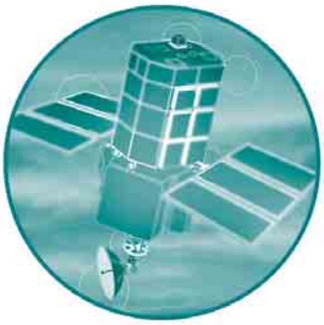
Defra / Environment Agency
Flood and Coastal Defence R&D Programme



Benchmarking Hydraulic River Modelling Software Packages

Results – Test F (Monoclinal Wave)

R&D Technical Report: W5-105/TR2F

Department for Environment Food and Rural Affairs

Environment Agency

TECHNICAL REPORT W5-105/TR2F

Defra/Environment Agency
Flood and Coastal Defence R&D Programme

BENCHMARKING HYDRAULIC RIVER MODELLING SOFTWARE PACKAGES

Results – Test F (Monoclinal Wave)

R&D Technical Report: W5-105/TR2F

RA Crowder, AT Pepper, C Whitlow, A Sleigh, N Wright, C Tomlin

Research Contractor: Bullen Consultants

Publishing organisation
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: +44 (0)1454 624400 Fax: +44 (0)1454 624409 Web: www.environment-agency.gov.uk

 ISBN: 1 8443 2290 4

Dissemination Status
Internal: Released to Regions and Areas
External: Released to Public Domain

Statement of use
This document provides the results and findings from undertaking the Environment Agency's Benchmarking Test F (Monoclinal Wave) 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, Flood Wave, Monoclinal Wave

Research Contractor
This document was produced under R&D Project W5-105 by:
Bullen Consultants Ltd, 11/12 Eldon Place, Bradford, West Yorkshire, BD1 3AZ
Tel: +44 (0)1274 370410 Fax: +44 (0)1274 734447 Web: www.bullen.co.uk.

Contractor's Project Manager: Dr Richard Crowder
Halcrow Group Ltd, Arndale House, Headingly, Leeds, West Yorkshire LS6 2UL
Tel: +44 (0)113 220 8220 Fax: +44 (0)113 274 2924 Web: www.halcrow.com

Environment Agency's Project Manager
The Environment Agency's Project Manager: Mr Andrew Pepper, ATPEC Ltd,
External Advisor to Engineering Theme

Further copies of this report are available from the Environment Agency's Publications Catalogue

TECHNICAL REPORT W5-105/TR2F **Product Code** SCHO0305BIXU-E-P

EXECUTIVE SUMMARY

The monoclinal wave is an approximation to the propagation of a storm event flood wave and as such provides an excellent method of assessing the accuracy and ability of the software packages.

The test has demonstrated that each of the software packages is capable of modelling the monoclinal wave to an acceptable degree of accuracy, with only marginal variation in the calculated water levels. However, the representation of roughness has a measurable influence of the predictive qualities of the software packages most notably the propagation of the wave front.

For this test neither ISIS nor HEC-RAS are capable of appropriately modelling the bed friction in accordance with the test specification as they cannot apply Chézy's *C* to a channel reach. Consequently, the choice of a representative Manning's n value is required which has led to either an underestimation or overestimation of water levels and the velocity of the wave front. Conversely, MIKE 11 was the only package able to maintain the correct wave profile and velocity.

HEC-RAS can consider a varying Manning's n value with flow. For this test this feature has provided improved accuracy in results and is of considerable benefit.

CONTENTS

Appendices

List of Figures

1 INTRODUCTION

1.1 Background

This report presents the results and findings from Test F (Monoclinal Wave) 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
MIKE 11	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 F (Monoclinal Wave), (Crowder *et al,* 2004):

	Role	Affiliation
Mr Andrew Pepper	EA Project Manager	ATPEC River Engineering
Dr Richard Crowder	Study Project Manager	Bullen Consultants Ltd
Dr Nigel Wright	Advisor	University of Nottingham
Dr Chris Whitlow	Advisor	Eden Vale Modelling Services
Dr Andrew Sleigh	Advisor	University of Leeds
Dr Chris Tomlin	Advisor	Environment Agency
Mr David Cross	Tester	University of Leeds

1.2 Aim of Test

The aim of the test is to:

- determine whether each of the software packages is able to recreate the special case of unsteady flow, known as the monoclinal rising wave, described by Chow (1959) as a typical case of uniformly progressive flow; and

- present the particulars for developing and undertaking the test (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 AND MODEL RUNS

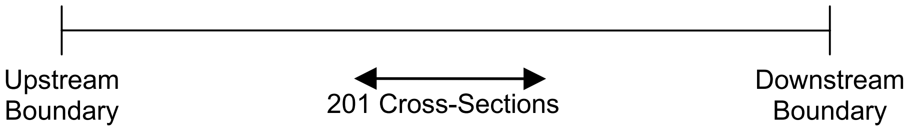
2.1 Test Configuration

The test has been undertaken in accordance with the Benchmarking Specification – Test F, with initial and boundary conditions used being those when a Q/h/t boundary is not available.

The test was specified with a uniform channel of rectangular cross-section, width b = 1000m, depth d = 50m, and length L = 1000km. The slope of the channel bed was set at 0.0004, and the channel was made up from 201 cross-sections, equally spaced at 5000m.

A constant Manning's 'n' roughness value of 0.024 was specified along the whole length of the channel, so as to be representative of a Chezy friction coefficient of 55, the coefficient used in the analytical solution. The test configuration is illustrated schematically in Figure 2.1.

Figure 2.1: Schematic Illustration of Test Configuration



The upstream boundary was specified in all three programs as a flow/time boundary with constant inflow of 24693.395m^3/s. It was not possible to define a constant Q/h/t boundary (see Section 2.2). The downstream boundary was specified with a h/t boundary with constant stage of 3.0m. More details on the choice of boundary conditions are provided in Section 2.2.

A specific analytical profile was produced based on the solution of the monoclinal wave equations, see Appendix A of the test specification (Crowder *et al*, 2004), and using the values provided by the Excel spread sheet specified in that Appendix.

In order for the friction coefficient to be incorporated into the computer models, the Chézy coefficient had to be converted to an equivalent Manning's n value by the relationship $C=R^{1/6}/n$, where R is equal to the hydraulic mean radius[†] A/P.

As Manning's n is a function of the hydraulic mean radius, it is therefore also a function of the depth of flow. For this reason, Manning's friction coefficient is perfectly suited to continuous steady flow conditions, and thus steady river flow analysis. However, applying a constant Manning's *n* value to a case of flow such as the monoclinal progressive wave, will only give rise to an approximation of the true analytical solution. This is because the depth of flow in the channel along the profile of the wave is variable, resulting in a Manning's *n* value which must not only vary with distance along the wave, but also with time as the wave propagates over any given point. In contrast, the Chézy coefficient *C*, which has dimensions LT-2, is a constant for all values of discharge and depth, as specified by the Chézy equation for flow in open channels;

[†] *hydraulic mean radius was given by R in Chow's derivation of the monoclinal wave profile*

$$Q = AC\sqrt{RS} \quad \text{Equation (2.1)}$$

Therefore, for any given channel of constant slope and breadth, Chézy's *C* can be determined from Equation (2.1) for any instantaneous discharge and depth of flow at any chosen point along the channel.

Manning's *n* assumes a uniform distribution of the friction effect over the given depth of flow. Therefore, specifying a continuous value for Manning's *n* over the length of the channel means that when the depth of flow within the channel rises above the initial depth used to calculate n, the friction effect is reduced as the effective distribution of the friction becomes a lesser proportion of the cross-sectional area of the flow. Conversely, when the depth of flow reduces the distribution of the friction effect becomes a significantly increased proportion of the cross-sectional area of flow. The net effect is an overestimation of the effective resistance for a lesser depth of flow, and underestimation when the depth of flow is greater.

Therefore, as Manning's *n* is the only way to apply friction in ISIS and the default approach in HEC-RAS (the alternative is to use k values), it was decided to determine a value based on the mean depth of flow over the length of the wave profile. Manning's *n* was therefore calculated as 0.0241 based on a depth of flow of 5.5m. Even though it is possible to specify Chézy *C* in MIKE 11, it was decided to use the Manning's value in all three packages to maintain consistency with the models. However, the test has also been undertaken with MIKE 11 using a Chézy *C* value.

It should be noted that HEC-RAS has the ability to define a variation in Manning's *n* with respect to depth of water, however, for this study it was considered beyond the scope of the test to configure HEC-RAS for this approach. Furthermore, HEC-RAS can consider a roughness height k as an alternative to a Manning's *n* representation for channel roughness.

