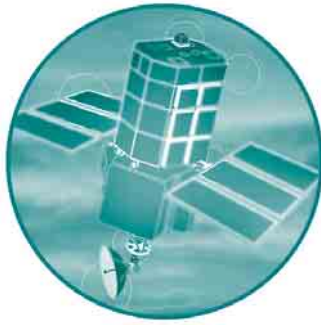


# Defra/Environment Agency Flood and Coastal Defence R&D Programme



## Benchmarking Hydraulic River Modelling Software Packages

Results – Test K (Culverts)

R&D Technical Report: W5-105/TR2K



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

**BENCHMARKING HYDRAULIC RIVER  
MODELLING SOFTWARE PACKAGES**

**Results – Test K (Culverts)**

R&D Technical Report: W5-105/TR2K

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Research Contractor: Bullen Consultants

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This document provides the results and findings from undertaking the Environment Agency's Benchmarking Test K (Culverts) 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, Culvert

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

## **EXECUTIVE SUMMARY**

The test has successfully demonstrated that ISIS, MIKE 11 and HEC-RAS are capable of modelling culverts of mild and steep slopes under unsteady flow regimes.

The water level results obtained from each software package are very similar and show no instabilities or inconsistencies. However, velocity and discharge results from each of the software packages show some degree of variability.

When considering quasi-steady flow conditions (i.e. constant boundary conditions) each of the software packages accurately predict, for both Parts A and B, the theoretical full culvert flow capacity of the culvert.

The results suggest that the downstream (unsteady) boundary has a different numerical effect on the software packages and that the culvert computations are treated differently. Comparing ISIS and HEC-RAS, ISIS initially exhibits a reduction in discharge in the lower part of the channel and, surprisingly given that the water levels are almost identical, also exhibits a reduction in velocity that is greater than HEC-RAS. In comparison, MIKE 11 has produced notably lower velocities and discharges than ISIS. Further investigation is recommended in to the performance of these software packages; however, for this test configuration it is clear that the ISIS and HEC-RAS software packages produce results that are the most representative.

It is suggested by the developers of MIKE 11 that “the applied model set-up is not suitable for this test” i.e. the culvert structure unit is not suited to this test configuration. The developers of MIKE 11 have recommended that the culvert, as defined by the test specification, would be best modelled by the use of closed circular cross sections. Since this approach does not use the “culvert” functionality/feature of the software, as intended by the test specification, this approach has not been tested as part of this study.

Investigations with MIKE 11, which has exhibited some oscillations in the predicted discharge and velocities, have been shown to be a consequence of the test boundary conditions and the system configuration.

The test has shown that the oscillations exhibited by MIKE 11 can be damped by increasing the implicit weighting coefficient; however, this has simply illustrated the danger of using high default values for this parameter.



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# 1 INTRODUCTION

## 1.1 Background

This report presents the results and findings from Test K (Culverts) 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 K (Culverts), (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
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/Reporter	University of Leeds

## 1.2 Aim of Test

The aim of the test is to:

- assess the ability of the software package to model unsteady fluid flow in a circular culvert, such that the flow correctly changes from free surface open channel flow to fully pressurised pipe flow;

- test the performance of culverts with both mild (Part A) and steep (Part B) bed slopes, in order that the software can also be analysed for subcritical and supercritical flow respectively; 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

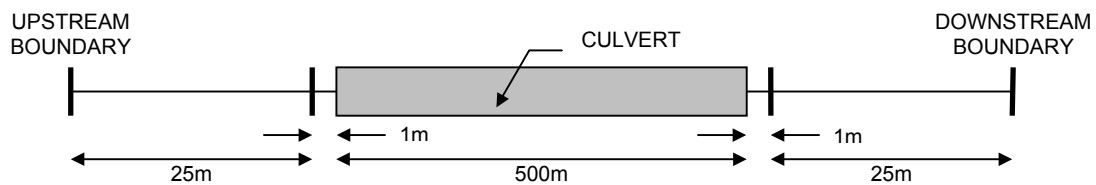
The test has been undertaken in accordance with the Benchmarking Test Specification - Test K (Crowder *et al*, 2004).

The test configuration for both Parts A and B is illustrated schematically in Figure 2.1

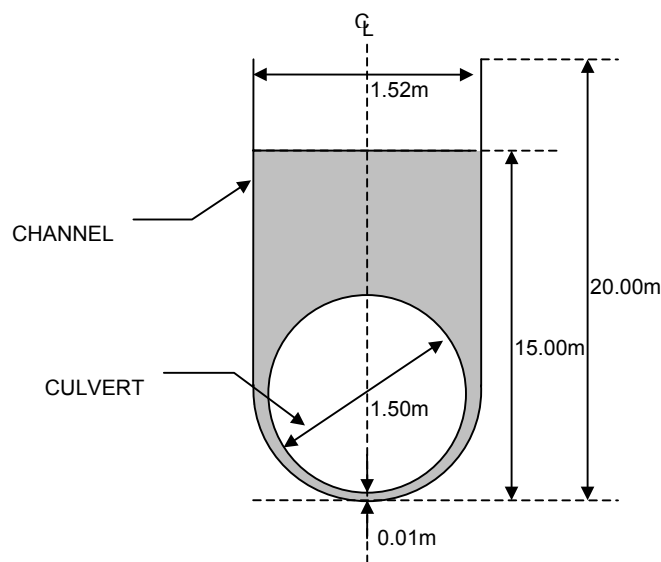
For each of the software packages a single reach has been defined with a minimum of four cross-sections and a constant Manning's  $n$  value of 0.025.

For Part A of the test the bed slope is 0.0025 (mild) and for Part B 0.01 (steep).

**Figure 2.1: Schematic illustration of test configuration**



**Figure 2.2: Schematic illustration of culvert dimensions**



The culvert dimensions are the same for both Parts A and B and are illustrated schematically in Figure 2.2. The culvert diameter is 1.5m and is defined with a culvert Manning's roughness ( $n$ ) of 0.025 or Colebrook-White  $K_s$  value of 0.075m.

The ability of the software to model culvert i) entry and exit losses, ii) overtopping, or iii) other specific features, has not been a primary consideration. However, the ability of each software package to consider these capabilities has been tested and reported upon where relevant.

For Parts A and B of the test, separate unsteady flow boundary conditions have been used.

For Part A, the upstream boundary was defined with a constant inflow of  $0.75\text{m}^3/\text{s}$ . The downstream boundary was defined as a water level boundary that was initially set at 0.5mAD at 0.0hrs, which was then linearly increased to 4.2mAD at 1.36hrs (82.0 min) with a 1 minute data interval defined to two decimal places. The downstream boundary was then fixed at this level through to 2.0hrs.

For Part B, the upstream boundary was defined with a constant inflow of  $1.5\text{m}^3/\text{s}$ . The downstream boundary was defined as a water level boundary that was initially set at 0.5mAD at 0.0hrs, which was then linearly increased to 9.7mAD at 1.36hrs (82.0 min) with a 1 minute data interval defined to two decimal places. The downstream boundary was then fixed at this level through to 2.0hrs.

## **2.2 Building the Model in ISIS**

The modelling of a culvert within a river reach in ISIS can be done in one of two ways:

- The use of two or more culvert units and two junction units, which connect the upstream and downstream river cross-sections to the culvert units.

or

- The use of two or more culvert units and a culvert inlet and outlet unit, which connect the bounding cross-sections to the culvert units, such that entrance and exit losses, respectively, can be considered.

Any losses, as a result of a bend in the culvert structure, can be taken into account by use of a 'Culvert Bend' unit. This has not been considered in the test.

The main upstream and downstream reach lengths were defined with "river section" units at the prescribed locations. However, since ISIS treats culverts as individual reaches within a channel, the model required additional "river section" units at the culvert entrance and exit (i.e. at chainage 26.0m and 526.0m). These were used to signify the end of the upstream river reach, and the beginning of the downstream river reach respectively.

The additional river section units were copied from the cross sections at chainage 25.0m and 527.0m with the elevations adjusted so as to maintain a constant channel slope.

The modelling of the culvert has been undertaken by use of the inlet and outlet units as described above. The alternative method of using junctions has not been considered in the test. In all seven circular culvert units of lengths 100.0m, 100.0m, 50.0m, 50.0m, 100.0m, 100.0m and 0.0m were specified to give the total culvert length of 500.0m (see Section 3.1 for further comment).

As an alternative to the circular culvert the test has been repeated using a symmetrical culvert unit.

It should be noted that when using the junction units flow continuity and water level balance is applied i.e.  $Q_1 + Q_2 + Q_3 + \dots = 0$  and  $h_1 = h_2 = h_3 = \dots$  respectively.

The inlet unit models the inlet of a culvert (with an optional trash screen) based on the methodology contained within the Culvert Design Manual (Ramsbottom *et al*, 1997). The culvert inlet unit can operate either under inlet control or outlet control, and can switch freely between these modes depending on the hydraulic conditions.

When the unit is in outlet control, the unit's governing equations are based on a simple velocity head multiplier and the head downstream of the unit will affect the calculation of the upstream head.

Under inlet control the upstream water level is solely dependent on the culvert flow and the properties of the culvert entrance. Head losses are based upon empirical formulae presented in the Culverts Design Manual (Ramsbottom *et al*, 1997). This requires empirical values (control parameters) to be defined by the user that relate to the shape, type, material and geometry of the culvert inlet and outlet.

Empirical values for these parameters are available within the ISIS Help files, from which the following values were chosen and used to model the defined culvert.

Symbol	Value	Description
K	0.0078	Unsubmerged control loss coefficient
M	2.0000	Exponent of flow intensity for inlet control
C	0.0292	Submerged inlet control loss coefficient
Y	0.7400	Submerged inlet control adjustment factor
K <sub>i</sub>	0.3000	Outlet control loss coefficient

These values were chosen based upon a concrete culvert with a headwall and socket end of pipe of circular cross-section.

The culvert roughness was defined with a Manning's n value of 0.025 for both the upper and lower halves. As an alternative a Colebrook-White  $K_s$  value can be defined in ISIS, however, this has not been tested.

### **2.3 Building the Model in MIKE 11**

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 (inlet chainage used), the culvert attributes, head loss factors and geometry need to be defined.

The culvert attributes include setting the upstream and downstream culvert invert levels, the culvert length, and the Manning's n value. The values used in the test were those as defined by the test specification.

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 as follows:

	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 in-flow and out-flow 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, 1st Edition, 1997. Details are not fully provided in the on-line help of the printed manuals of the version being tested.

The cross sectional geometry of a culvert can be specified as, rectangular, circular, irregular level-width table, irregular depth-width table and section DB. For the test the circular type was selected with the dimensions as provided by the test specification.

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, which is complicated, can be found in the MIKE 11 Reference Manual, 1st Edition, 1997. Details are not provided in the on-line help of the printed manuals of the version being tested.

Further to the analysis of the results of this test (see Section 4) the software developers (DHI Software) for MIKE 11 were contacted regarding oscillations observed in the velocity and discharge results. From this it was suggested that an alternative modelling approach for this test could be adopted. This approach involves representing the culvert as a separate branch with closed circular cross sections as opposed to a culvert structure and with entry and exit losses being represented using the Energy Loss structure. Additional computational points within this closed section can then be added by the use of setting DX-max setting. This approach has not been tested here as it falls outside of the scope/requirements defined by the test specifications.

## 2.4 Building the Model in HEC-RAS

The modelling of a culvert requires a reach with a minimum of four cross-sections, two downstream and two upstream of the structure.

The first cross section should be located sufficiently downstream from the culvert (expansion length) so that the flow is not affected by the structure (i.e. the flow has fully expanded). Details on how to determine this expansion reach length,  $L_e$ , are provided in the HEC-RAS manual. As a 'rule of thumb' the Corps of Engineers suggest a distance of four times the average length of the side constriction caused by the structure abutments for the expansion reach length,  $L_e$ .

The second cross section should be located immediately downstream of the culvert (i.e. within a few metres). This cross section should represent the effective flow just outside the structure.

