and bends in both the positive and negative flow directions. The default values, as used in the test, are given below in Table 2.3.

Table 2.3: Default Head Loss Values in MIKE 11 Outfall

	In-Flow	Out-Flow	Free Overflow	Bends
Positive Flow	0.5	1.0	1.0	0.0
Negative Flow	0.5	1.0	1.0	0.0

The inflow and outflow loss coefficients are used to calculate contraction and expansion loss coefficients, which are functions of the culvert and channel cross-sections immediately upstream and downstream of the culvert respectively. The loss coefficients are then used to calculate an inlet and outlet head loss, which is based on the respective velocity heads. Details on the method of calculating these head losses, and those that are a result of friction and bend losses, can be found in the MIKE 11 Reference Manual which is provided in pdf.

Further to entering all the above data, Q/h relationships are calculated for the culvert for each of the possible flow conditions. Details on the method of calculating the Q/h relationships can be found in the MIKE 11 Reference Manual.

The Q/h calculations are carried out by MIKE 11 and cannot be edited (it should be noted that the special structure feature allows the user to define a Q-h relationship). However, they are displayed for verification purposes. The culvert option is designed for modelling culverts of any shape, length or slope. All flow conditions are represented including full submergence, partial submergence, critical inflow and outflow, orifice flow and full culvert flow with a free outflow (MIKE 11 reference manual 2001). The flow through a culvert can be broadly classified into three categories for computational purposes, namely zero flow, upstream controlled flow and downstream controlled flow. The software package automatically considers these flow categories as required.

2.4 Building the Model in HEC-RAS

This test could not be undertaken with HEC-RAS as the test version did not have the capability to implement rules for controlling the sluice gate based on downstream locations.

The test version of HEC-RAS software does have the ability to control sluice gates with either a time series of gate openings, or an elevation controlled gate operation. The elevation controlled gate operation is a rules based controller, however it only looks at the cross-section immediately upstream of the gate for applying the rules.

Through discussions with the developers of HEC-RAS, it was suggested that the downstream sluice gate could be modelled with a time series of gate opening option. The time series would initially have had to have been set to fully open and then once an initial run was made, the output could have been reviewed to see at what time the downstream water surface exceeded the upstream water surface at the sluice gate. The time series of gate openings could then have been modified to close the gate at this time. This approach was considered to be out with the test specification (i.e. logical control of sluice) and hence, it not been tested.

3 RUNNING THE MODEL

3.1 Introduction

In all cases default options were used unless specified otherwise in this report.

3.2 Running the Model in ISIS

Before starting an unsteady simulation, the model was run in steady mode to provide initial conditions and to consider Froude number and velocity values. Further to this, the timestepping approach was adopted so as to improve the initial conditions.

The unsteady simulation was carried out using the adaptive time step strategy in ISIS. In this strategy, the initial time step was set to 37.5s and the minimum time step to 9.375s. The model was run for 32 hours and all other parameters were set to default values. During the simulation the timestep varied from 9.375s to 150s whilst mainly staying within the range 37.5s to 75.0s.

To enable the extraction of results, for use in post processing, the "Run Tabular" option in ISIS was used.

The running of the model was relatively easy and straightforward. However, as part of the model build process, interpolated cross-sections were added so as to eliminate/reduce warning messages about poor convergence. The location of these interpolated cross-sections is given in Section 2.2.

3.3 Running the Model in MIKE 11

Initial conditions were calculated automatically by MIKE 11 by using the steady state initial condition option provided in the software.

Running the model with the default implicit weighting coefficient (delta) of 0.55 produced oscillations in the results. To ensure non-oscillatory solutions the value of delta was increased to 0.7. A timestep of 10s was used.

Delh was increased from the default value of 0.1m to 0.5m. As stated in the MIKE 11 manual, the Delh factor controls the dimensions of an artificial slot (commonly known as a "Preissmann Slot"), which is introduced in a cross-section to prevent drying out of the section. The artificial slot is a small void introduced at the base of the section and it allows a small volume of water to remain in the section to prevent computational instabilities at low flows. The slot is inserted at height Delh above the river bottom and extends to a depth of 5.Delh below this level. This change was necessary to prevent instabilities in tributary Mi due to the steep channel just upstream of the culvert (Slope>0.01) and the low flow (0.3m3/s). This change can obviously have an effect on the accuracy of the results.