The depths of flow, relative to the level of the channel bed, upstream and downstream of the wave, y1 and y2, were set at 8.0m and 3.0m respectively, and the corresponding flows (based on analytical solution) in the channel upstream and downstream of the wave, Q1 and Q2, at 24,693.395m^3/s and 5,698.697m^3/s. The upstream and downstream flows were chosen to give normal depths of flow consistent with y1 and y2, for uniformly progressive flow.

Based upon these analytical values, the theoretical velocity of the travelling wavefront V_w, was calculated as 3.7989m/s, and the length of the wave profile approximately equal to 191.5km. For these given values it would take the wave 13hrs and 59min to travel through a corresponding length of channel.

2.2 Building the Model in ISIS, MIKE 11 and HEC-RAS

Building the model in each of the three packages was very straight-forward. The upstream and downstream channel cross-sections were entered into the software packages, from which all other cross-sections were interpolated within the respective software package.

In HEC-RAS interpolations were defined within the interpolation editor by setting the maximum distance between cross-sections to 5000m.

In ISIS interpolations were defined by use of the "interpolation unit" at each of the required cross-section locations. For ease of setting up/defining, this was done outside of the ISIS graphical user interface using a text editor.

In MIKE 11 interpolations were created by defining a "DX-max" for the branch at 5000 m. This has the effect of adding computational h-points to the model grid at 5000m intervals.

When the analytical solutions to this test were originally defined, it was intended that the model would be set up in such a way that the wave profile would be generated by the software packages in a length of channel equivalent to the length of the given wave. Setting up the model in this way would require the initial discharge and depth of flow, specified over the entire length of the channel, to be made equal to Q2 and y_2, the discharge and stage downstream of the wave. The wave profile would then be generated by specifying a flow/head/time (Q/h/t) boundary at the upstream end of the channel, and a head/time (h/t) boundary at the downstream end. It was then intended that the simulation would be run for less time than it would take the wave to reach the end of the channel, and examination of the wave profile be made at successive time intervals thereafter, in order to check that the wavefront remained parallel in conjunction with the primary property of the wave highlighted earlier.

The model was initially defined in this way to make allowance for the fact that the analytical solution for the monoclinal wave is asymptotic. This property of the solution means that the wave is in fact of infinite length, as both the flow and stage at the upstream end of the channel never reach maximum constant values. It is for this reason that a Q/h/t boundary was intended for the upstream end of the channel so that the asymptotic increase in stage and discharge could be controlled over the simulation time.

Attempting to set up the model in this way gave rise to some immediate limitations, not only of the software packages, but of the quality of the results generated.

The first and most significant limitation of the model, was the inability of both ISIS and MIKE 11 to have Q/h/t boundary relations specified at the upstream end of the reach. This limitation is often a consequence of the numerical discretisation/scheme adopted by the software package and then hence, the practical use and implementation of such a boundary. A fuller discussion on these issues is given by Cunge (1980). It is stated in the MIKE 11 User Guide (2000), that 'As a rule, Q/h boundaries should only be used at boundary points where outflow from the model takes place'. For this reason it is not possible to specify the intended Q/h/t relation at the upstream end of the channel, as the model requires an inflow at this location in order to generate the change in stage and discharge.

A trial run of the simulation was made using ISIS, specifying a Q/h boundary at the upstream end of a suitable channel. The simulation could not be performed by the software, confirming the difficulties highlighted.

In contrast to ISIS and MIKE 11, the modeller does have the option of specifying a Q/h/t boundary at the upstream end of the reach in HEC-RAS. A trial model was built in HEC-RAS specifying a Q/h/t boundary at the upstream end in order to determine whether the model could be built in this way when using this software. The unsteady simulation gave rise to instability warnings at each successive channel cross-section, and finally that the calculation matrix had gone 'completely unstable' at the end of the simulation. It was therefore decided not to use this model in the testing as it would not only be inconsistent with the limitations of the other software packages, but the results of the test are too poor to be of any value.

As the purpose of the test is to ensure that each of the software packages are able to recreate and maintain the profile of the monoclinal wave over time, such that the basic properties of the wave are correctly maintained, it was considered that the original definition of the test would not show the desired characteristics of the wave, as the profile would not be fully developed at each successive examination. It was therefore decided to redefine the test in a manner that would be simpler to model, yet allow comparison of a fully developed wave at successive time intervals.

In order to be able to examine the profile of a fully developed monoclinal wave at specified time intervals, it was decided that the wave should be allowed to propagate down a channel significantly longer than the length of the profile, such that the wavefront can be examined at later times than required for the wave to form. However, because it was established that the given analytical wave could not reliably be generated by any of the software packages using Q/h boundary conditions upstream, it was decided that it was necessary to specify initial conditions for both stage and flow over the entire length of the channel. The analytical solutions for stage and flow were determined at successive channel spacings of 5000m over the length of the wave profile, with the final values for both stage and flow being extended over the remaining length of the channel, again at a spacing of 5000m.

The simulation would then be performed by simply applying a Q/t boundary of constant inflow at the upstream end of the channel, the inflow being equal to the maximum discharge specified in the initial conditions, and an h/t boundary of constant depth specified at the downstream end of the channel, the stage being equal to the final water level, also in the initial conditions.

2.3 Initial Conditions

Initial conditions for stage and flow at every cross section were entered into the model based upon Chow’s analytical solutions, the exact values for which are specified in the test specification.

2.4 Running the Model

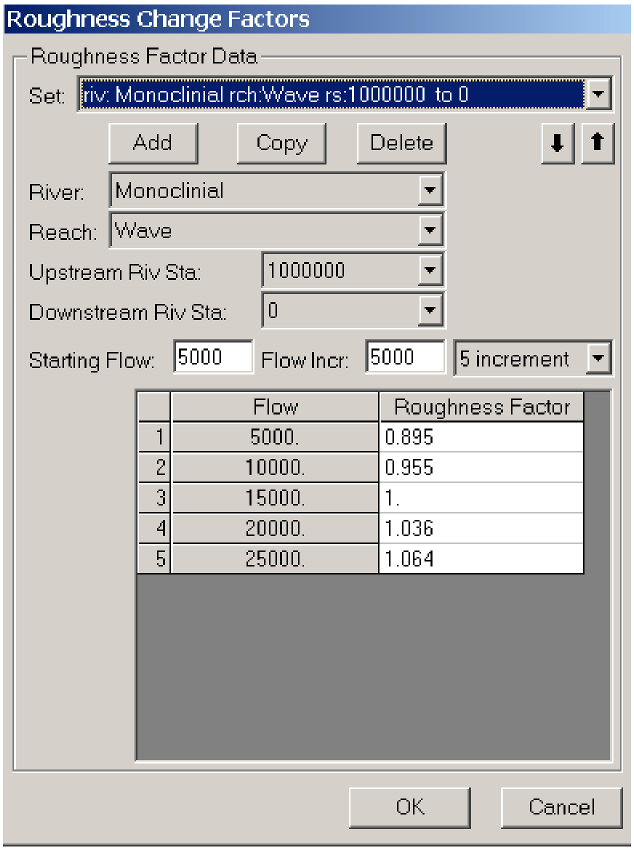
The simulation was run in each software package for 30hrs, and performed using a calculation time-step of 60s, the results of which were recorded after every 360s. In all instances default calculation settings were used unless other wise stated.

2.5 Alternative Calculation Settings in HEC-RAS

When testing the Flow v’s Roughness option in HEC-RAS (see Section 3.5) the roughness change factors were defines as illustrated in Figure 2.1, which is a HEC-RAS screen capture from the test.

When testing the alternative calculation tolerances/setting the implicit weighting coefficient theta was reduced from the default value of 1.0 to 6.0 and the time step during warm up was set to 0.000028hrs.

Figure 2.2: HEC-RAS Roughness Change Factors



3 RESULTS

3.1 Introduction

The results of the simulations are presented in Graphs 1 to 9, Appendix A. Each graph shows the initial analytical water surface profile of the wave entered at the start of the simulation, together with successive profiles of the calculated water levels after 5, 10, 15 and 20 hours of the simulation.

Because friction is accounted for in the analytical solutions to this test using Chézy's *C*, the friction applied to the model has had to be approximated using Manning's *n*. It was first decided to calculate a value for *n* based upon a mean depth of flow over the length of the wave profile of 5.5m, as stated earlier. Therefore Graphs 1 to 3, Appendix A, give the generated water surface profiles when a Manning's *n* of 0.0241 is applied to the model. In comparison, Graphs 4 to 6, Appendix A, give the calculated water surface profiles for a Manning's *n* of 0.0256, based upon the maximum theoretical depth of flow in the channel of 8.0m. These profiles were generated to provide some comparison to the mean Manning's value applied in Graphs 1 to 3, and to establish the response of the three software packages to this increased bed friction.