The third cross section should be located just upstream of the culvert and is intended to represent the effective flow area just upstream of the structure. The distance between this cross section and the culvert should be relatively short. This distance should only reflect the length required for the abrupt acceleration and contraction of the flow that occurs in the immediate area of the opening.

The fourth cross section should be upstream of the culvert where the flow lines are approximately parallel and the cross section is fully effective. Details on how to determine the contraction reach length,  $L_c$ , are provided in the HEC-RAS manual. However, as a 'rule of thumb' the Corps of Engineers suggest a distance of one times the average length of the side constriction caused by the structure abutments.

It is recommended in the HEC-RAS manual that at both the second and third cross sections "ineffective flow areas" are defined on either side of the culvert opening. However, due to the similarity of the culvert and channel dimensions the test has omitted the inclusion of these ineffective flow areas. Details on how to set the ineffective flow area stations and elevations are provided in the HEC-RAS manual.

Additional cross sections were not considered, so as to conform with the suggested contraction and expansion lengths, since contraction and expansion losses were considered to be minimal given the structure and channel geometry. However, it should be noted that additional cross-sections were used for Part B of the test (see Section 3.3) so as to eliminate the warning messages that were produced when running the model with just the test specification cross-sections.

When the user adds a culvert at a particular chainage (river station), the program automatically formulates two additional cross sections inside of the culvert structure. The geometry inside of the culvert is a combination of the bounding cross sections and the culvert geometry.

The culvert hydraulic computations in HEC-RAS are similar to the bridge hydraulic computations, except the Federal Highway Administration's (FHWA) standard equations for culvert hydraulics under inlet control are used to compute the losses through the structure.

The culvert routines in HEC-RAS have the ability to model eight different types of culvert shapes. These shapes include box (rectangular), circular, elliptical, arch, pipe arch, semi circular, low-profile arch, and high-profile arch culverts. For each shape of culvert the user needs to select a specific Chart No. (relevant to the type of culvert) and Scale No. (relevant to the entrance shape), which is in accordance to the FHWA. The options chosen for this test are given below:

Type	-	Circular
Chart No.	-	1 - Square edge
Scale No.	-	1 - Entrance with headwall

The HEC-RAS culvert routines compute the headwater required to produce a given flow rate through the culvert for inlet control conditions and for outlet control conditions. The higher headwater "controls", and an upstream water surface is computed to correspond to that energy elevation.

For inlet control, the required headwater is computed by assuming that the culvert inlet acts as an orifice or a weir. Therefore, the inlet control capacity depends primarily on the geometry of the culvert entrance. Extensive laboratory tests by the National Bureau of Standards, and the Bureau of Public Roads (now, FHWA), and other entities resulted in a series of equations, which describe the inlet control headwater under various conditions. These equations are used by HEC-RAS in computing the headwater associated with inlet control.

For outlet control flow, the required headwater must be computed considering several conditions within the culvert and the downstream tailwater. For culverts flowing full, the total energy loss through the culvert is computed as the sum of friction losses, entrance losses, and exit losses.

Friction losses are based on Manning's equation, for which a Manning's  $n$  value of 0.025 was defined for both the lower and upper halves of the culvert.

Entrance losses are computed as a coefficient times the velocity head in the culvert at the upstream end. The HEC-RAS manual provides guidance on the appropriate choice of entrance loss coefficient, which is in accordance the FHWA manual (1985). A value of 0.5 was used for the test, based on a sharp-edged culvert entrance.

Exit losses are computed as a coefficient times the change in velocity head from just inside the culvert (at the downstream end) to outside the culvert. The HEC-RAS manual provides guidance on the appropriate choice of exit loss coefficient, which is in accordance the FHWA manual. A value of 1.0 was used for the test, based on a sudden expansion of flow.

When the culvert is not flowing full, the direct step backwater procedure is used to calculate the profile through the culvert up to the culvert inlet. An entrance loss is then computed and added to the energy inside the culvert (at the upstream end) to obtain the upstream energy (headwater).

Although not tested in the study, HEC-RAS has the ability to consider a depth of blockage at the culvert entrance so as to take into account any reduced flow area.



### **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**

ISIS was first run in steady state mode for Part A of the test and the diagnostics file (zzd) checked for errors/warnings.

The diagnostics file indicated that more culvert units were required, hence, for both Parts A and B of the test, seven circular culvert units of lengths 100.0m, 100.0m, 50.0m, 50.0m, 100.0m, 100.0m, and 0.0m were specified to give the total culvert length of 500.0m. These distances were chosen so that velocity results could be obtained at mid-culvert.

Following the above revisions, successful steady runs were performed with no further error/warnings for both Parts A and B of the test.

For both Parts A and B of the test, a quasi-steady simulation was undertaken i.e. an unsteady simulation with the initial boundary conditions set constant. The simulation was run for a period of 1.0hr with a time step of 10s. The results at 1.0hr were subsequently used as initial conditions for the respective unsteady simulations.

In order to stay within recommended model convergence limits, as defined by the ISIS Flow runtime window, time steps of 20s and 10s were used for Parts A and B of the test respectively. In both cases results were recorded every 60s.

#### **3.3 Running the Model in MIKE 11**

For both Parts A and B of the test an unsteady simulation was initially undertaken with the type of initial condition set to steady state and with the boundary conditions constant with respect to time (referred to as a quasi-steady for the ISIS and HEC-RAS tests). The simulation was run for a period of 1.0hr with a time step of 60s and an implicit weighting coefficient of 0.75. The result at 1.0hr was subsequently used as initial conditions (“hot-start”) for the respective unsteady simulations.

The default implicit weighting coefficient of 0.5 was increased to 0.75 as instabilities were otherwise observed in the results (see Section 5 for further discussion and an explanation for these oscillations).

For the unsteady simulations a time step of 60s was used for both Parts A and B of the test with the default implicit weighting coefficient of 0.5. In both cases results were recorded/extracted at every time step (60s). No errors or warnings were reported in the log report file.

In addition a second series of tests were undertaken for both Parts A and B of the test with the implicit weighting coefficient increased to 0.75.

### **3.4 Running the Model in HEC-RAS**

HEC-RAS was first run in steady state mode for Parts A and B of the test and the warnings dialogue summary box checked for errors/warnings.

For Part A of the test no errors or warnings were given, however, for Part B it was reported that the flow convergence ratio was outside recommended limits between chainages 552.0m and 527.0m. Hence, for Part B additional cross sections were added between chainages 552.0m and 527.0m at 5.0m spacing.

Additional cross-sections were added by copying the cross section at chainage 552.0m and then by lowering the cross-section elevations such that the bed-slope of 1:100 was maintained. Cross section interpolations were not considered.

Following the above revisions, successful steady runs were performed with no further error/warnings for Part B of the test.

For both Parts A and B of the test a quasi-steady simulation was undertaken i.e. an unsteady simulation with the initial boundary conditions set constant. The simulation was run for a period of 1.0hr with a time step of 60s. The result at 1.0hr was saved to a restart file and then subsequently used as initial conditions for the respective unsteady simulations.

For the unsteady simulations a time step of 60s was used for both Parts A and B of the test. In both cases results were recorded every 60s, which is the smallest output time interval possible within HEC-RAS.

In undertaking the simulations the Energy (standard step) method option (selected in the “Bridge Modelling Approach Editor”) was used for both high and low flow computations.

## **4 RESULTS**

### **4.1 Introduction**

For each Part of the test the results from all the software packages have been discussed, compared and presented in combination so as to provide a direct comparison.

For ISIS additional analysis has been undertaken which compares the results of the circular and the symmetrical culvert units.

The analysis of results for each part of the test has been limited to the following:

- Stage verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Velocity verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Discharge verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Froude number verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary; and
- Stage and Flow Velocity verses Time at the culvert inlet, mid culvert and culvert outlet, were possible by the software.

### **4.2 Analysis of Water Level Results (Part A)**

Inspection of Graphs 1 to 4 shows that the water levels produced by ISIS in Part A of the test are very smooth with no visible fluctuations. The water levels at a chainage of 552.0m remain constant at just above 2.0mAD for the first 27 minutes of the simulation. These levels then begin to rise after 28 minutes at first gradually, and then at the same rate as the water levels at the downstream end of the channel, 0.0m. The same identical trend can be observed in Graph 2, 1.0m upstream of the culvert entrance. These water levels remain constant at 2.0mAD again for the first 27 minutes of the simulation after which they are observed to rise at the same rate as the downstream water levels. The delay of 1 minute in the change in water level between chainages 526.0m and 552.0m being due to the celerity within the channel. The water levels at chainage 25.0m begin at approximately 0.7mAD, though almost immediately start to rise joining the same trend as the downstream water levels after only approximately 6 minutes. Finally, the water levels recorded at 0.0m in Graph 4 simply demonstrate that the head/time boundary condition applied at that channel cross-section is being correctly applied to the simulation.

From the same graphs, it can be seen that the water levels generated in MIKE 11 are almost identical to those produced by ISIS when the rate of change in water level is constant. However, when the water levels change from a constant level to a linearly increasing level after 27 minutes and 28 minutes for chainages 527m and 552m respectively, MIKE 11 water levels rise slightly above those calculated by ISIS until they converge again at 44 minutes. It must also be noted from Graph 3 at a chainage of 25.0m that the water levels calculated by MIKE 11 start at a lower level than those generated by ISIS and HEC-RAS, though quickly converge after only 7 minutes.

The water levels generated by HEC-RAS at the upstream channel cross-sections of 552.0m and 527.0m start at a higher level than those generated by ISIS and MIKE 11, but do also remain perfectly constant for the first part of the simulation. This would indicate that the head loss calculated by HEC-RAS in the culvert unit is less than that calculated by ISIS and MIKE 11. These higher water levels not unsurprisingly break at the marginally earlier time when compared to ISIS and MIKE 11, after which they then rise in a similar manner to the downstream water levels, but not perfectly linearly and always above those generated by the other two packages. Conversely, the HEC-RAS water levels calculated at the downstream channel cross-section of 25.0m follow those generated in ISIS exactly.

Graphs 17 and 18 provide a comparison of water levels calculated by ISIS and HEC-RAS at chainages of 526.0m and 26.0m respectively. The purpose of these graphs is to give a comparison of the water levels generated by the two packages inside the culvert at the entrance and the exit. These graphs can also be used to determine the time during the simulation at which the culvert inlet and outlet become fully submerged. It must therefore be noted from where these water levels are taken.

The water levels displayed for ISIS are taken from the calculated water levels at the upstream culvert unit cross-section and the equivalent downstream cross-section. The water levels displayed for HEC-RAS are taken from the 'Culv WS Inlet' variable, which gives the 'Water Surface Elevation inside the Culvert at the Inlet'. For the water levels at chainage 26.0m, the equivalent 'Culv WS Outlet' variable was employed, giving 'Water Surface Elevation inside the Culvert at the Outlet'. MIKE 11 was not included in this comparison, as water level information is not provided by MIKE 11 at these points.

The water levels calculated by ISIS within the culvert reach are the piezometric water levels as opposed to the actual water levels, which would be equal to the soffit of the culvert. It can be seen in Graphs 17 and 18 that the piezometric water levels generated by ISIS inside the culvert inlet and outlet are identical to the actual water levels generated at the channel cross-sections immediately upstream and downstream of the structure. Any actual difference is too small to be observed on the graphs, which would be expected, as these channel cross-sections are located only 1.0m from the inlet and outlet of the culvert.

HEC-RAS however, does display the actual water level within the culvert's entrance and exit. It can be seen from Graphs 17 and 18 that the water level cease to rise above the soffit level of the culvert at the respective chainages of 526.0m and 26.0m. It can also be seen that the water level mirrors those produced by ISIS up to this point. It can therefore be determined that the culvert outlet becomes fully submerged after 24 minutes of the simulation, and the inlet after 48 minutes.

The water levels calculated by HEC-RAS inside the culvert inlet start at a value slightly greater than those recorded by ISIS as was observed at channel cross-section 527.0m. The slightly higher water levels generated in HEC-RAS at the upstream end cause the inlet of the culvert to become submerged after only 45 minutes, earlier than demonstrated by ISIS.