3.4 Running the Model in HEC-RAS

The HEC-RAS software package was not able to undertake this test.

4 RESULTS

4.1 Introduction

For each part of the test the results from both of the software packages that managed to complete the test are discussed, compared and presented in combination so as to provide a direct comparison.

4.2 Analysis of Results for ISIS and MIKE 11

Graphs 1, 2, 3 and 4 (Appendix A) show flow and water levels at the flapped outfalls located in tributary Mi and Lo for the 32 hours of the simulation. It can be seen that there is no negative flow so tide locking is being correctly modelled. Further, the two packages are switching from open to closed at approximately the same time as the downstream depth rises above the upstream depth. The discharge values themselves do differ, mainly as the flow reverses or attempts to reverse.

Graph 5 (Appendix A) shows the discharge against time for the most downstream cross-section of the model, which is the tidal boundary. These are broadly similar, but there are differences at hours 5, 18 and 30 as the tidal flow reverses. Leading up to these times ISIS has a lower, almost zero, discharge compared with MIKE 11. At these times there is a sudden increase in discharge indicated by ISIS when a decrease may be expected. There is no apparent explanation for this occurrence.

Comparison of Graphs 6-10 (Appendix A) shows that the difference in water levels between the packages was up to 0.15m (approx.). This may explain some of the difference in performance of the structures. This difference can be explained, in part, by the different ways that the packages use to represent the channel cross-sections and junctions.

Graphs 6-10 (Appendix A) show the maximum water levels in each of the channels. Graph 6 for the main channel clearly shows the extent of the backwater from the tidal influence up to the chainage of 6000m. It is only in Graph 6 that any difference between the two packages can be seen, but this difference is only slight. Graphs 7-10 show insignificant differences. The maximum water levels for the two channels containing outfalls (Graphs 7 and 10) show the backwater effect behind the outfall.

4.3 Evaluation of Volume through the System

A mass conservation test was carried out. For each package the boundary conditions were extended beyond 32 hours to 50 hours by using the initial boundary values. This was done to ensure that the mass within the system at the end of the simulation was identical to that within the system at the start. The values of the discharge entering the system through each channel and leaving it at the downstream end were integrated over the 50 hours for results saved every 60s. If mass is being correctly conserved this should result in a value of zero. A percentage error was calculated by dividing the error by the total inflow. For ISIS, the inflow was greater than the outflow by 2.97% and for MIKE 11, 0.02%. These lie within acceptable limits for practical modelling.

5 DISCUSSION AND CONCLUSIONS

The results show that ISIS and MIKE 11 perform well in modelling flow through outfalls, and both correctly model tide locking and flap operation, as there is no flow in the negative direction.

HEC-RAS was not able to model this test due the absence of the ability to control sluice gates by rules. This is a significant limitation, which has been addressed by the developers in a subsequent release of the software.

The difference in performance of the structures, as indicated by the two packages, can be attributed in part to the difference in water levels between the packages. However, there may be some differences in the way that the units chosen for the structures in each package perform.

Considering the main channel of the test (Ri), it is evident that MIKE 11 and ISIS predict slightly differing results. For engineering design purposes this may lead to either over-engineered or under-engineered solutions in different lengths of the channel. Notwithstanding this, should calibration data be available then this issue would be less relevant.

As stated above, to model the tidal outfalls in MIKE 11, culverts were used. Results show that MIKE 11 is able to model flow outfalls satisfactorily in this way.

For this test ISIS required fewer amendments to ensure stability. In particular the changes made in MIKE 11 to accommodate the low flow in the Mi tributary required some iteration of parameter values. In contrast ISIS, which also has similar functionality (Preissmann slot), did not require these changes.

In calculating the mass error a save interval of 60s was used. This was seen to give better results for each package than when a save interval of 600s was used. As might be anticipated, the shorter interval gives a more accurate representation of the unsteady inflows and outflow.

The observed increases in discharge described in Section 4 were investigated. However, no ready explanation could be found and further work was beyond the scope of this study.

6 RECOMMENDATIONS

As a result of undertaking this test the testers recommend that the following improvements to the software packages would benefit the modeller.