Further to this, additional testing of the channel was performed exclusively in MIKE 11 to determine what effect applying friction to the model in different ways would have on the results of the test. It was decided that this test should be performed in order to take account of the different ways that MIKE 11 is able to model resistance forces acting on the travelling fluid. Essentially, bed friction can be applied to a channel in MIKE 11 using either Manning's *n* or Chézy *C* globally within the model, while the effect of the resistance at any given channel cross-section location can also be applied linearly or uniformly over the depth, referred to within the MIKE 11 literature (DHI Software, 2002) as 'Resistance Radius' and 'Hydraulic Radius' respectively. When Manning's *n* was applied to the model in Graphs 3 and 6, it was applied uniformly over the depth. Therefore, it was decided to perform two more simulations using the Manning's *n* values of 0.0241 and 0.0256, but this time applying the resistance linearly over the depth (see Graphs 7 and 8, Appendix A), and then one final simulation using Chézy's *C* the results of which are presented in Graph 9, Appendix A.

In addition to the Chézy *C* tests undertaken with MIKE 11 the advanced feature in HEC-RAS of Flow v's Roughness, which allows the global variation of Manning's *n* value with respect to flow, was tested. This was also tested in combination with alternative calculation settings/tolerances.

3.2 ISIS, HEC-RAS and MIKE 11 Results – Manning's *n* = 0.0241

It can be seen from Graphs 1 to 3 that the profile of the successive wavefronts is essentially maintained over the duration of the simulation by all three packages. However, the calculated water levels upstream of the progressive wave, generated in each package, converge on approximately the same value of 7.7m, slightly less than that specified by the analytical solution of 8.0m. This slightly lower water level generated by each package will be equivalent to the calculated normal depth of flow for the upstream maximum discharge according to the applied Manning's *n* value of 0.0241. However, it should also be noted that while both ISIS and MIKE 11 maintain the specified normal depth of flow for the minimum discharge in the channel of 3.0m downstream of the wavefront, HEC-RAS produces a slightly greater value of approximately 3.2m for the same applied friction coefficient.

It can be seen from Graphs 1 to 3, that the velocity of the generated wave profile is slightly different in each of the three packages. Graph 1 demonstrates that the wave velocity generated within ISIS is approximately equal to the wave velocity of the analytical solution as the successive calculated profiles coincide approximately with the corresponding analytical profiles. However, Graphs 2 and 3 show that the calculated wavefronts produced in both HEC-RAS and MIKE 11 propagate at velocities greater than the theoretical wave velocity for the test.

3.3 ISIS, HEC-RAS and MIKE 11 Results – Manning's *n* = 0.0256

By applying a Manning's *n* value based on the maximum discharge in the channel, it can be seen from Graphs 4 to 6 that the normal depth of flow calculated by each of the three packages upstream of the wavefront converges with the upstream analytical water level of 8.0m as would be expected. However, while both ISIS and MIKE 11 generate downstream water levels of 3.0m, equivalent to the specified downstream normal depth of flow, it can be seen from Graph 5, as was also observed in Graph 2, that the water level calculated in HEC-RAS downstream of the wavefront is slightly greater at approximately 3.3m.

In fact, the calculated depth of flow downstream of the wavefront, produced in HEC-RAS, is equal to the normal depth of flow for the minimum discharge in the channel for the appropriate Manning's *n* value (0.0241 or 0.0256). When using Manning's equation, the resistance effect on the flow is greater for the lower discharges, which would result in a lower velocity of flow, and consequentially, a greater depth of flow. This could also explain why the gradient of the successive wavefronts calculated in ISIS and MIKE 11 are steeper than the analytical wavefronts. The increased effect of the resistance as the depth of flow becomes shallower would effectively cause more drag at the bottom of the wave profile than the top. In comparison, the wave profiles generated in HEC-RAS are parallel with the analytical solutions as the minimum depth of flow generated in HEC-RAS is equivalent to the normal depth of flow for the applied Manning's *n* value.

Further to this, it can be seen from Graphs 4 to 6 that the effective velocity of the generated wavefronts is variable dependent on the software. For the greater Manning's *n*, the propagation of the wavefront in ISIS is essentially the same as the analytical solution; however, the friction effect causes the wave to slow down at the lower water depth. The propagation of the wave in MIKE 11 is slightly faster than the analytical solution; however, the effect of friction slows the wave to approximately the correct velocity for the lower depths of flow. Finally, the propagation of the wave in HEC-RAS is also faster than that of the analytical solution, however, there is no slowing of the wave as the depth of flow decreases as HEC-RAS correctly calculates the normal depth of flow for the given applied friction.

3.4 MIKE 11 Results – Resistance Radius and Chézy C

It can be seen from Graphs 7 and 8 that there is no demonstrable improvement with the results of the test when Manning's *n* is applied linearly over the depth of the channel using the Resistance Radius function for the applied friction at each channel cross-section. The generated wave profiles still propagate through the channel faster than the analytical solutions, and the gradient of the generated wave profile is still steeper than the analytical solutions due to the constant Manning's *n* value. By using the linear resistance radius option the wave speed is slightly increased in comparison to the Resistance Radius option.

However, it can be seen from Graph 9 that by applying the constant Chézy's *C* value of 55 to the model, specified in the analytical solution for the test, and instead of an equivalent Manning's *n* value, the generated wave profile remains identically parallel with the same corresponding analytical profile, while each successive profile propagates through the channel at exactly the same rate as that specified in the analytical solution.

3.5 HEC-RAS Results – Alternative Calculation Options/Tolerances

It can be seen from Graph 10, which has the default calculation settings, that there is a demonstrable improvement with the results of the test when the Flow v's Roughness Option is applied. The generated wave profile is slightly ahead of the corresponding analytical profile with the difference ever increasing as the profile propagates through the channel.

It can be seen from Graph 11, which has the Flow v's Roughness Option applied and improved calculation settings, that the generated wave profile remains almost identically parallel with the same corresponding analytical profile as the profile propagates through the channel.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion and Conclusions

Each of the software packages was able to model the monoclinal wave to a degree of accuracy that would be acceptable in most practical situations, with only marginal variation in the calculated water levels.

The major finding of the software packages as a result of this test was the inability of ISIS and HEC-RAS to appropriately model the bed friction (with respect to test specification). Because it is not possible to apply Chézy's *C* to a channel reach in both packages, it was not possible to set this model up according to the specification. For this reason, MIKE 11 was the only package able to maintain the wave profile and velocity corresponding to the analytical solution.

HEC-RAS does have the ability to vary the Manning's *n* values with depth or flow. This has been tested here and has shown to provide a significant improvement in results.

The results generated in ISIS for the given Manning's *n* values do, however, show that the wave profiles and velocities are maintained by the software to a reasonable degree of accuracy. This suggests that if Chézy's *C* could be specified then it may be able to reproduce the analytical solutions. If a varying Manning's *n* value (with respect to water depth) could be specified in ISIS then closer agreement with the analytical solution might be made.

The results generated in HEC-RAS for the given Manning's *n* values show that the wave profiles and velocities are maintained by the software to a reasonable degree of accuracy, however, the wave speed is consistently too high.

For this test case it is apparent that the use of a Chézy *C* value, as opposed to a Manning's *n* value, is the most appropriate when modelling the propagation of flood waves. However, given that the analytical solution is based on this approach this is not surprising. The approach adopted by HEC-RAS to consider changes in Manning's *n* with respect to flow would also appear to be an improved and more practicable method of modelling the propagation of a flood wave when compared to the constant Manning's *n* approach.

It has been shown for HEC-RAS that the use of improved results can be obtained when using alternative model parameters/settings. This clearly demonstrates that the modeller needs to be aware of the potential impact of default values on model results and the need to make adjustments for specific modelling needs/problems.

With the exception of HEC-RAS none of the software packages is able to consider a Q/h/t boundary condition, although in practice this is not considered to be a limitation. However, there may be some distinct advantages to the modeller if each of the software were capable of modelling such a boundary condition. On the other hand, the numerical instabilities observed in HEC-RAS when attempting to apply a Q/h/t boundary in this test have highlighted the difficulties/problems in incorporating this functionality. It may be possible to reduce these instabilities; however, it has not been possible as part of this study to investigate this further.