### 4.3 Analysis of Velocity and Discharge Results (Part A)

Graphs 5 to 8 and 9 to 12 show the variation in velocity and discharge with time respectively at fixed locations for Part A of the test.

At the two upstream channel cross-sections of 552.0m and 527.0m chainage, the velocity, as with the observed water levels, remains constant for the first part of the test in all three packages. However, it must be noted that at 552.0m, the velocities begin to change after only 25 minutes in ISIS and MIKE 11, and 29 minutes in HEC-RAS. This change in velocity coincides with the water level break for each of the software packages respectively.

Upstream of the culvert, Graph 9 confirms that the inflow at the upstream boundary remains constant at  $0.75\text{m}^3/\text{s}$  throughout the test for each software package. Graph 10, for chainage 527.0m, shows a small reduction in the discharge from 25 minutes in MIKE 11 and 29 minutes in ISIS and HEC-RAS. This small reduction remains approximately constant while the water level upstream of the culvert rises. When the downstream water level boundary stops increasing at 82 minutes, the discharge returns to  $0.75\text{m}^3/\text{s}$  for each of the software packages.

Upstream of the culvert at chainage 552.0m the initial velocity is  $0.98\text{m/s}$  in ISIS,  $0.90\text{m/s}$  in MIKE 11 and  $0.83\text{m/s}$  in HEC-RAS. Conversely, at the two cross sections downstream of the culvert, the velocities calculated by ISIS are lower than those calculated by HEC-RAS up to the end of the transitional period, 48 minutes into the simulation, but greater than MIKE 11. After this time an identical rate of change of velocity, as calculated at the upstream channel sections, can be observed in both HEC-RAS and ISIS.

As stated earlier, it can be seen from Graph 18 that the culvert outlet becomes fully submerged after 24 minutes. Likewise, it can be seen from Graph 17 that the culvert inlet becomes fully submerged after 48 minutes. This time period within the simulation may be referred to as a transitional stage in which the flow within the culvert changes from open channel flow to full culvert pressurised pipe flow. It can therefore be seen from Graphs 5 and 6 that each software package calculates the change in flow velocity within this transitional period slightly differently.

Downstream of the culvert, Graphs 7, 8, 11 and 12 shows that the velocity and discharge calculated by each of the software packages is notably different while the downstream water level boundary is rising.

The velocities calculated by MIKE 11 at the downstream channel cross-section start at similar values to those calculated by HEC-RAS and ISIS, but quickly fall away before oscillating above  $0.0\text{m/s}$ . The oscillations show time steps of negative discharge indicating that flow is re-entering the system at the downstream boundary (further discussion in Section 4.10). Both ISIS and HEC-RAS exhibit a smooth and gradual reduction in the velocity, although ISIS initially shows a greater rate of reduction, which is reflected in the discharge results.

ISIS initially calculates a gradual reduction in the discharge; achieving approximately  $0.4\text{m}^3/\text{s}$  at 28 minutes, after which the discharge gradually increases to a value that is the same as HEC-RAS at around 48 minutes. This coincides with the time at which the inlet becomes fully submerged. Conversely HEC-RAS initially has a constant discharge of  $0.75$  up to 29

minutes at which point there is a small reduction, which remains approximately constant while the down boundary rises. When the downstream boundary stops increasing at 82 minutes the discharge returns to  $0.75\text{m}^3/\text{s}$ . During the period in which the downstream water level boundary is increased, MIKE 11 produces discharge results that oscillate at values that are much lower than the stable results calculated by both ISIS and HEC-RAS. When the downstream water level boundary stops increasing the results then oscillate around the stable results calculated by ISIS and HEC-RAS.

In addition to running MIKE 11, with the default implicit weighting coefficient of 0.5, the test was repeated with the value set at 0.75, the results of which are presented in Graphs 22 to 25 and 26 to 29 for velocity and discharge respectively. As can be seen from these graphs the results show that the oscillations are generally smoothed out (dampened) when using the implicit weighting value of 0.75.

When using an implicit weight value of 0.75 MIKE 11 calculates a velocity and discharge profile that is notably lower than that of ISIS and HEC-RAS during the period in which the downstream water level boundary is increasing. However, after 82 minutes, which is when the downstream boundary remains constant, MIKE 11 produces a discharge and velocity value that is very similar to that as calculated by ISIS and HEC-RAS.

Graphs 19 to 21 provide a comparison of the calculated velocities within the barrel of the culvert. These graphs have been plotted as a means by which to compare how each of the three packages calculate the variation in velocity as the flow within the culvert changes from open channel flow to pressurised pipe flow. An important part of this test is to compare the calculated full flow velocity with the theoretical full flow velocity of  $0.42\text{m/s}$  once full culvert flow has been achieved. Because of the way the culvert is modelled in HEC-RAS and MIKE 11, data about the velocity of flow within the culvert is very restricted. HEC-RAS gives flow velocity information inside the culvert at the inlet and outlet, but at no other sections along the culvert. MIKE 11, however, does not give any information specific to the culvert itself. The only information available within MIKE 11, in the region of the culvert, is at the flow-point halfway between the channel cross-sections of  $526.0\text{m}$  and  $26.0\text{m}$ . For this reason, Graphs 19 and 20 compare flow velocities calculated in ISIS and HEC-RAS at the inlet and outlet of the culvert, while Graph 21 compares flow velocities between ISIS and MIKE 11 at chainage  $276.0\text{m}$ , the mid-way point of the culvert. For all three graphs, the relevant data for the ISIS plots is extracted from culvert cross-section  $526.0\text{m}$  for the inlet,  $276.0\text{m}$  for mid-way point and  $26.0\text{m}$  for the culvert outlet.

The velocities calculated by ISIS inside the culvert inlet remain constant at the same value as those recorded in the channel at chainage  $527.0\text{m}$  of  $0.99\text{m/s}$  for the first part of the simulation. These velocities then begin to change after 24 minutes, the time at which the culvert outlet becomes fully submerged. At 48 minutes, the velocity of flow then remains at  $0.41\text{m/s}$  until 82 minutes, which is when the downstream water level boundary stops rising, the velocity then increases to a constant value of  $0.42\text{m/s}$ , the theoretical full culvert velocity.

The same velocity behaviour is observed in HEC-RAS as for ISIS. However, it must be noted that even though these velocities also begin at  $0.99\text{m/s}$ , identical to the value calculated by ISIS, the velocities calculated by HEC-RAS in the channel just upstream of the inlet are much lower at  $0.83\text{m/s}$ . These velocities also begin to fall at the earlier time of 21 minutes, reaching approximately the same full culvert flow velocity recorded by ISIS, but again 3 minutes earlier than ISIS at 45 minutes. This difference can be attributed to the time at which

the culvert inlet becomes fully submerged. As noted earlier for Graph 19, the inlet becomes fully submerged after only 45 minutes when the model is run in HEC-RAS.

The velocities calculated by ISIS at the culvert outlet begin at 1.01m/s and fall away immediately, eventually reaching a minimum value 0.22m/s. The velocity then begins to rise again settling at the same constant value recorded at the inlet of 0.41m/s after 48 minutes. At 82 minutes, which is when the downstream water level boundary stops rising, the velocity then increases to a constant value of 0.42m/s, the theoretical full culvert velocity.

The velocities calculated by HEC-RAS however, follow a slightly different path. Starting at 1.16m/s, the velocity quickly peaks at 1.19m/s at 1 minute, after which the velocity then falls in the same manner as recorded by ISIS, but settling at just below the theoretical full flow velocity after 25 minutes, 1 minute after the culvert outlet becomes fully submerged. At 82 minutes, which is when the downstream water level boundary stops rising, the velocity then increases to a constant value of 0.42m/s, the theoretical full culvert velocity.

The velocity calculated by MIKE 11 at the mid-culvert point starts at 1.22m/s, similar to that recorded at the downstream channel cross section of 25.0m chainage (1.23m/s). This value then drops quickly to 0.98m/s at 5 minutes, almost identical to the value recorded by ISIS at the same time (0.99m/s). The recorded velocity then increases dramatically to 1.76m/s at 7 minutes, after which it remains constant at this level until 24 minutes. It must be noted that 5 minutes coincides with the time at which the water level at chainage 25.0m starts to rise at the same rate as that at 0.0m. Therefore, between the times of 5 minutes and 24 minutes, as the water level at the culvert outlet increases at the same rate as the downstream head/time boundary condition, the velocity inside the culvert remains constant. Once the culvert outlet is fully submerged at 25 minutes, MIKE 11 records a dramatic decrease in the culvert flow velocity to 0.57m/s. The velocities then continue to decrease in much the same way as demonstrated at the culvert outlet in HEC-RAS, reaching a value of 0.41m/s at around 49 minutes, the time the culvert inlet becomes fully submerged. At 82 minutes, which is when the downstream water level boundary stops rising, the velocity then increases to a constant value of 0.42m/s, the theoretical full culvert velocity.

#### **4.4 Analysis of Froude Number Results (Part A)**

As expected, a similar relationship to velocities can be observed in Graphs 13 to 16 showing the calculated Froude numbers. It must also be noted that all calculated Froude numbers are significantly less than 1.0 demonstrating subcritical fluid flow.

#### **4.5 Analysis of Water Level Results (Part B)**

The water levels recorded by each of the three packages at all the channel cross-sections in Part B of the test demonstrate the same behaviour as in Part A. It can be seen from Graphs 30 and 31 that the water levels recorded at 552.0m and 527.0m remain constant for the first 44 minutes and 43 minutes of the simulation respectively for both ISIS and MIKE 11, and 47 minutes for HEC-RAS. Also, as observed in Part A, the water levels generated in HEC-RAS remain slightly above those of the other two packages, further indication that the head loss calculated by HEC-RAS in the culvert unit is less than that calculated by ISIS and MIKE 11.

The water levels at chainage 25.0m also begin to rise quickly as in Part A, increasing at the same rate as the downstream water levels after only 5 minutes.

It can be seen from Graph 46 that the water levels generated in both HEC-RAS and ISIS inside the culvert inlet follow exactly the same behaviour as those at chainage 527.0m. Starting at 6.0mAD, these water levels remain constant until the 42nd minute of the test. They then both begin to rise at the same rate as the downstream boundary condition, HEC-RAS stopping at the soffit level of the culvert after 49 minutes, and the ISIS piezometric water level crossing the soffit level of the culvert at 50 minutes. Likewise, the water levels at the culvert outlet start at approximately 1.0mAD in both HEC-RAS and ISIS, quickly following the same trend as the downstream boundary condition after 6 minutes of the simulation. Both packages then meet the soffit level of the culvert outlet after only 12 minutes of the simulation.

#### **4.6 Analysis of Velocity and Discharge Results (Part B)**

The velocities calculated by ISIS, HEC-RAS and MIKE 11 in Part B of the test show very similar behaviour to those calculated in Part A for the channel upstream of the culvert. Each of the three packages displays slightly varying velocities, which remain constant for the first part of the simulation. HEC-RAS once again records the least value, starting at chainage 552.0m at 1.79m/s. Also, as in Part A, the velocity calculated in HEC-RAS is the last to break, in this case at 47 minutes. The velocities calculated by ISIS at chainage 552.0m start at 1.84m/s and break after 43 minutes, while those calculated in MIKE 11 start at 2.06m/s and break after 42 minutes.

The discharges upstream of the culvert show a very similar behaviour to that observed in Part A. Graph 38 confirms that the inflow at the upstream boundary remains constant at 1.5m<sup>3</sup>/s throughout the test for each software package. Graph 39, for chainage 527.0m, shows a small reduction in the discharge from 42 minutes in MIKE 11, 43 minutes in ISIS and 47 minutes in HEC-RAS. This small reduction remains approximately constant while the water level upstream of the culvert rises. When the downstream water level boundary stops increasing at 82 minutes the discharge returns to 1.5m<sup>3</sup>/s for each of the software packages.