- Incorporation of an outfall unit in MIKE 11. Whilst MIKE 11 was able to model an outfall through adaptation of the CULVERT unit, model implementation would be more transparent if there was a specific outfall unit as there is in ISIS. It may also be appropriate to consider the inclusion of a "long culvert" unit rather than a standard Q/h relationship.

- Investigation of why MIKE 11 is particularly prone to difficulties with the low flow encountered during the testing. The increase in Delh solves this problem, but may introduce errors due to the unphysical representation of the channel. Less experienced users might find its determination difficult.

- It may be of interest to repeat this test with the VERTICAL SLUICE option in ISIS.

The absence of the ability to control sluice gates by water level rules in HEC-RAS has been addressed in a subsequent release of the software. Hence it is recommended that this be now benchmarked.

Further investigation of the sensitivity of the mass conservation calculation to the save interval and other factors, such as averaging over the save interval, would be useful clarification for modellers.

The inclusion/impact of a slot to improve numerical stability has not been investigated as part of this study. It is considered by the benchmarking team that such investigations would be beneficial especially in the case where the slot is large relative to the channel.

It is recommended that the simulations with ISIS be repeated using a culvert and rules based operation to investigate whether this gives improved development of initial conditions or revised results.

It is recommended that further investigation into the increase in discharge with ISIS, reported in Section 4, be carried out to determine whether it occurs physically or whether it is part of the numerical solution.

It is recommended that the effects of the implicit weighting coefficient on results be tested so as to assess and measure of any damping that may be caused by this numerical scheme parameter.

7 REFERENCES

Crowder, R.A., Chen, Y., Falconer, R.A., (1997) Benchmarking and Scoping of Hydraulic River Models, Environment Agency Research and Technical Report, W88

Crowder, R.A., Pepper, A.T., Whitlow, C., Wright, N., Sleigh, A., Tomlinson, C., (2004) Benchmarking and Scoping of 1D Hydraulic River Models, Environment Agency Research and Technical Report, W5-105/TR1

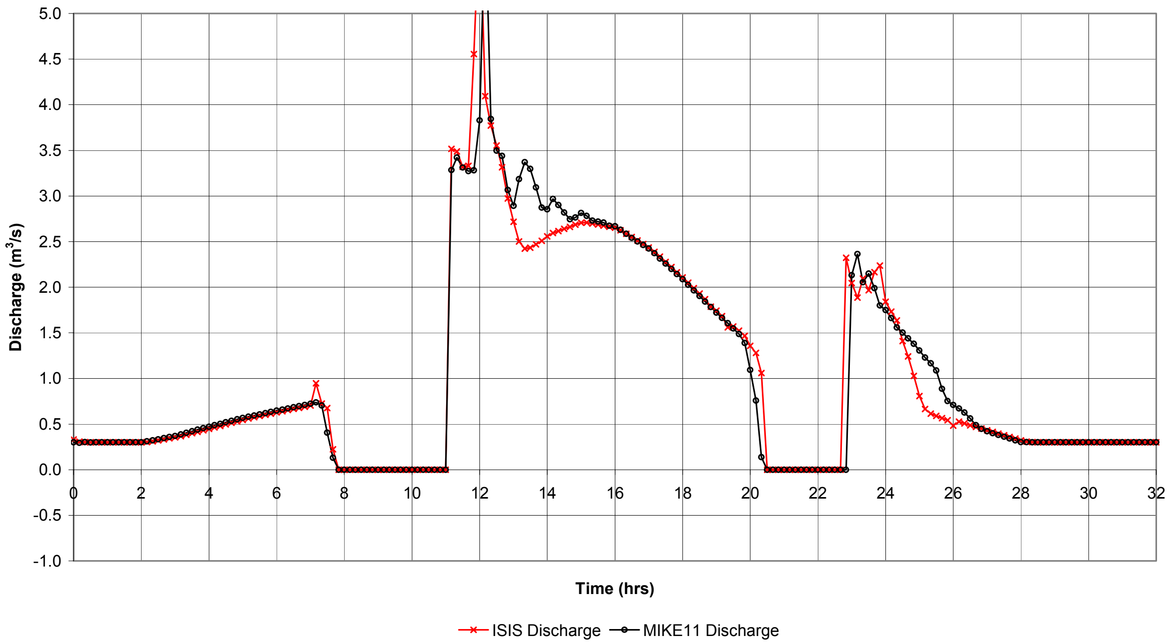
Bos, M., (1989) Discharge Measurement Structures, Wiley, John & Sons, Incorporated