4.2 Numerical Damping Parameter/Weighting Parameter

The effect of changing the default numerical damping parameter or weighting parameter in the software packages has not been extensively tested as part of this test; however, it is noted that this may have an influence on the results.

The numerical damping parameter or implicit weighting parameter in both the Preissmann Box scheme (used in ISIS and HEC-RAS) and the Abbott Scheme (used in MIKE 11) reflect the forwards or backwards time weighting of a function or derivative evaluated using the current or previous time-step values. If this parameter is zero, the function is fully weighted to the current or new time-step. If it is 0.5, the function is equally weighted towards the previous or current time-step and if it is 1.0, the function is fully weighted towards the previous time-step. Only values greater than or equal to 0.5 and less than or equal to unity are stable.

A value of 0.5 is formally second order accurate but is only marginally stable which explains why oscillations in a solution can be obtained in both ISIS and MIKE 11 if the weighting parameter is set to 0.5. In practice from an accuracy perspective it is best to set the weighting parameter as close to 0.5 as possible without compromising stability.

The default value in ISIS is 0.7 which the user is advised to reduce to 0.55 for tidal problems as the numerical dissipation can compromise the peak level and flow results. The default value in MIKE 11 is 0.5 which should be more accurate but can generate instability as demonstrated in the Culvert Test case. The default value in HEC-RAS is unity (1.0) which introduces a considerable amount of mathematical damping and associated error but should guarantee stability. It should be noted, however, that the HEC-RAS user manual does recommend that the default value should be reduced once a model is running and stable.

Given the above comments it is recommended that the affect of the damping/weighting parameters in each of the software packages be investigated fully as part of further study.

5 RECOMMENDATIONS

Consideration of the test results yields the following recommendations:

- The option of Chézy *C* should be provided in ISIS and HEC-RAS for channel friction.

- Consideration to the inclusion/applicability of Q/h/t boundaries should be considered in both ISIS and MIKE 11, but only if this does not lead to numerical instabilities. HEC-RAS may require modification to reduce the inherent instabilities apparent when this boundary condition was adopted for this test.

- Further detailed study of applying the varying Manning *n* roughness options/functions should be investigated with HEC-RAS. Furthermore this functionality could be considered for inclusion within ISIS and MIKE 11.

When undertaking a modelling study serious consideration should be made as to the most appropriate representation of channel roughness. The benefits of using a Chézy *C* value as opposed to a Manning's *n* value for friction should be considered and appropriately evaluated at the conception stage.

The affect of the damping/weighting parameters on the results obtained for this test should be investigated in detail with each of the software packages.

The test should be repeated once the Environment Agency's conveyance estimator R&D study is complete and the methodologies/procedures have been integrated to the software package/packages.

Guidelines for use of modelling parameters/settings should be developed so as to aid modellers in undertaking model studies.

6 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, 2003

Chow, V.T., (1959) Open Channel Hydraulics, 1st Edition. USA, McGraw-Hill, Inc., p 528

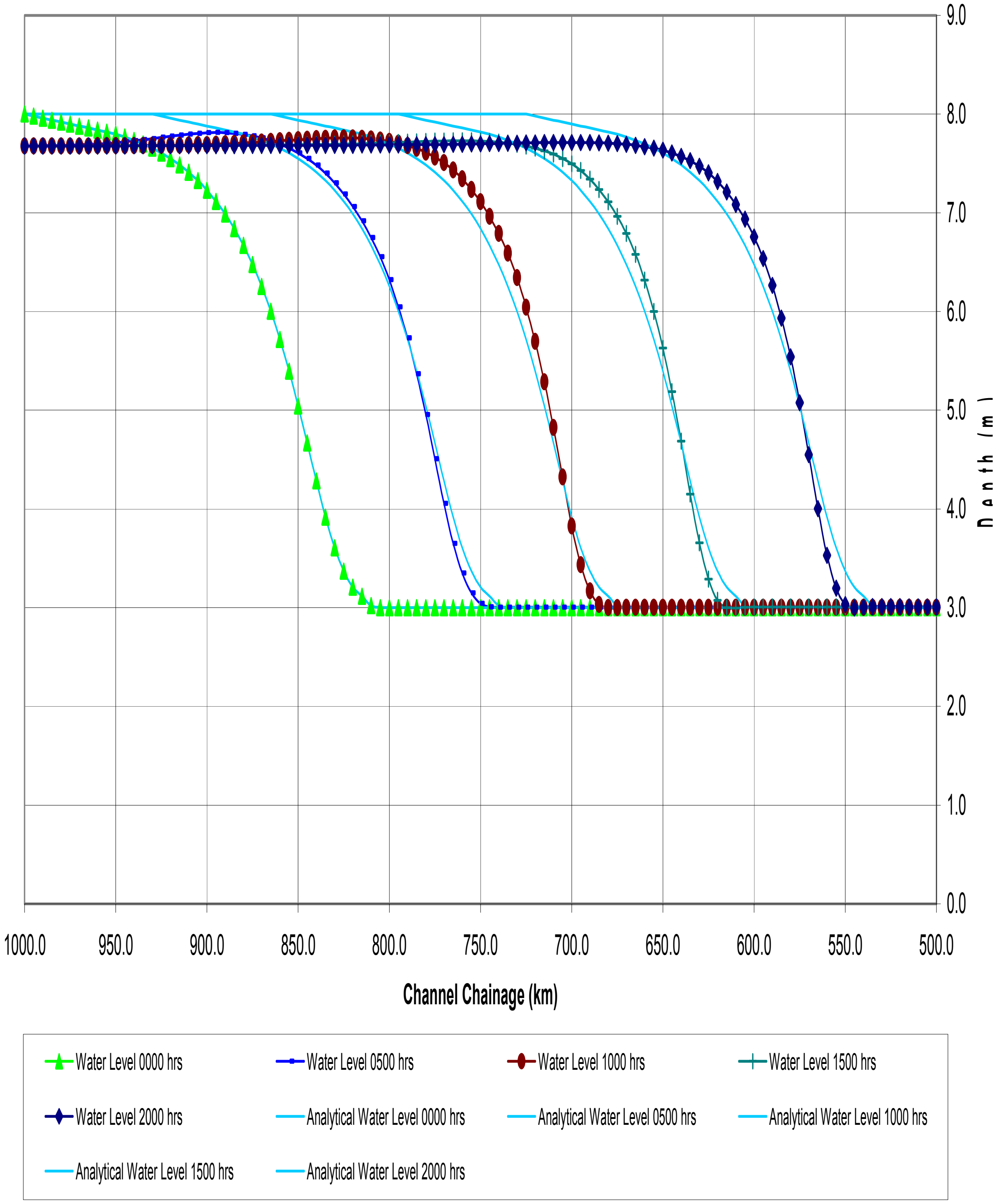
Cunge, (1980) Practical Aspects of Computational River Hydraulics, Holly and Verwey, Pitman.

DHI, (27 February 2002) Water and Environment, MIKE 11 Training Course Notes, Section 6, Resistance vs. Hydraulic.