The velocities calculated in the channel downstream of the culvert also show similar behaviour to that observed in Part A. It can be seen from Graph 36, at chainage 25.0m, that the velocities recorded by both ISIS and MIKE 11 start at approximately the same value of 2.0m/s. HEC-RAS records a very similar pattern to ISIS, starting at 1.56m/s, the velocity initially peaks at 1.92m/s at 3 minutes after which time the velocities calculated by HEC-RAS follow almost exactly the velocities generated by ISIS, eventually converging exactly with ISIS at 48 minutes. Again the MIKE 11 velocities are oscillating and go negative.

The discharges downstream of the culvert show a similar behaviour to that observed in Part A, although for ISIS the initial gradual reduction in the discharge is not as pronounced. After the initial reduction there are clearly fluctuations in the calculated discharge when you compare with HEC-RAS, but they are small when compared with the MIKE 11 solution, as observed in Graphs 40 and 41. At around 48 minutes the discharge then slightly increases to approximately 1.35m<sup>3</sup>/s. This matches and coincides with a reduction in discharge calculated by HEC-RAS. This small reduction remains approximately constant while the water level



upstream of the culvert rises. When the downstream water level boundary stops increasing at 82 minutes the discharge returns to  $1.5\text{m}^3/\text{s}$  for both of the software packages.

During the period in which the downstream water level boundary is increased, MIKE 11 produces discharge results that oscillate (and are also negative) at values that are much lower than the stable results calculated by both ISIS and HEC-RAS. When the downstream water level boundary stops increasing the results then oscillate around the stable results calculated by ISIS and HEC-RAS.

In addition to running MIKE 11 with the default implicit weighting coefficient of 0.5, the test was repeated with the value set at 0.75; the results of which are presented in Graphs 51 to 54 and 55 to 57 for velocity and discharge respectively. As can be seen from the discharge results the oscillations are reduced in size up to 82 minutes, when using the implicit weighting value of 0.75, and are eliminated after 82 minutes, which is when the downstream water level is constant.

Again as for Part A, when using an implicit weight value of 0.75, MIKE 11 calculates a velocity and discharge profile that is notably lower than that of ISIS and MIKE 11 during the period in which the downstream water level boundary is increasing. However, after 82 minutes, which is when the downstream boundary remains constant, MIKE 11 produces a discharge and velocity value that is very similar to that as calculated by ISIS and HEC-RAS.

The velocities calculated by both ISIS and HEC-RAS inside the culvert inlet start at  $1.98\text{m/s}$ , and remain constant in HEC-RAS for 40 minutes, but show some variation in ISIS after 24 minutes. Between 41 and 50 minutes, both ISIS and HEC-RAS record a similar velocity value and drop to just above  $0.80\text{m/s}$ , less than the theoretical full flow velocity of  $0.85\text{m/s}$ . The velocities recorded by ISIS at the culvert outlet however, start at  $1.59\text{m/s}$  and fall away after 1 minute to a minimum value of  $0.67\text{m/s}$  at 15 minutes. The ISIS velocities then fluctuate about  $0.7\text{m/s}$  until they remain constant at 52 minutes, at  $0.803\text{m/s}$ . In contrast, the velocities recorded by HEC-RAS at the culvert outlet start at  $1.67\text{m/s}$  but quickly increase to a maximum value of  $2.08\text{m/s}$ , after which time they then fall at approximately the same rate recorded by ISIS. However, the velocities calculated by HEC-RAS then converge exactly with the theoretical full flow velocity for the supercritical culvert of  $0.85\text{m/s}$ . It must be noted that this occurs after 12 minutes of the simulation, the time at which the culvert outlet becomes fully submerged. The velocities then break away from this value after 47 minutes, converging with the ISIS velocities at 48 minutes and settling at the similar value of  $0.81\text{m/s}$  after 52 minutes. At 82 minutes, which is when the downstream water level boundary stops increasing, the velocity calculated by both ISIS and HEC-RAS at the culvert inlet and outlet returns to the theoretical full culvert velocity.

#### **4.7 Analysis of Froude Number Results (Part B)**

As expected, a similar relationship to velocities can be observed in Graphs 42 to 45 showing the calculated Froude numbers.

By inspection of the Graphs for the cross-sections at 552.0m, 25.0m and 0.0m it can be seen that ISIS, HEC-RAS and MIKE 11 initially calculate a Froude number of either close to or greater than 1. This suggests that the flow is either close to critical or is supercritical. As the

downstream water level boundary increases the velocities reduce and hence, the Froude number reduces.

At cross-section 527.0, the Froude number is initially around 0.6 for each of the software packages, indicating subcritical flow, and then at around 42 minutes it starts to reduce due to the effects of the downstream water level boundary.

#### 4.8 Analysis of Additional ISIS Results (Part A)

As an alternative to the circular culvert unit in ISIS the symmetrical culvert cross-sectional unit has also been tested. This unit is essentially provided in ISIS as a means of building culverts of any cross-sectional shape, so long as that shape is symmetrical. The cross-section is specified in this unit by inputting co-ordinate data for the right-hand side of the desired cross-section.

The circular shape of the culvert unit for Part A of the test at 26.0m was specified as the co-ordinates given below in Table 4.1.

**Table 4.1 Co-ordinates defining circular culvert in ISIS**

Co-ordinates (Right half) – Part A. Culvert section 26.0m	
(x) co-ordinate	(y) co-ordinate
0.000	0.065
0.287	0.122
0.530	0.285
0.624	0.399
0.693	0.528
0.736	0.669
0.750	0.815
0.736	0.961
0.693	1.102
0.624	1.231
0.530	1.345
0.287	1.508
0.000	1.565

It can be seen from Graphs 59 and 60 that the velocity profiles produced by the two culvert unit types are identical at both the inlet and outlet of the culvert. The only noticeable difference is that the starting velocity calculated by the symmetrical culvert at the inlet is marginally lower than that produced by the circular culvert function.

#### 4.9 Analysis of Additional ISIS Results (Part B)

Initially, when running the model, the diagnostics file advised that more culvert cross-sections should be added. As such, culvert units were placed every 50m along the culvert. The model was then able to run successfully with a 20s time-step.

The results, which are presented in Graphs 61 and 62, display a notable difference between the two ISIS culvert unit types. At the culvert inlet, the velocity profile produced by the symmetrical culvert unit shows a similar behaviour to the velocities produced in HEC-RAS at the same location. Essentially, the fluctuation in culvert velocity recorded by the circular culvert function after 24 minutes is almost eliminated by the symmetrical unit. Furthermore, the fluctuation recorded at the outlet after 12 minutes is also significantly reduced.

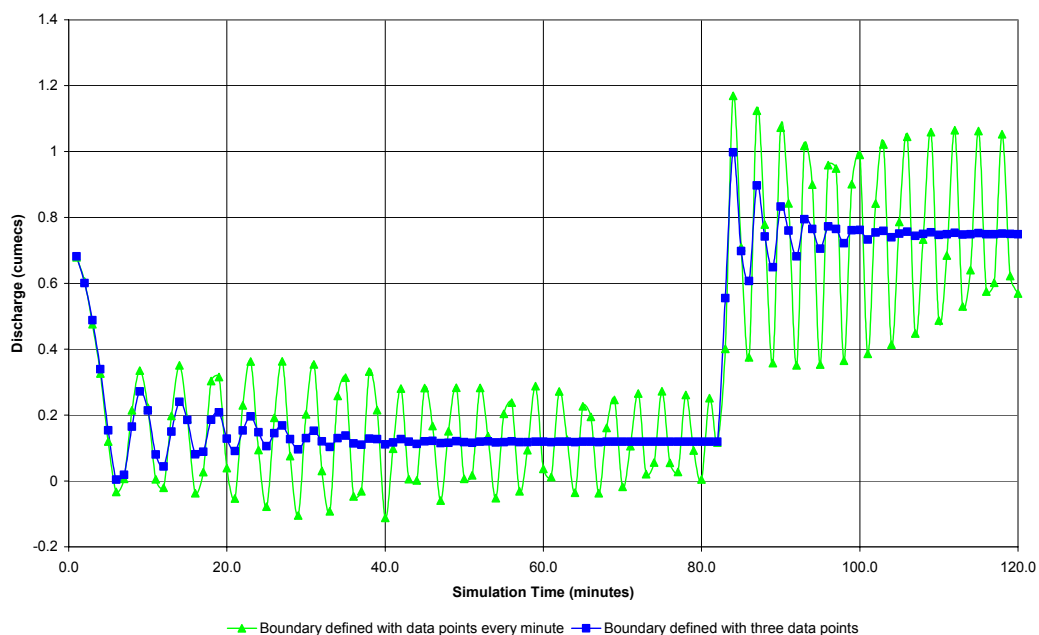
#### 4.10 Investigations with MIKE 11

Further to discussion with the developers of MIKE 11 several investigations in to the cause of the oscillations observed with MIKE 11 were made namely tests on the a) location, b) definition of the downstream boundary, and c) removal of the culvert from the system. In each instance the Part A test configuration was considered with default calculation settings i.e. implicit weighting coefficient of 0.55.

The reach downstream of the culvert was extended by 200.0m with the same bed slope and channel geometry maintained and the downstream boundary adjusted so as to provide the same rate of water level change. Although not presented in this report, the results of this sensitivity test were no different to the initial test configuration.

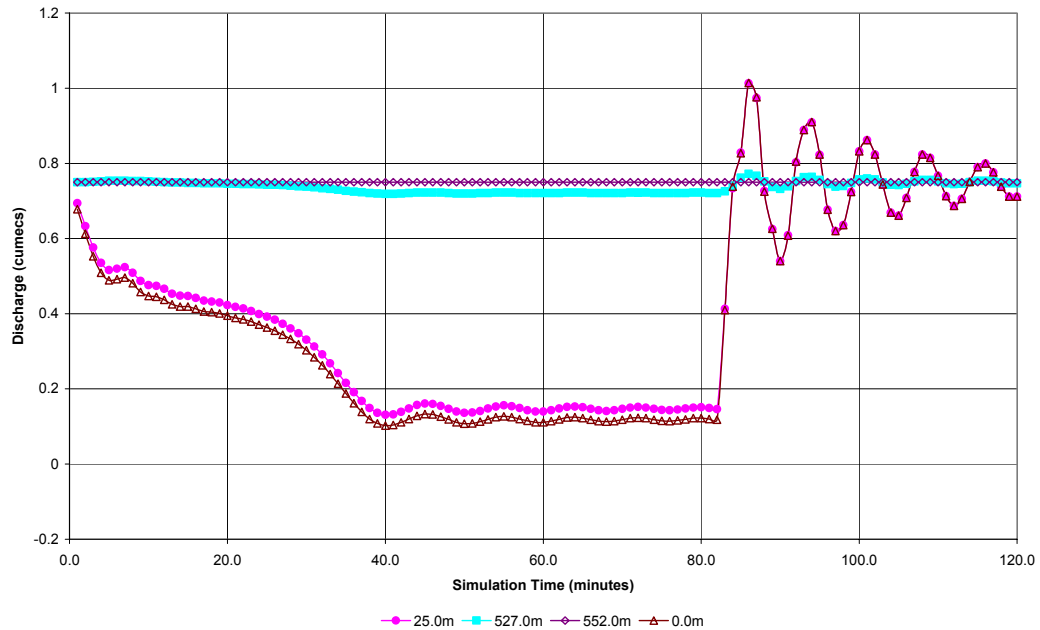
As an alternative to the specified boundary (i.e. data points very minute) the downstream boundary was defined with just three data points (the minimum possible) namely 0 minutes, 82 minutes and 120 minutes. MIKE 11 was then allowed to interpolate between the data points automatically. This has a significant effect on the results, as illustrated below in Figure 4.1. The oscillations (large-scale) are significantly reduced from the solution; however, the resultant discharge is still noticeably different to that produced by ISIS and HEC-RAS.

**Figure 4.1: Effect of number of data points used to define boundary condition (Discharge at 0.0m)**



Removing the culvert from the system and also defining the downstream boundary with just three data points produced the results as illustrated in Figure 4.2 below. As can be seen, removal of the culvert still produces oscillations in discharge at both the downstream and upstream end of the channel.