MIKE 11 Reference Manual (2000), DHI Software, Denmark

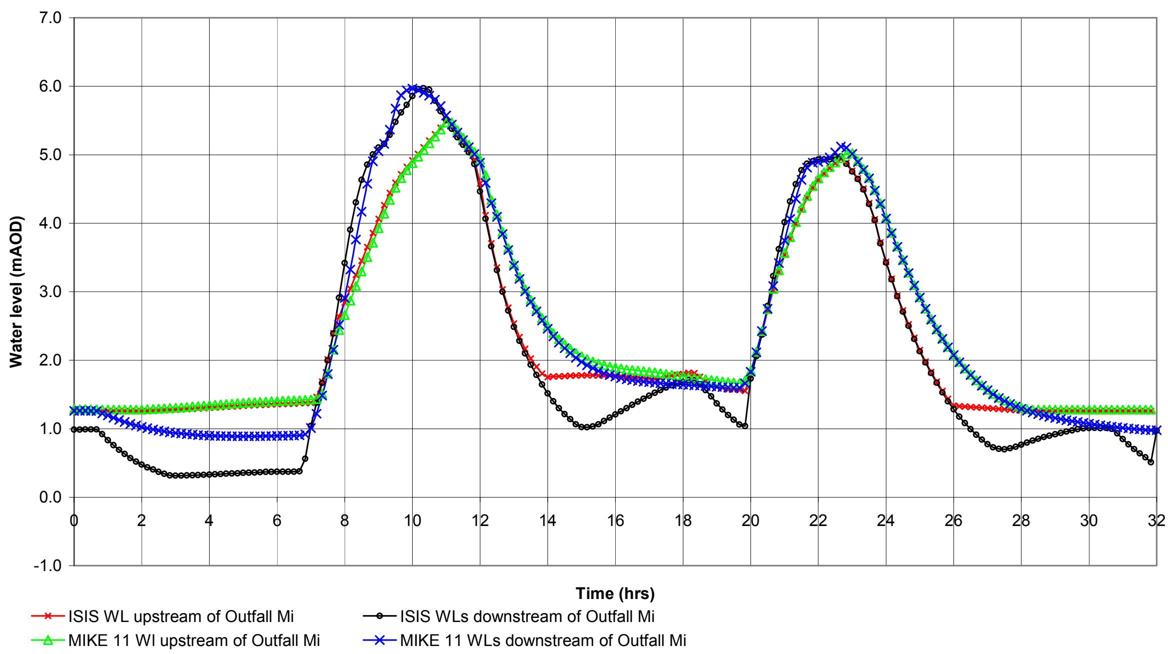
MIKE 11 User Guide, (2000) DHI Software, Denmark

APPENDIX A RESULTS

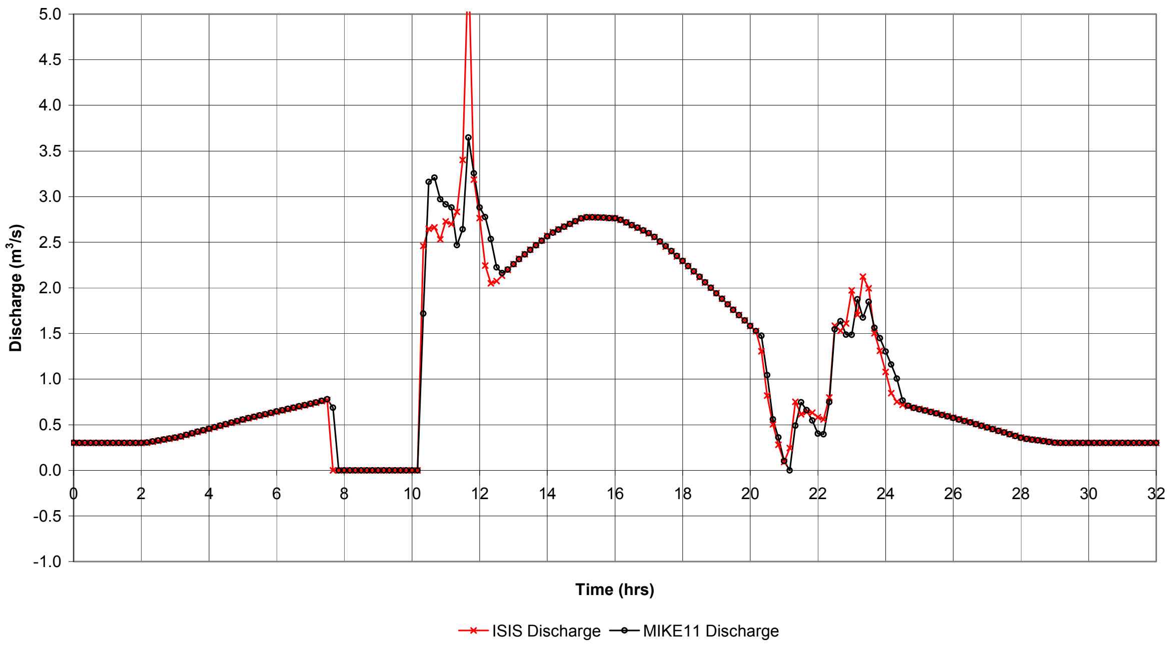
Graph 1 - Test O: Comparison of Calculated Discharge through Outfall in Mi