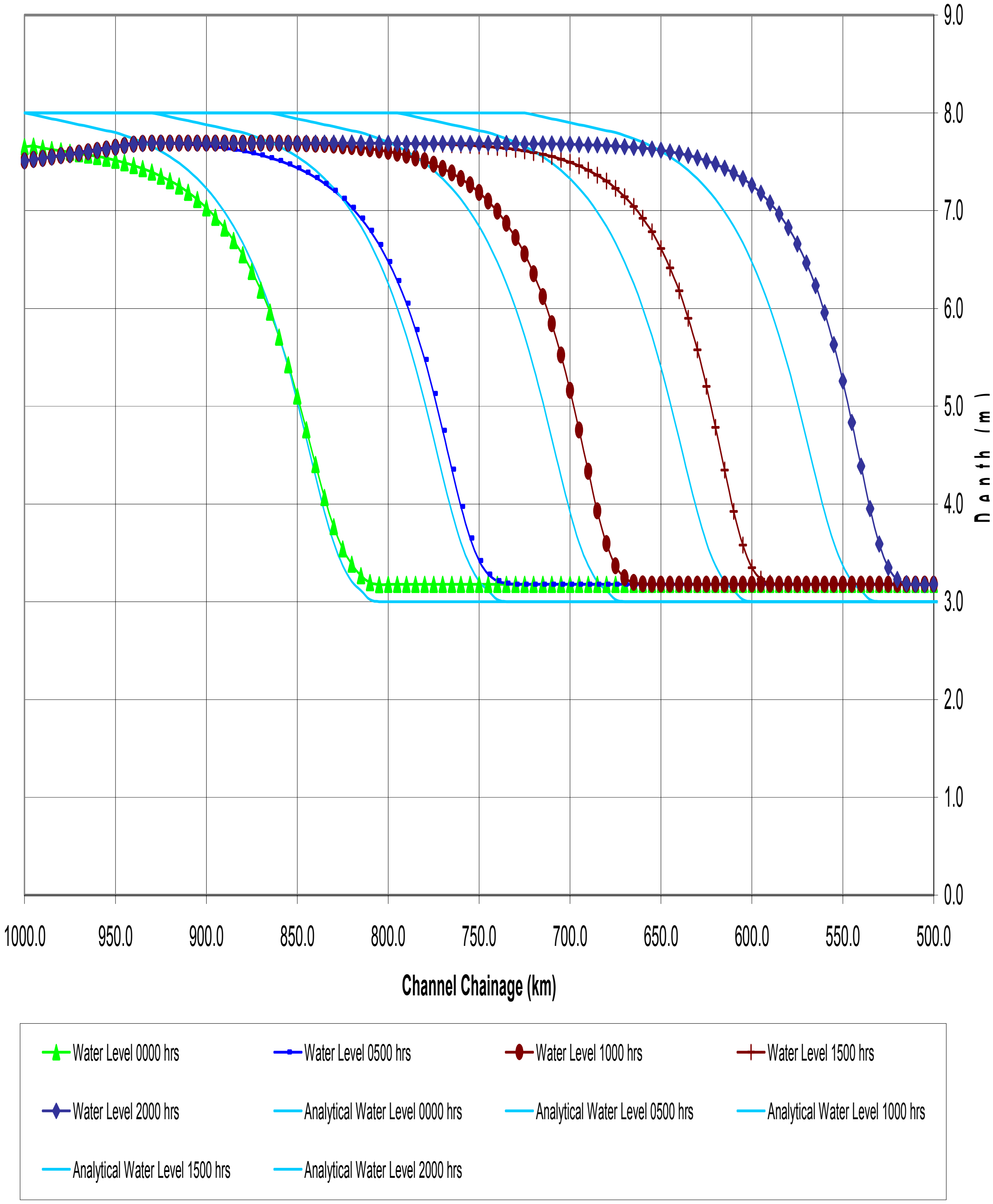
MIKE 11 User Guide, (2000) DHI Software, Denmark

APPENDIX A RESULTS

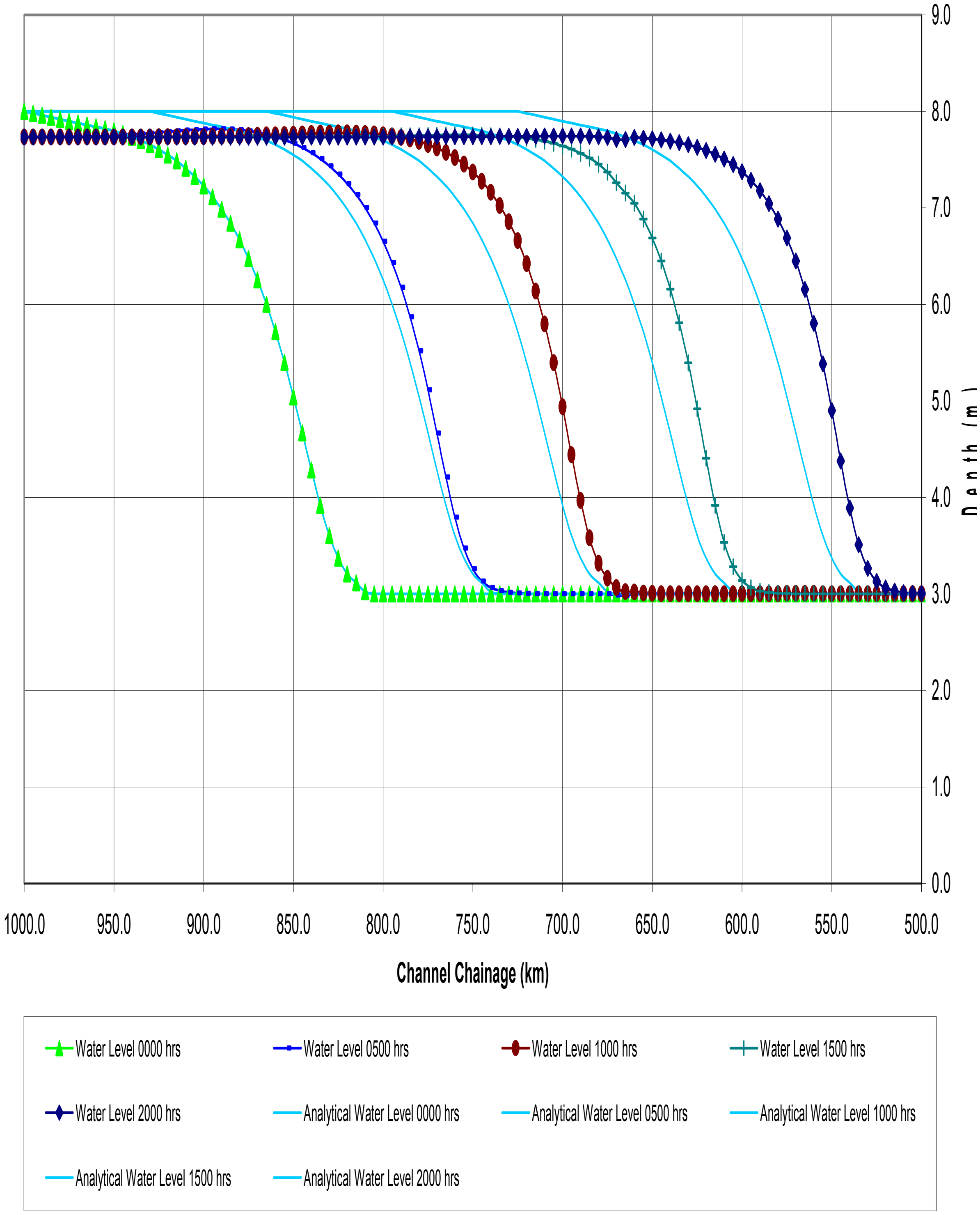
Graph 1: ISIS - Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0241



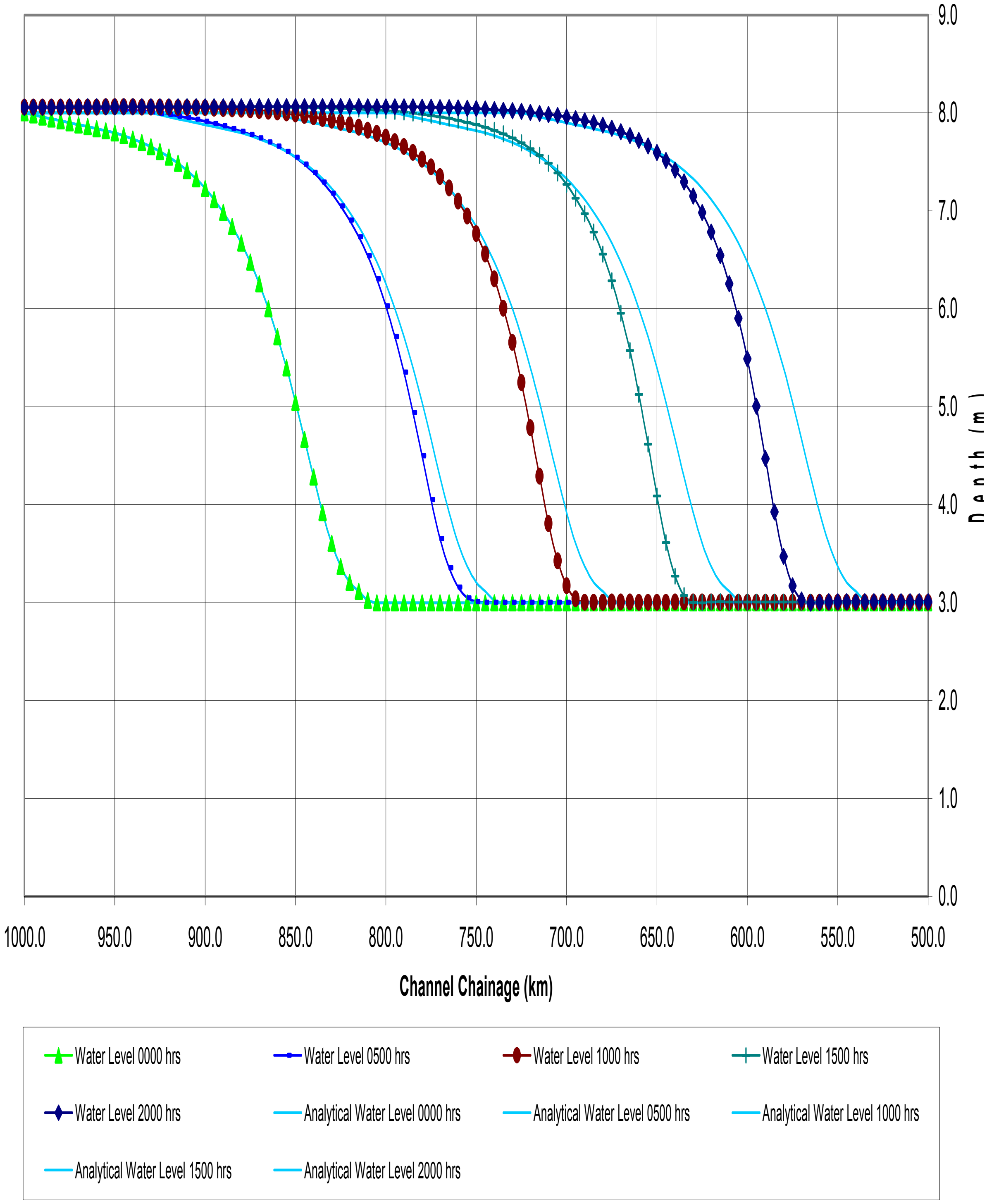
Graph 2 - HEC-RAS: Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0241