**Figure 4.2: Effect of removing culvert from system altering number of data points used to define boundary condition**



## 5 DISCUSSION AND CONCLUSIONS

Each of the software packages generates very similar water level histories at each of the channel cross-sections and at the culvert inlet and outlet. Despite the fact that some variation was recorded in the arrival time of the changing water level, and that the calculated levels are only slightly different in each package, the variation is not significant enough such that any of the results should be deemed unsuitable for engineering purposes.

However, there is a pronounced variation in the calculated velocity, discharge and Froude number histories. For much of the simulation time, it is not possible to assess from the plotted results, which calculated velocity, discharge or Froude number is most appropriate value as all three packages give quite different values.

From the results is suggested that the downstream boundary has a different numerical effect on each of the software packages. Comparing ISIS and HEC-RAS, ISIS initially exhibits a reduction in discharge in the lower part of the channel and, surprisingly given that the water levels are almost identical, also exhibits a reduction in velocity that is greater than HEC-RAS. MIKE 11 has produced notably lower velocities and discharges when compared to ISIS.

As soon as the water level upstream of the culvert begins to increase both ISIS and HEC-RAS calculate the discharge within the channel as being slightly smaller than the theoretical full culvert capacity. However, when the downstream boundary ceases to increase (i.e. quasi-steady flow conditions) both software packages calculate the discharge that is the same as the theoretical full culvert capacity. In addition, at this point MIKE 11 also calculates a discharge that matches the full culvert capacity.

For both parts of the test HEC-RAS has calculated water levels generated that remain slightly above those of the other two packages. This would indicate for the test configuration settings used in the test that the head loss calculated by HEC-RAS in the culvert unit is less than that calculated by ISIS and MIKE 11, although these are small in terms of engineering practice.

It is suggested by the developers of MIKE 11 that, “the applied model set-up is not suitable for this test”. The developers of MIKE 11 have suggested that the culvert, as defined by the test specification, would be best modelled by the use of closed circular cross-sections within a separate branch. The DX-max parameter could then be set to a value that generates additional computational points inside the culvert and the entry and exit losses could then be represented using the Energy Loss structure. Since this approach does not use the “culvert” functionality/feature of the software as intended by the test specification this approach has not been tested as part of this study.

Further to discussion with the developers of MIKE 11, and investigations made within this report, it is concluded that the oscillations observed in the MIKE 11 results are not caused by the culvert structure but are a consequence of the system boundary conditions.

Smoothing of the downstream boundary water level by removing all but three of the defining water levels for this profile removes the large-scale oscillations. This would indicate that the boundary, as defined by the test specifications, contains first order oscillations. The fact that both ISIS and MIKE 11 do not reproduce these oscillations could be due to the numerical

schemes and representation of the convective acceleration terms within each software package. It has been beyond the scope of this study to investigate this further.

With the culvert removed, and the boundary smoothed small oscillations can be seen in the water levels at both the downstream and upstream end of the channel. The developers of MIKE 11 have suggested that the higher frequency oscillations at the downstream end are due to “the non-uniformity of the applied space step”. At the upstream end “the longer period oscillation occurs at the point the water level boundary reaches its final value. These have a period of approx. 400s, and are caused by ‘natural seiching in the channel’”.

The test has shown that the oscillations can be damped by increasing the implicit weighting coefficient; however, this has simply illustrated the danger of using high default values for this parameter.

## 6 RECOMMENDATIONS

The novice and even expert modeller often needs the use of a good and well documented reference manual when using the software packages. From undertaking this test it is believed by the testers that the following improvements to the software packages would benefit the modeller.

- Details within the MIKE 11 manual or on-line help on the method of calculating the culvert head losses and those that are a result of friction and bend losses.

The ability to add additional computational points within a MIKE 11 culvert structure could be beneficial. Alternatively, checks within the software packages could be implemented or better guidance given so that modellers will know when alternative methods of modelling culvert within MIKE 11 (i.e. as closed cross-sections) may be more appropriate.

The alternative model configuration, as suggested by the developers of MIKE 11 (i.e. use of closed cross sections), should be tested.

Further investigation into the oscillations observed in the MIKE 11 results should be undertaken so as to gain a better understanding of their occurrence. Further to the findings of this, consideration should be given to defining additional or alternative boundary conditions and/or model configuration such that the oscillations are not a function of the boundary conditions or the system.

The test specification could be expanded so as to consider culverts with blockage and of different shape.





## 7 REFERENCES

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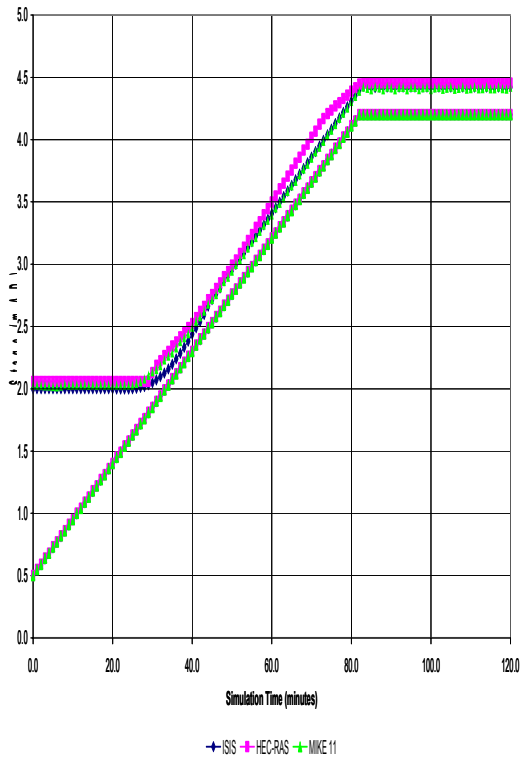
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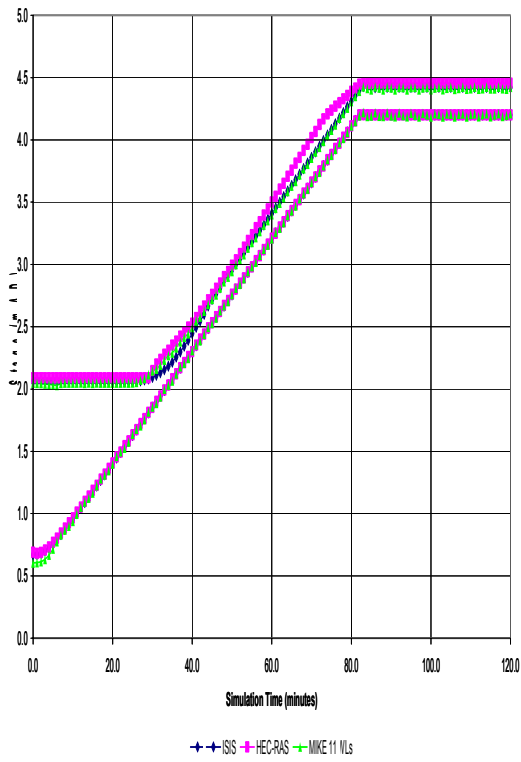
## **APPENDIX A RESULTS**



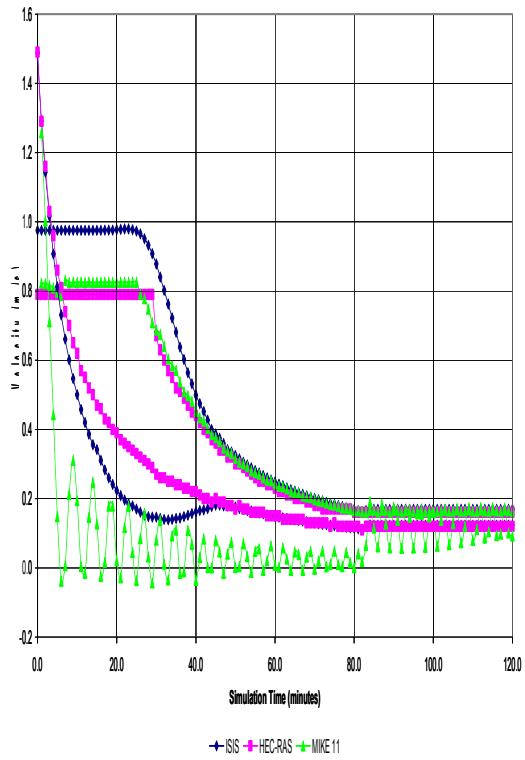
Graph 24 PBarrA Comparison of Stage v's Time at Chainage 5070m



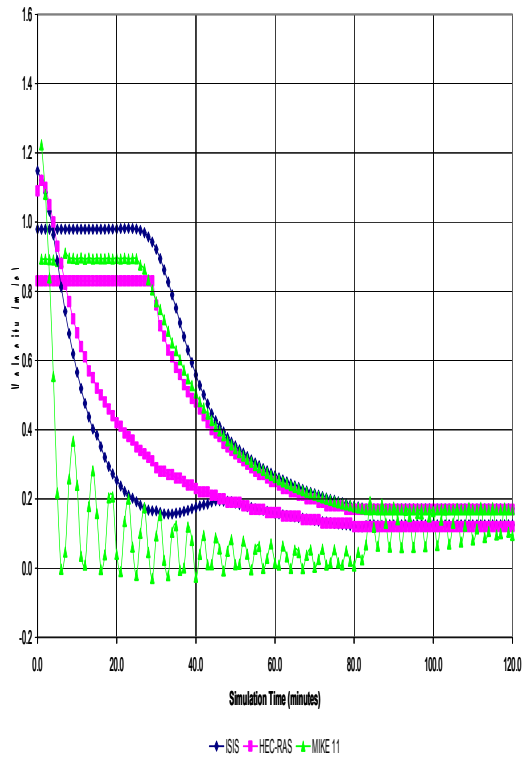
Graph 25 PBarrA Comparison of Stage v's Time at Chainage 8520m



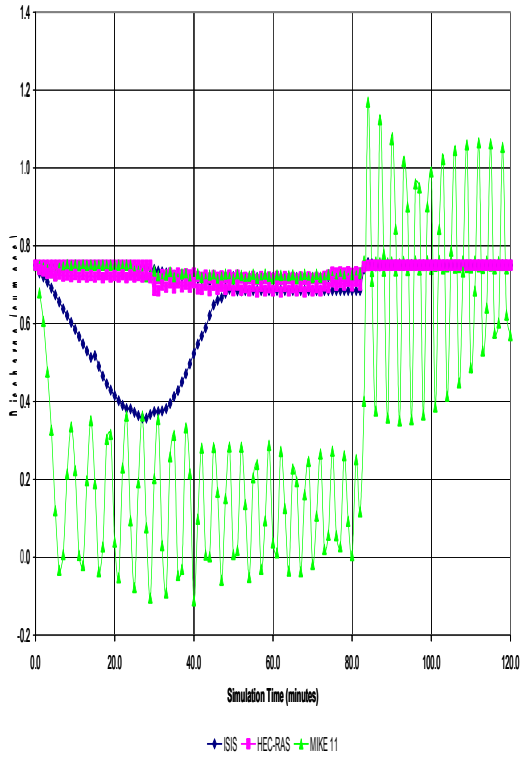
Graph 68 - Part A: Comparison of Velocity vs Time at Chirage 670m



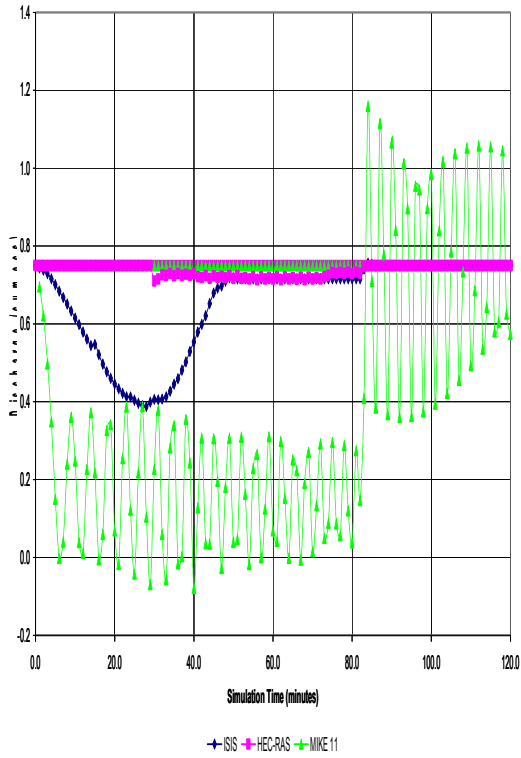
Graph 7 - Part A: Comparison of Velocity vs Time at Chirage 520m