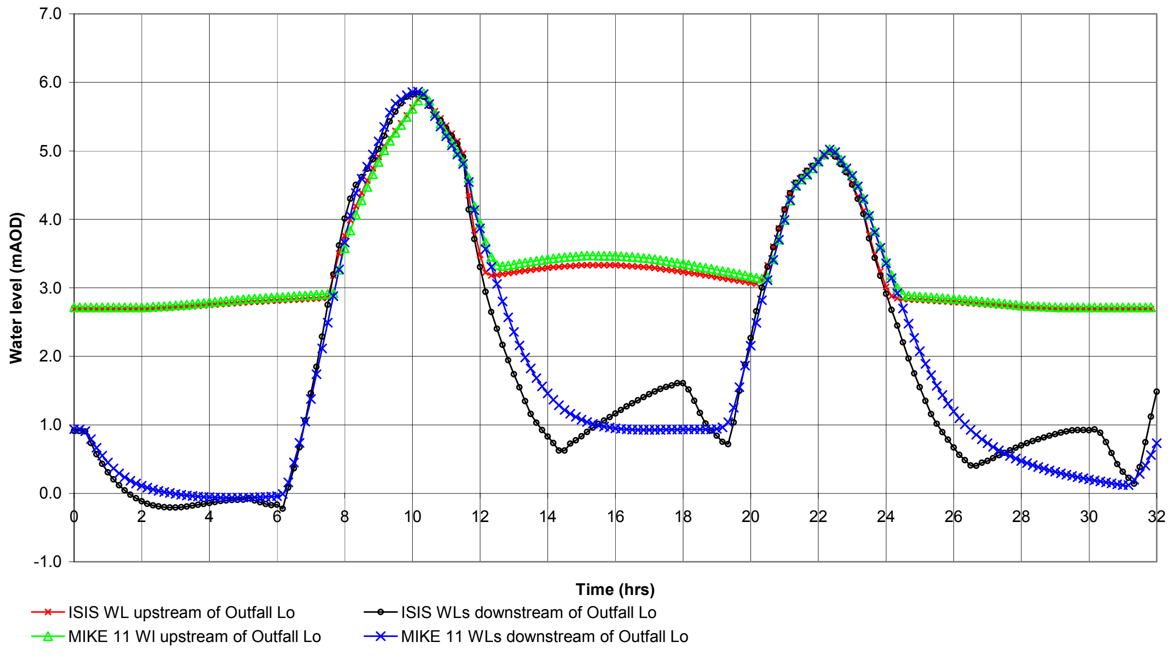
Graph 2 - Test O: Comparison of Water Levels at Outfall Mi