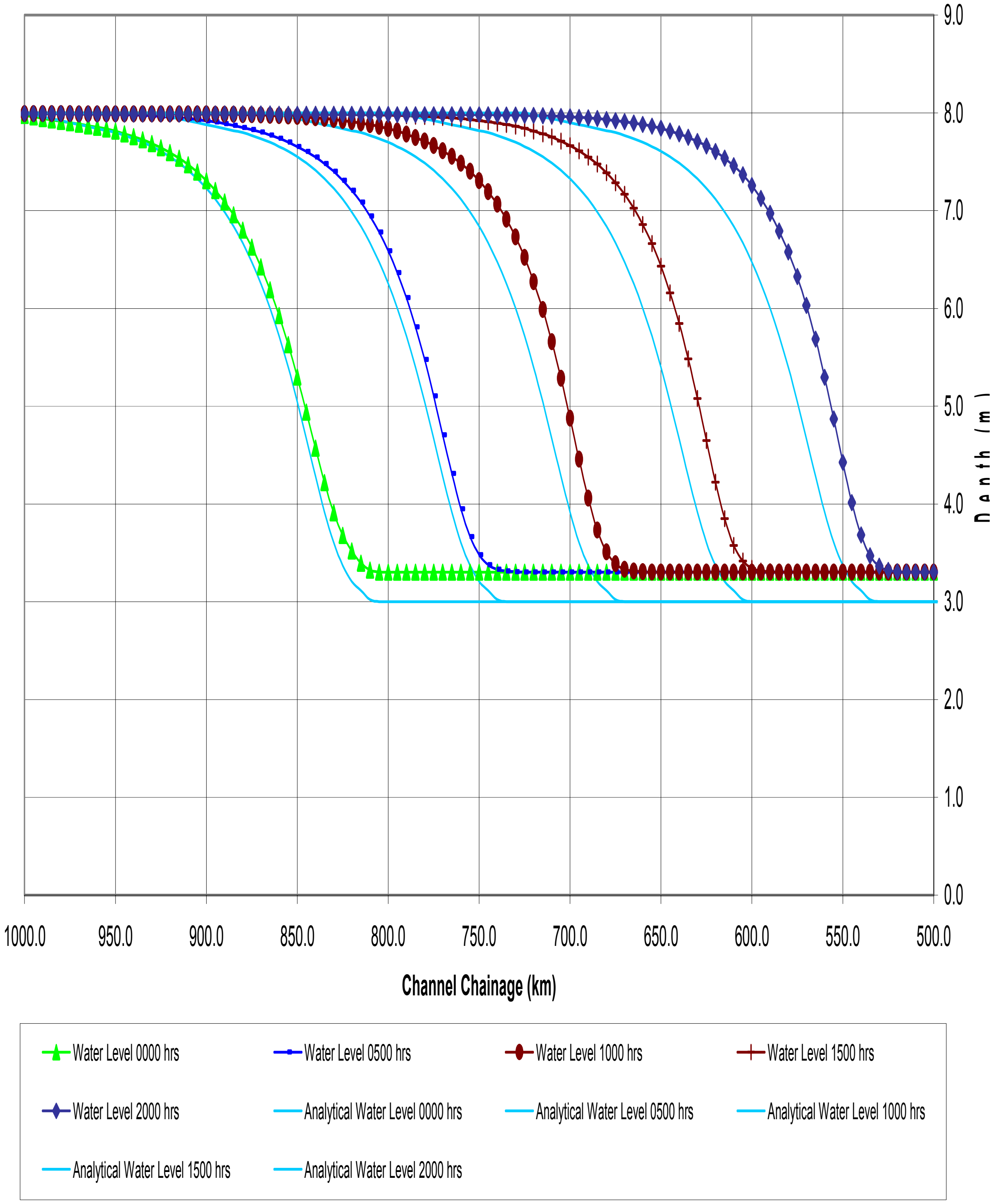
Graph 3 - MIKE 11: Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0241



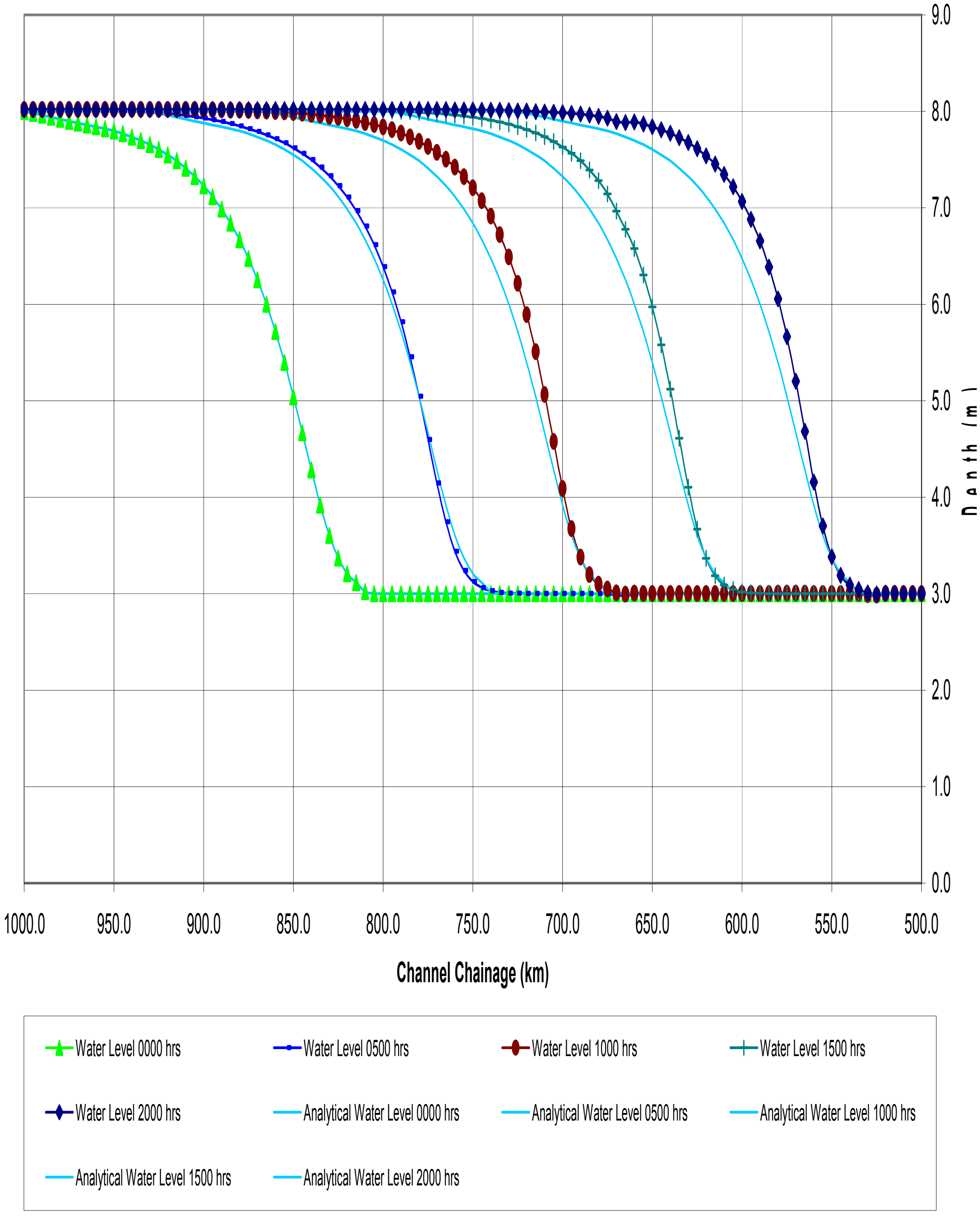
Graph 4 - ISIS: Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0256