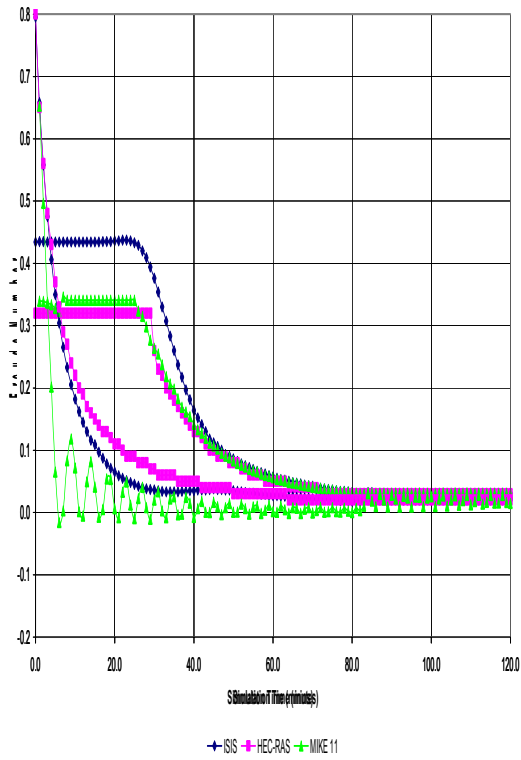
Graph 11: PBR1A Comparison of Discharge vs Time at Chainage 67.0m



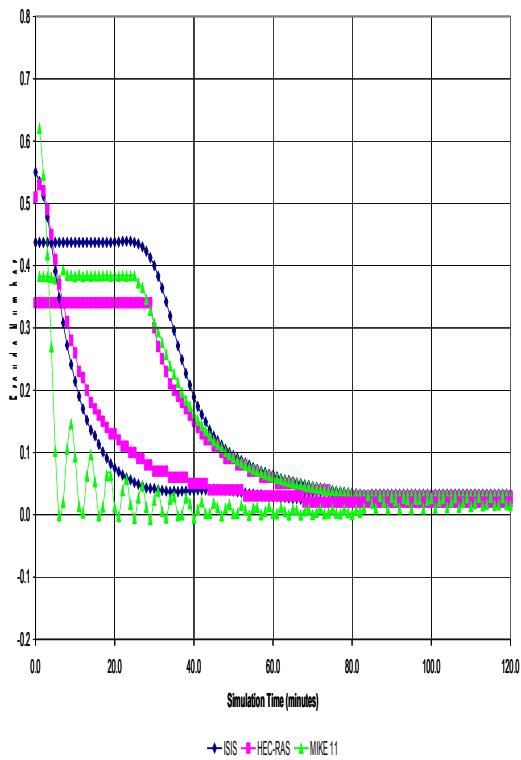
Graph 12: PBR1A Comparison of Discharge vs Time at Chainage 68.0m



Graph 146 - Part A: Comparison of Froude Number's Time at Chainage 507.0m

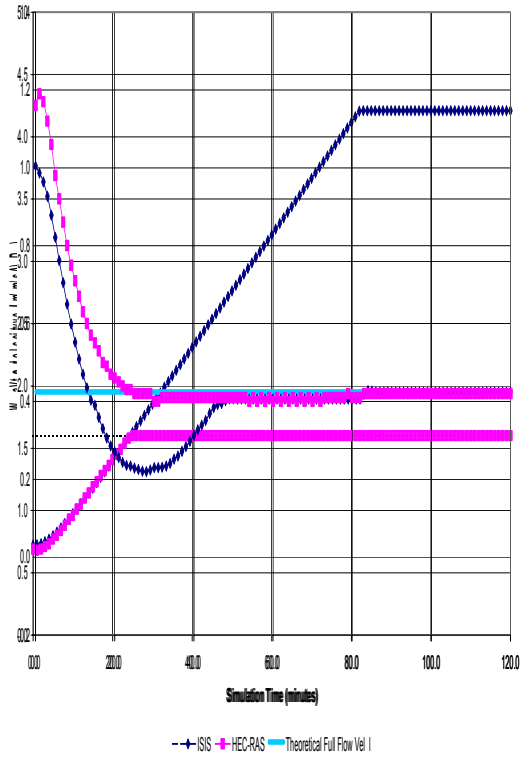


Graph 146 - Part A: Comparison of Froude Number's Time at Chainage 552.0m

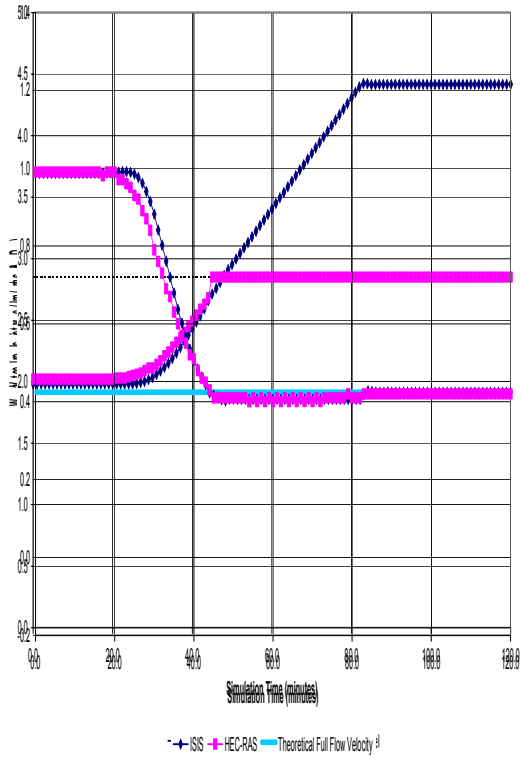




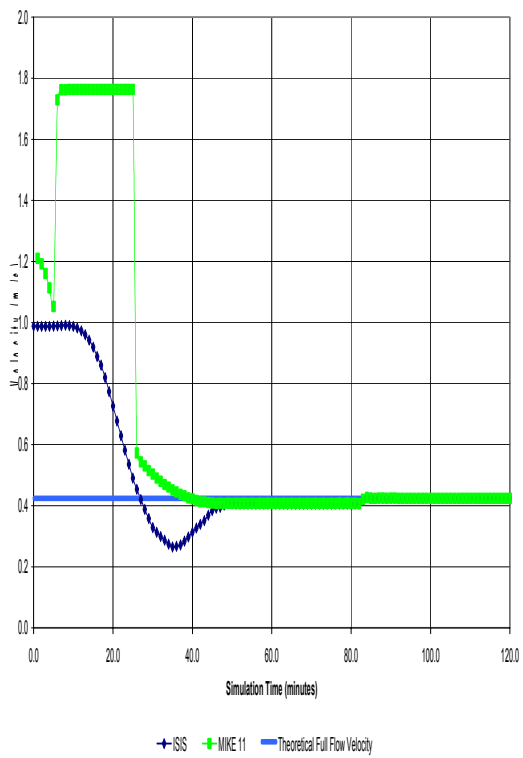
Graph 16: Comparison of Water Level's Time Change 200mm inside Outlet



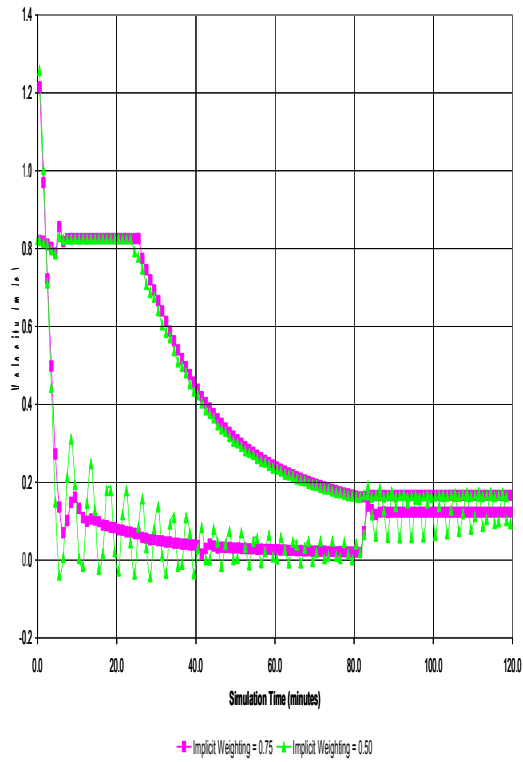
Graph 17: Comparison of Water Level's Time Change 300mm inside Outlet



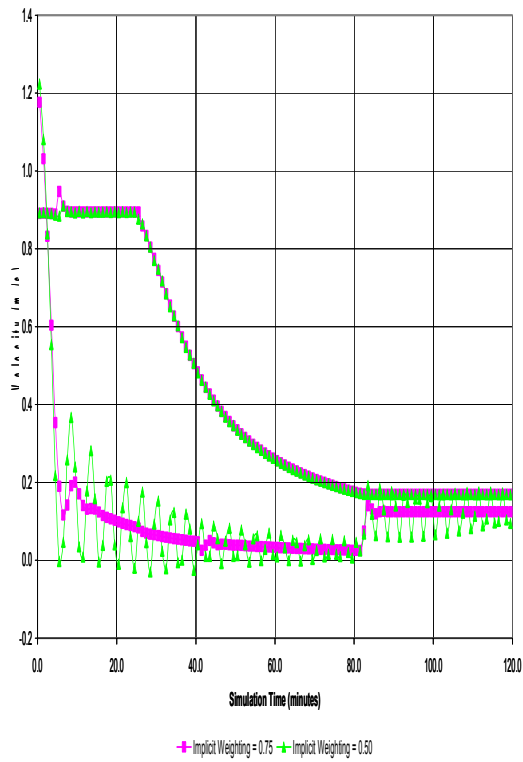
Graph 21 : Comparison of Velocity v's Time at Chainage 276.0m - Mid Culvert



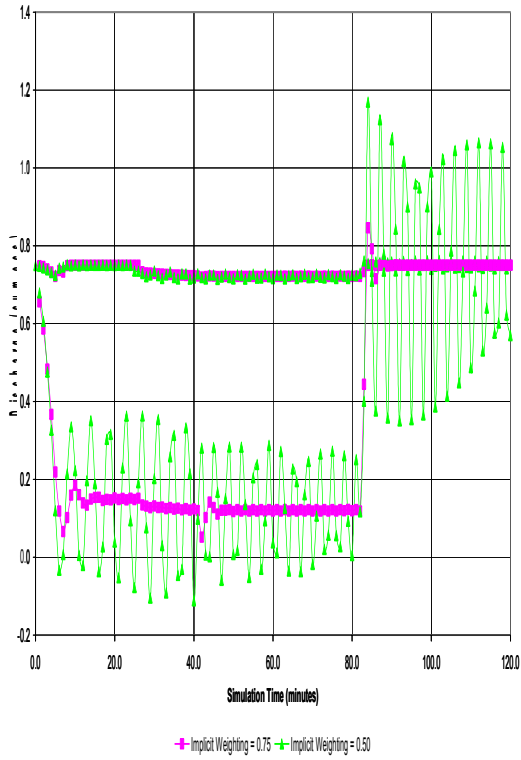
Graph 215 - ParaAA - MWE: 1 Implicit Weighting Comparison - Velocity vs Time at Chainage 5210m