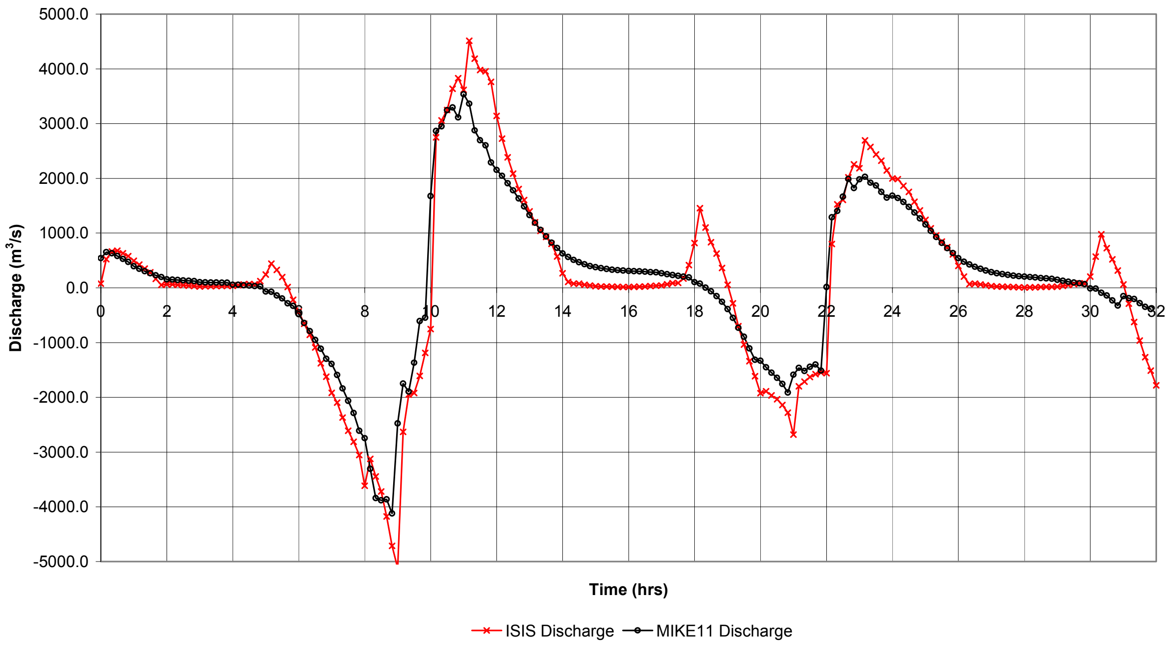
Graph 3 - Test O: Comparison of Calculated Discharge through Outfall in Lo



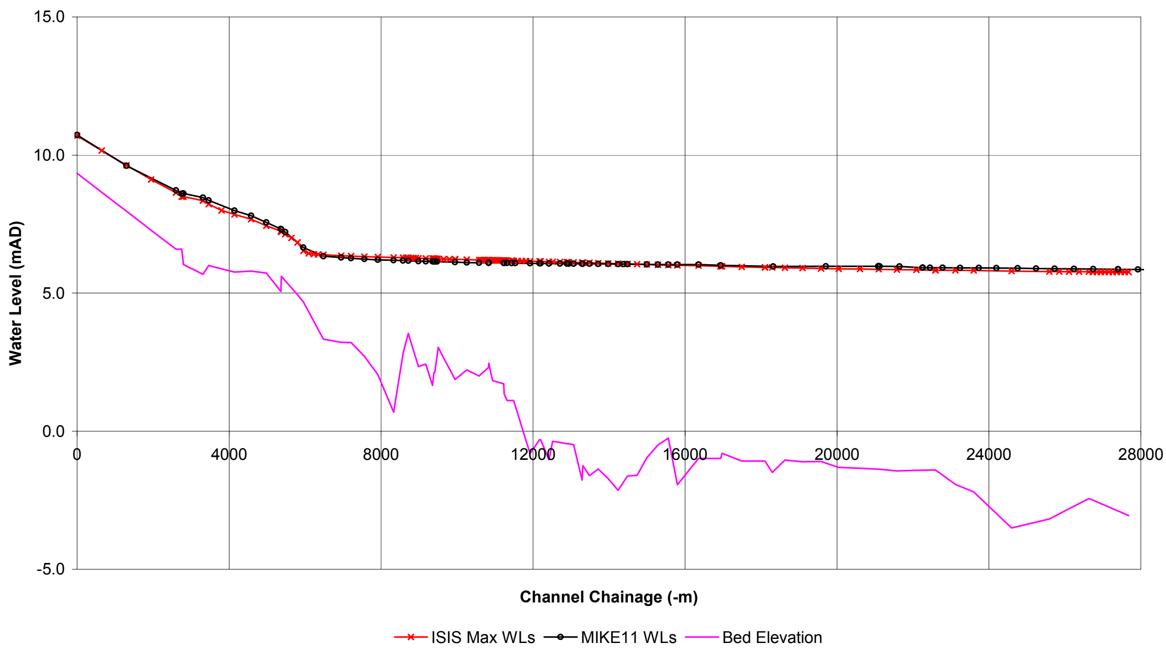
Graph 4 - Test O: Comparison of Water Levels at Outfall Lo