Graph 5 - HEC-RAS: Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0256

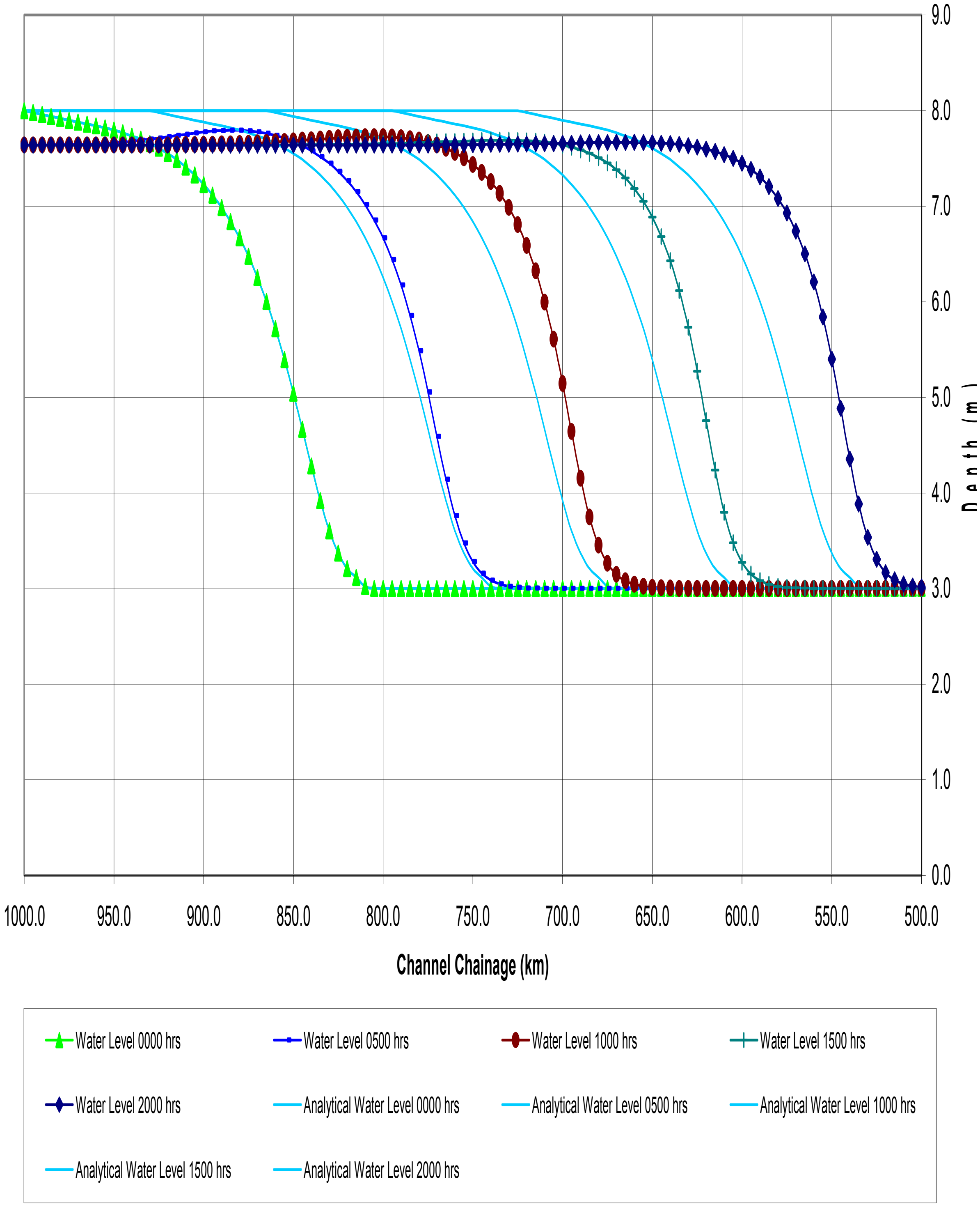


Graph 6 - MIKE 11: Successive Calculated and Analytical Water Surface Profiles
Applied Bed Friction - Manning's n=0.0256



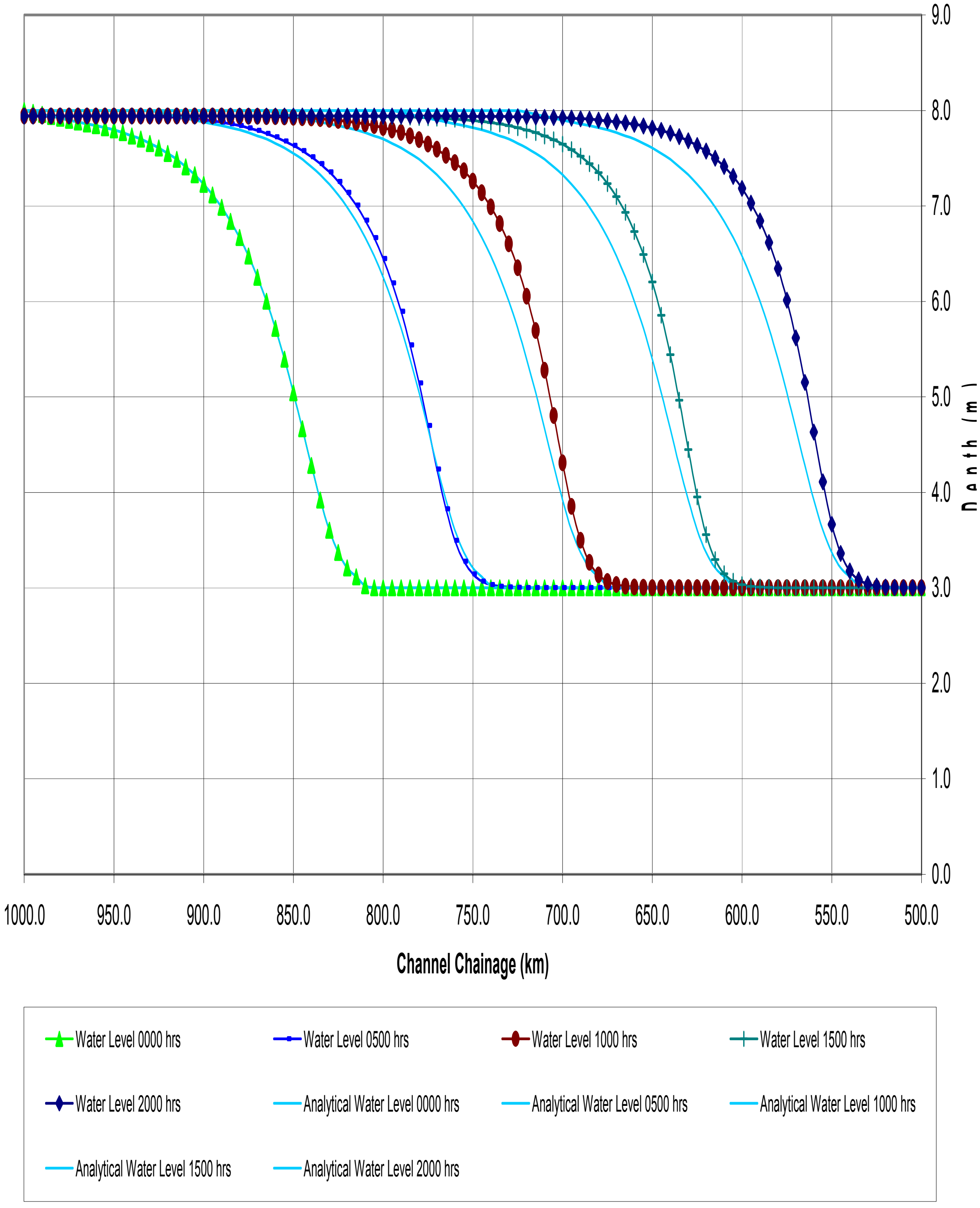
Graph 7 - MIKE 11: Successive Calculated and Analytical Water Surface Profiles