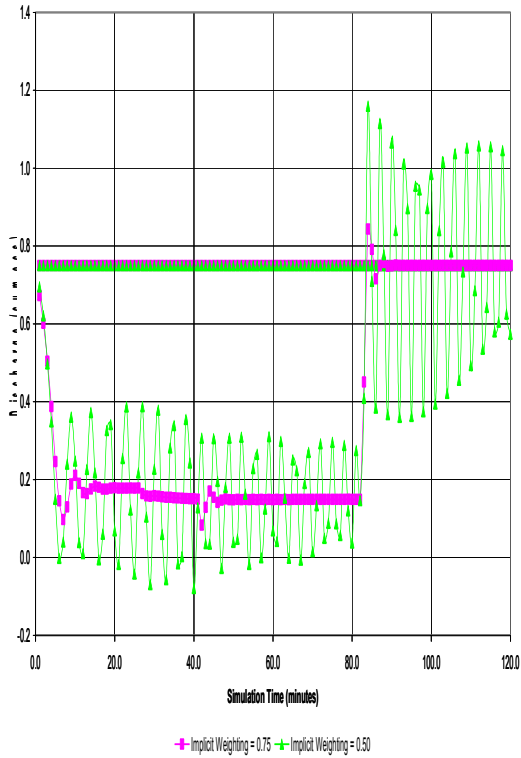
Graph 224 - Para1A - MWE: 1 Implicit Weighting Comparison - Velocity vs Time at Chainage 5520m



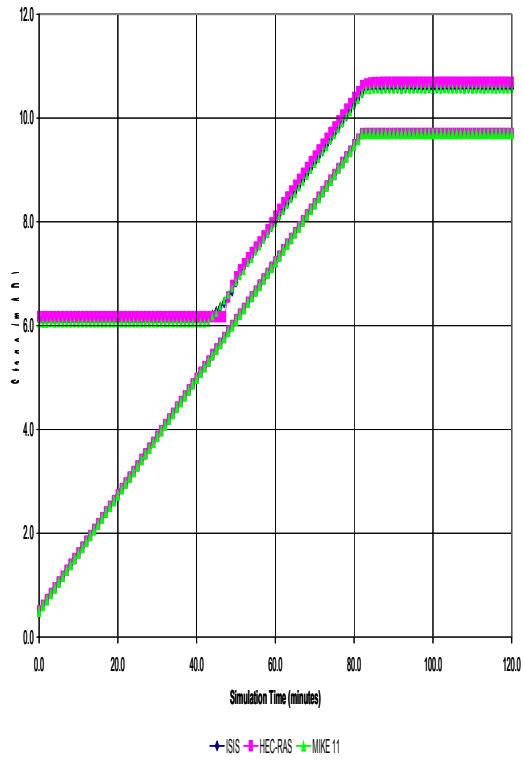
Graph 29-Part A: MIKE 11 Implicit Weighting Comparison - Discharge vs Time at Chainage 67.0m



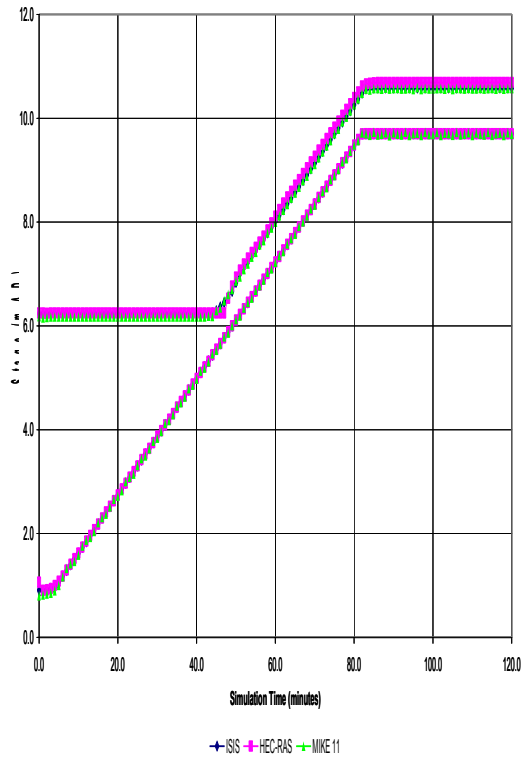
Graph 28-Part A: MIKE 11 Implicit Weighting Comparison - Discharge vs Time at Chainage 52.0m



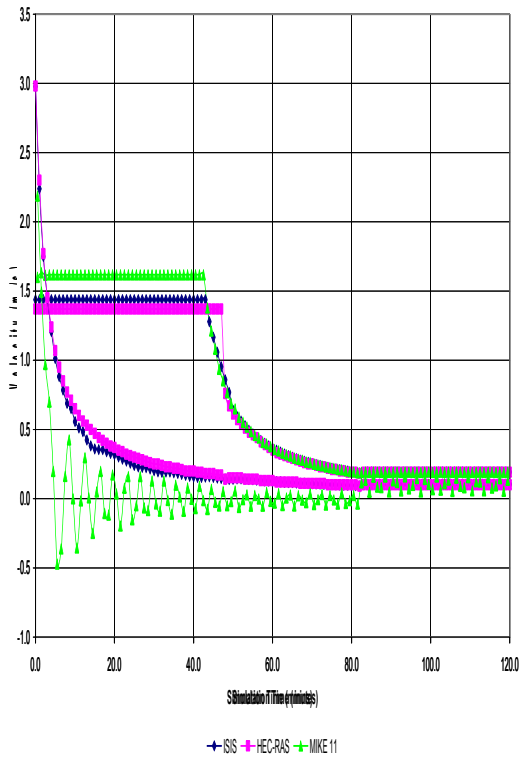
Graph 31 - Part B: Comparison of Stages vs Time at Change: 67.0m



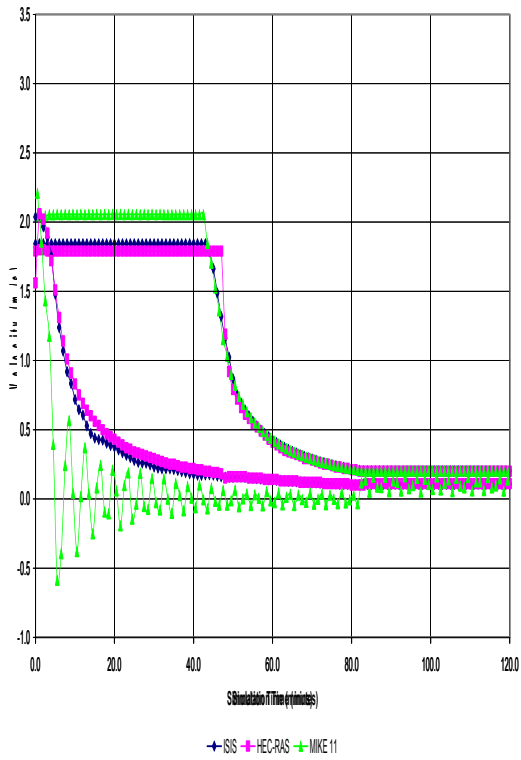
Graph 32 - Part B: Comparison of Stages vs Time at Change: 53.0m



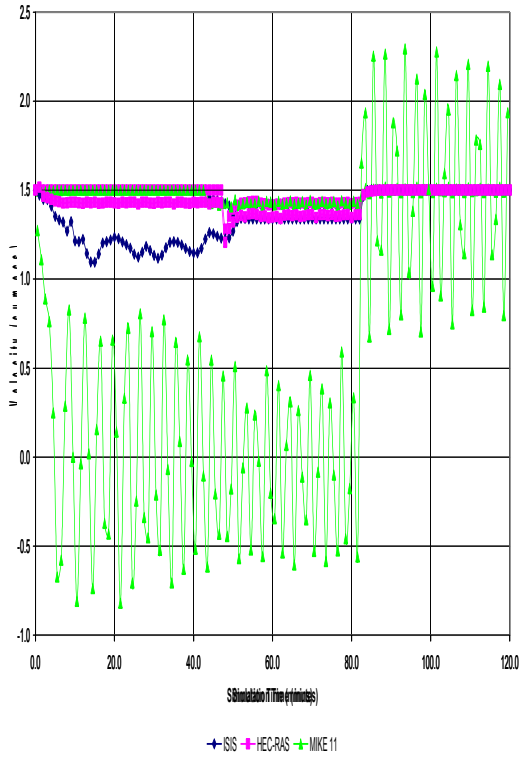
Graph 35 - Part B: Comparison of Velocity vs Time at Chainage 677.0m



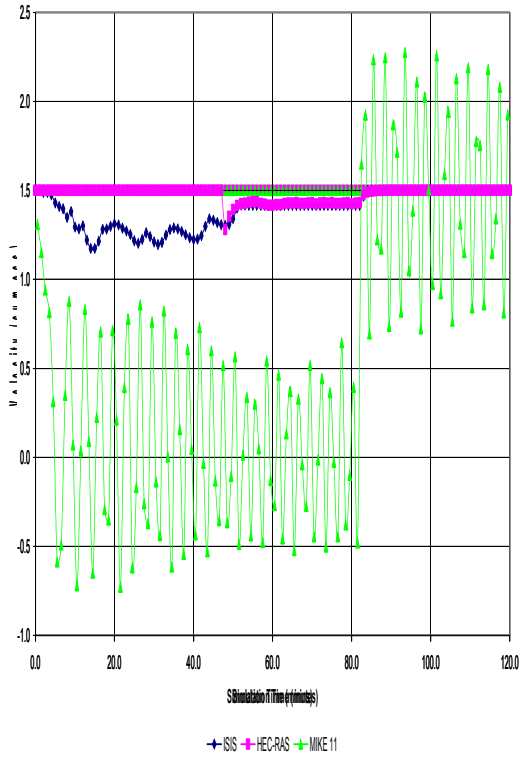
Graph 36 - Part B: Comparison of Velocity vs Time at Chainage 552.0m



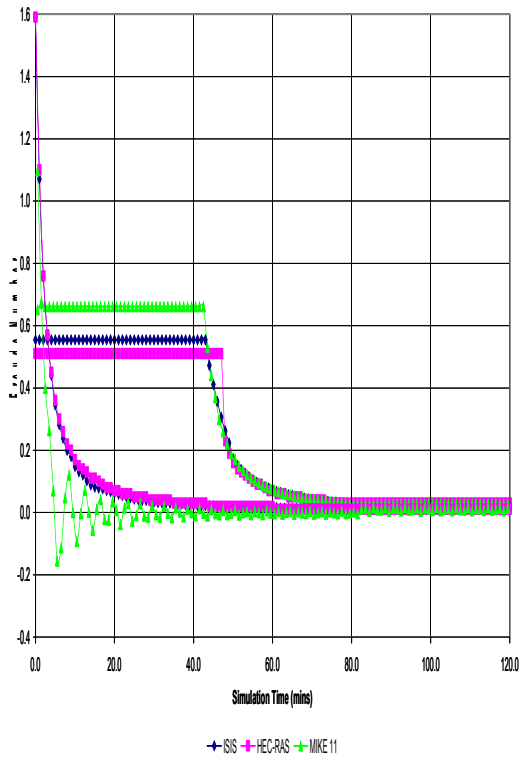
Graph 08 - Part B: Comparison of Discharge vs Time at Chainage 070m



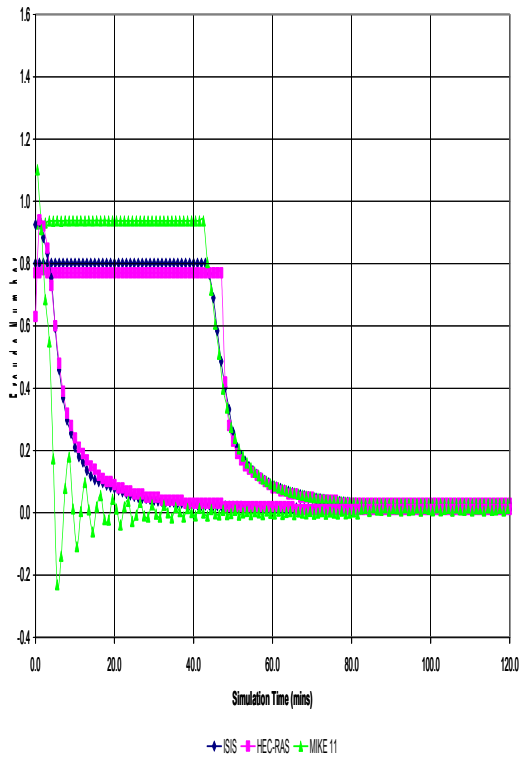
Graph 30 - Part B: Comparison of Discharge vs Time at Chainage 520m