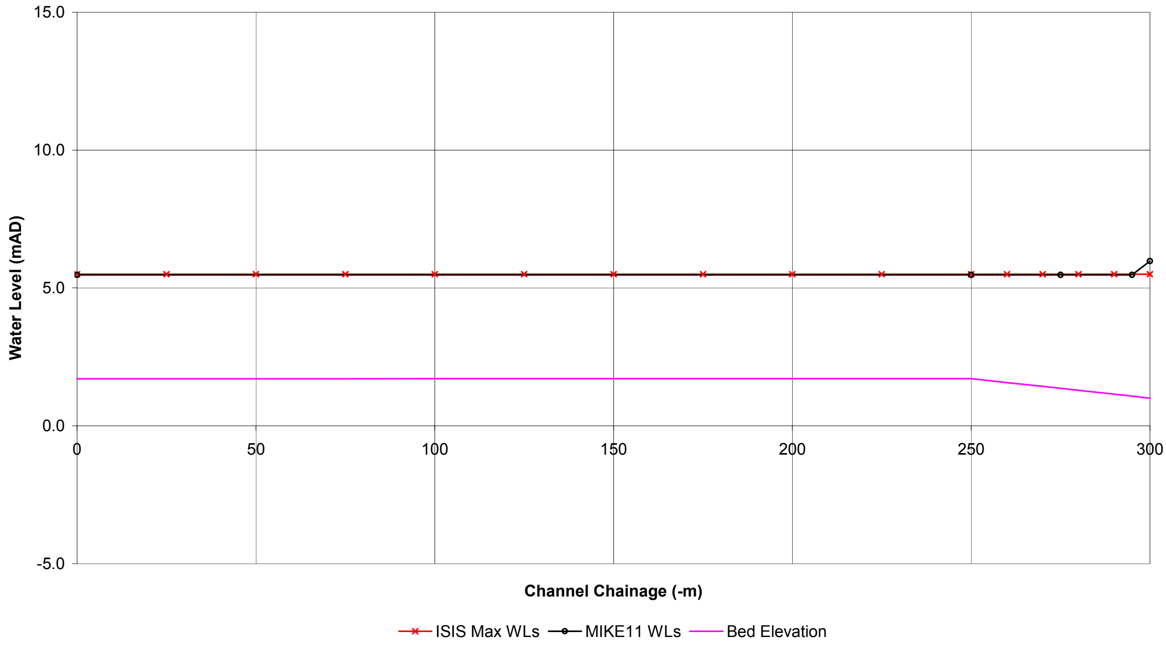
Graph 5 - Test O: Comparison of Calculated Discharge at Downstream Tidal Boundary