Applied Bed Friction - Linear Distribution Resistance Radius - Manning's n=0.0241



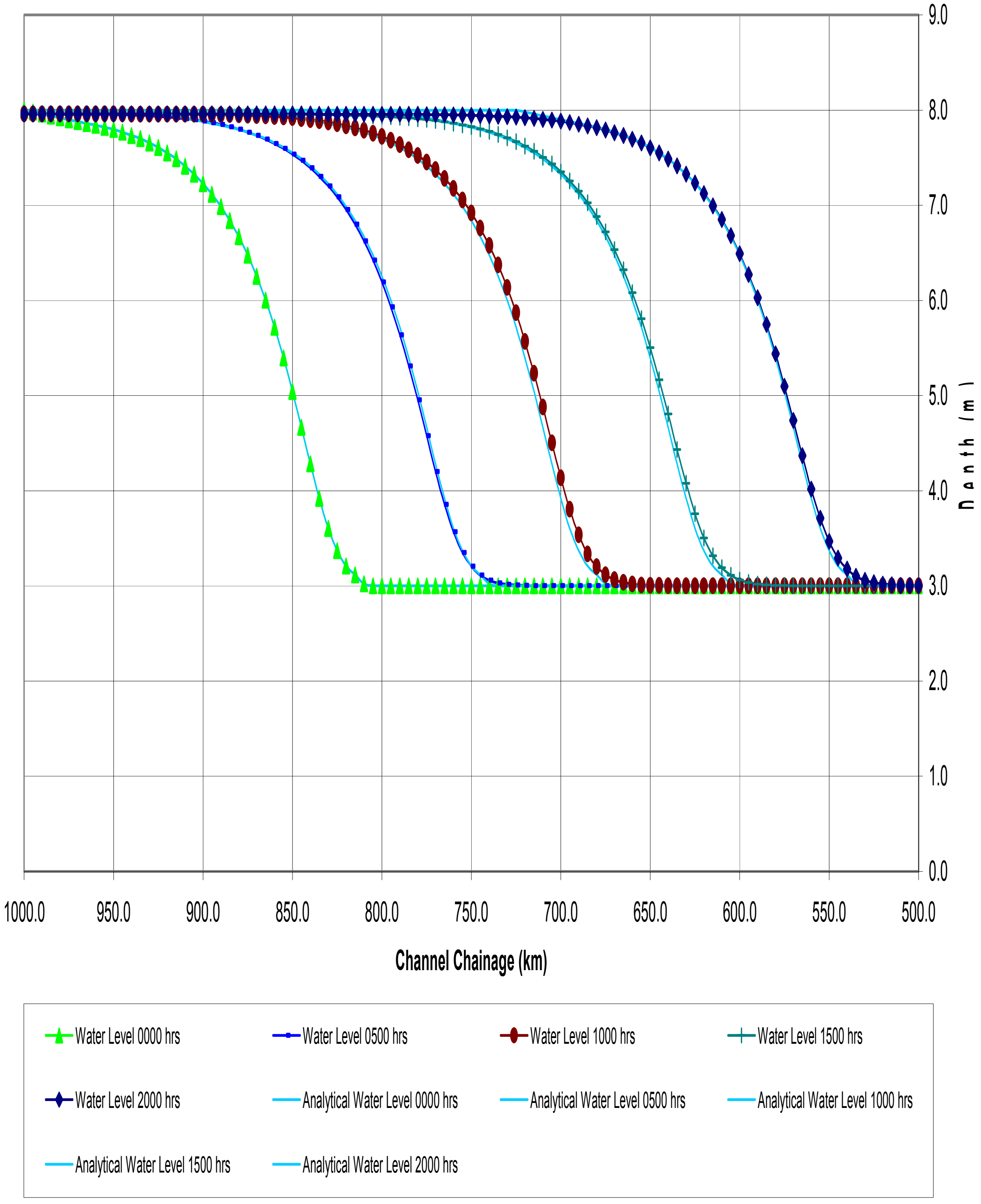
Graph 8 - MIKE 11: Successive Calculated and Analytical Water Surface Profiles

Applied Bed Friction - Linear Distribution Resistance Radius - Manning's n=0.0256

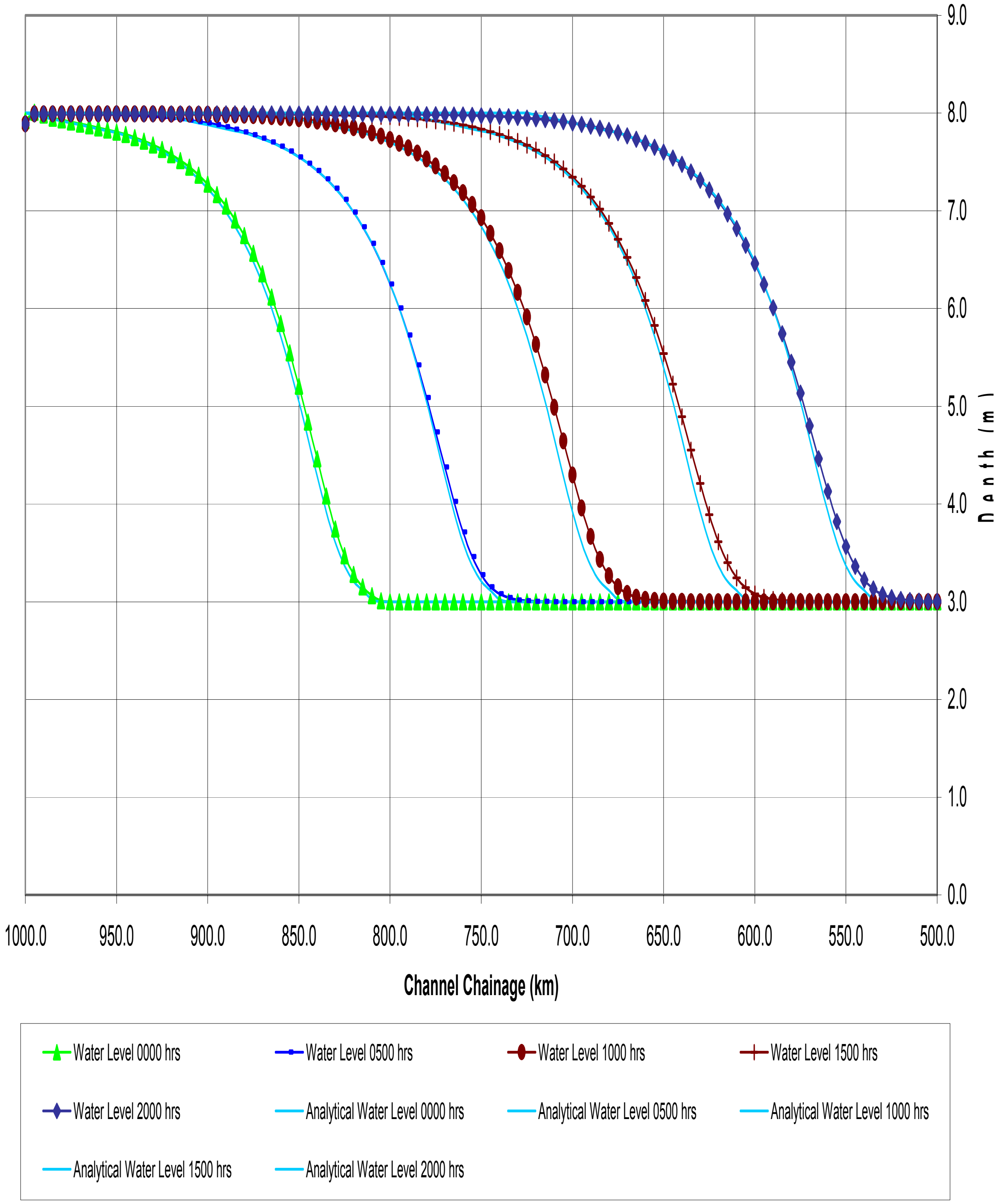


Graph 9 - MIKE 11: Successive Calculated and Analytical Water Surface Profiles

Applied Bed Friction - Chézy C=55



Graph 10 - HEC-RAS: Successive Calculated and Analytical Water Surface Profiles
Flow v's Roughness Option Applied



Graph 11 - HEC-RAS: Successive Calculated and Analytical Water Surface Profiles
Flow v's Roughness Option with Improved Calculation Settings/Tolerances