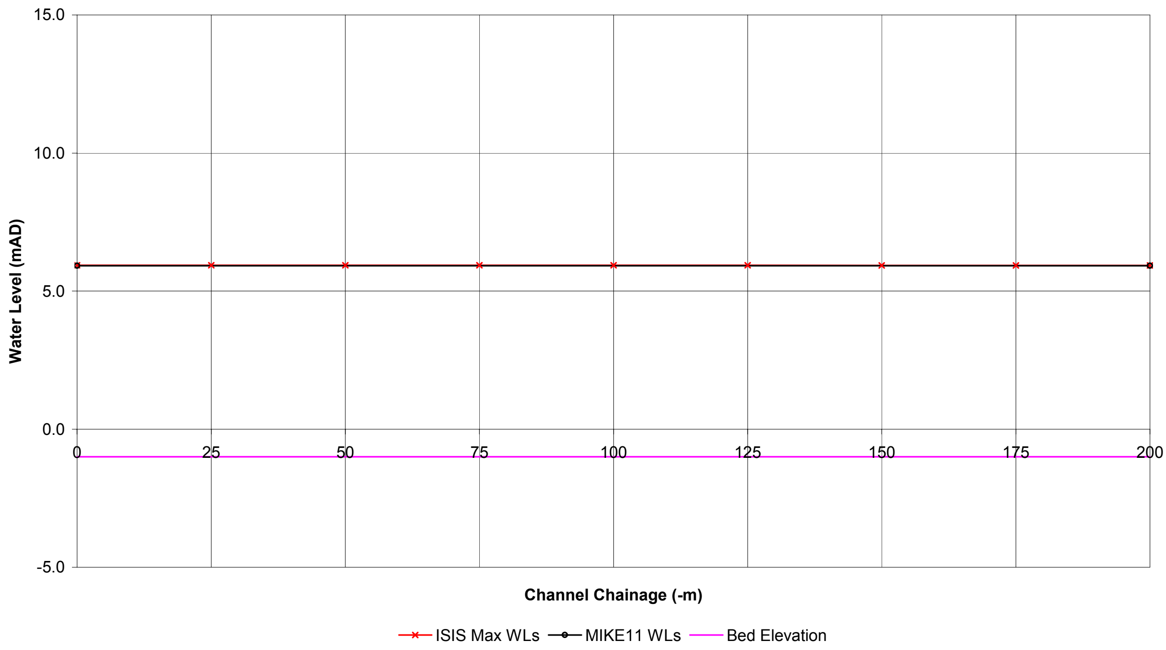
Graph 6 - Test O: Comparison of Calculated Longitudinal Maximum Water Level Profiles in Ri



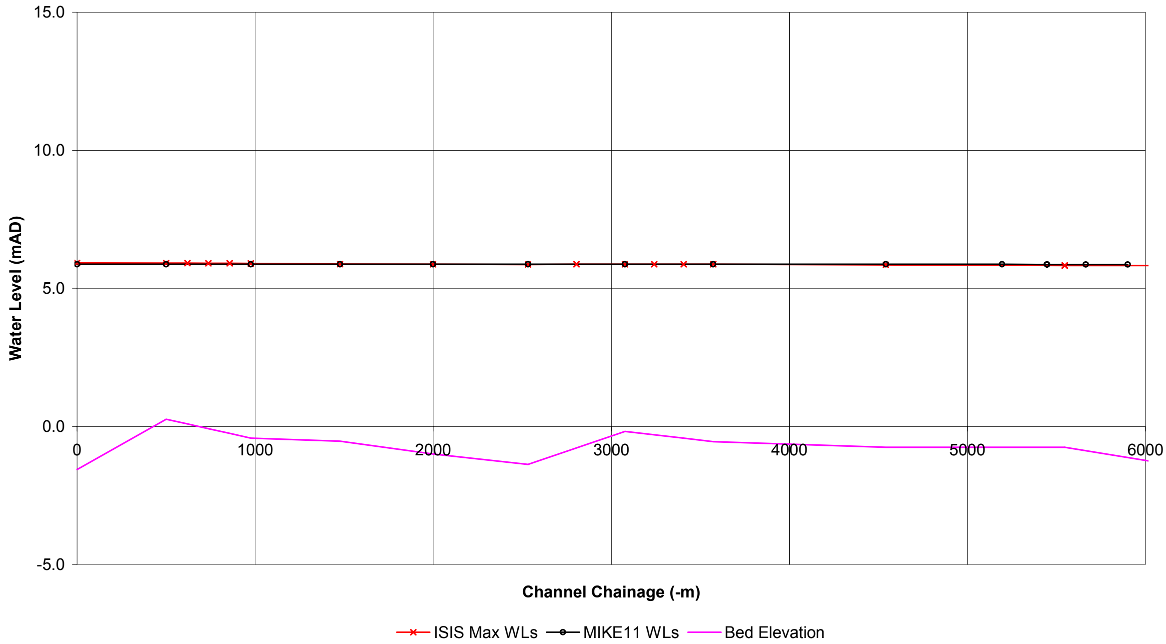
Graph 7 - Test O: Comparison of Calculated Longitudinal Maximum Water Level Profiles in Mi



Graph 8 - Test O: Comparison of Calculated Longitudinal Maximum Water Level Profiles in Sa



Graph 9 - Test O: Comparison of Calculated Longitudinal Maximum Water Level Profiles in Do



Graph 10 - Test O: Comparison of Calculated Longitudinal Maximum Water Level Profiles in Lo