Graph 43-Part B: Comparison of Froude Number's Time at Chaining 647.0m

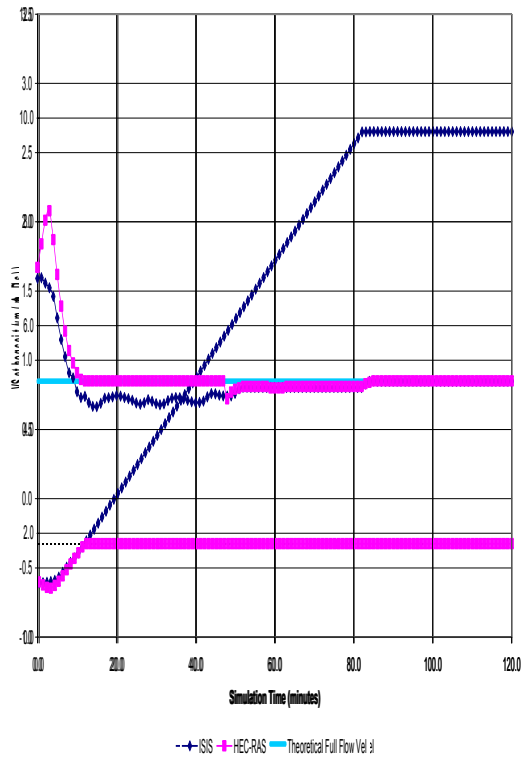


Graph 44-Part B: Comparison of Froude Number's Time at Chaining 552.0m

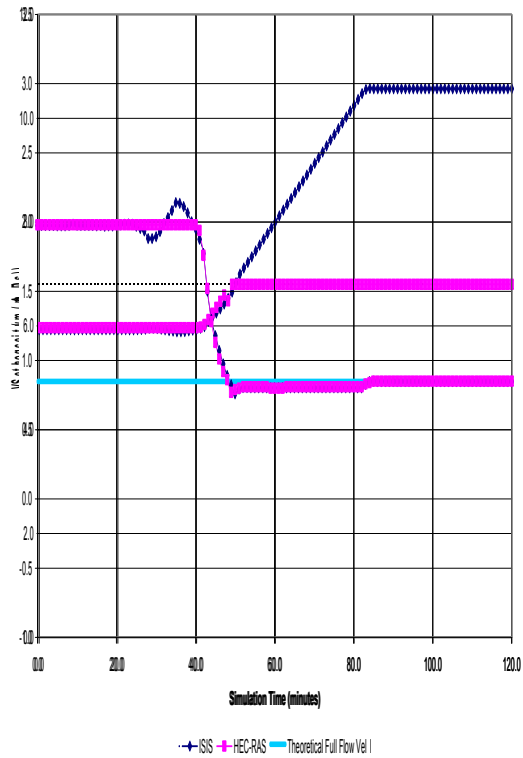




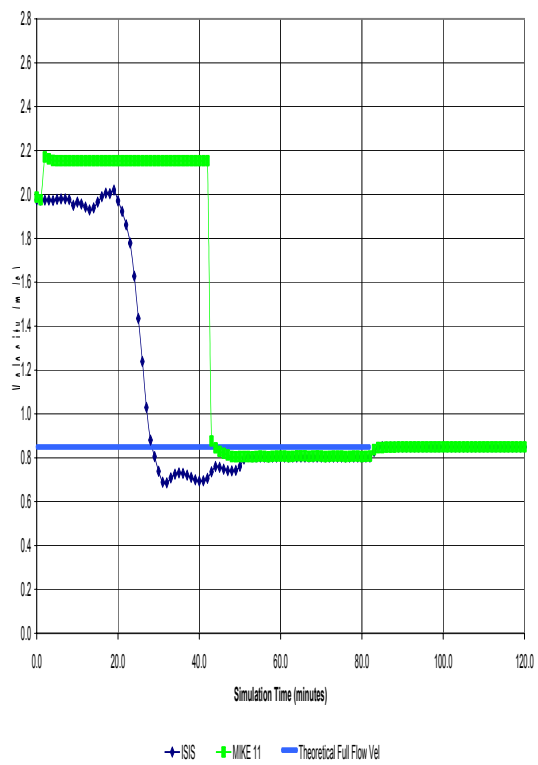
Graph 43: P&ES Comparison of Water Level Histories at Chiragega Dam Inside COiver Outlet



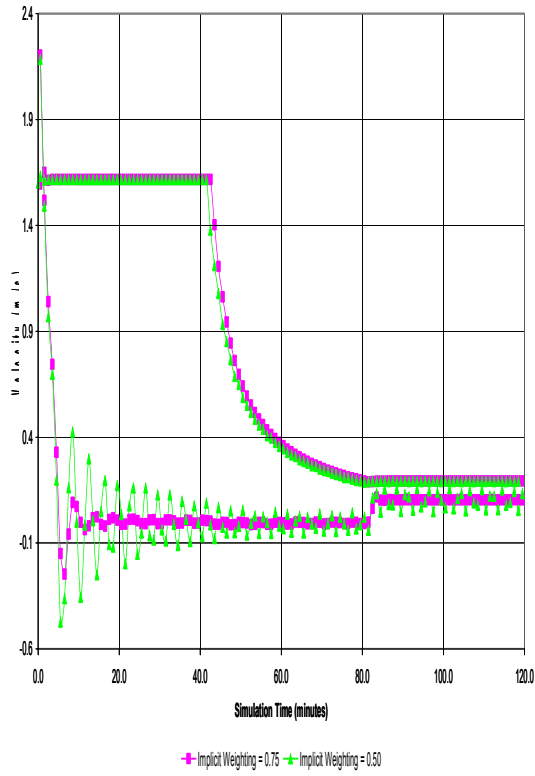
Graph 46: P&ES Comparison of Water Level Histories at Chiragega Dam Inside COiver Outlet



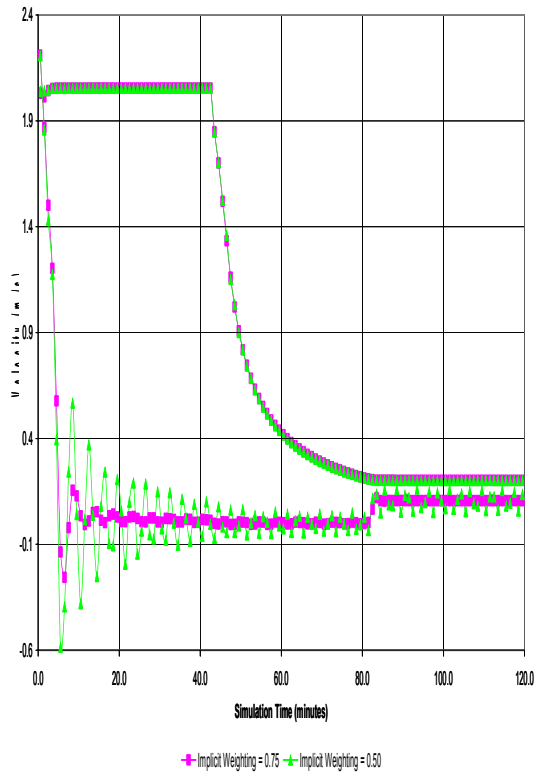
Graph 50 - Part B : Comparison of Velocity v's Time at Chainage 276.0m - Mid Culvert



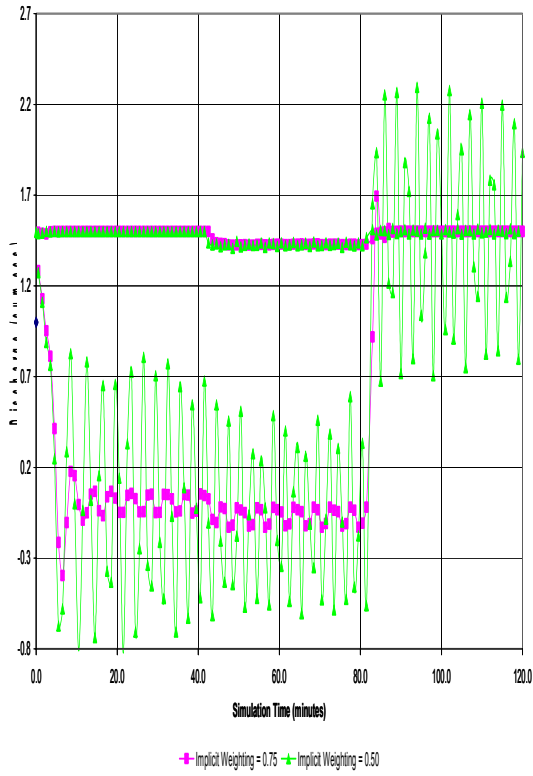
Graph 584 - Part B: MWK211 Implicit Weighting Comparison - Velocity vs Time at Chainage 6070m



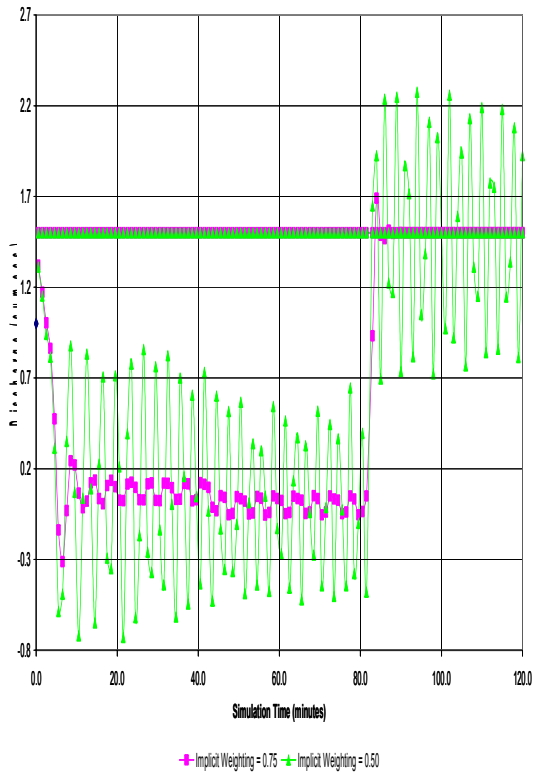
Graph 58 - Part B: MWK111 Implicit Weighting Comparison - Velocity vs Time at Chainage 5520m



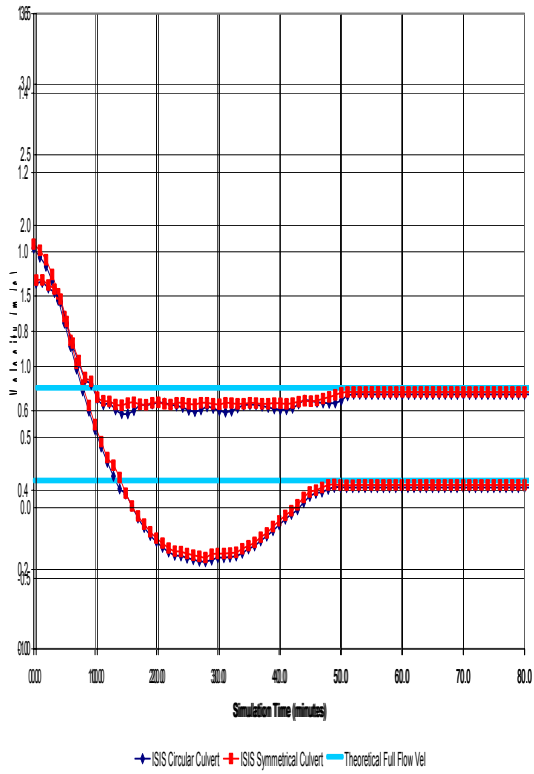
Graph 56 - Part B: NIKE 11 Implicit Weighting Comparison - Discharge v/s Time at Chainage 607.0m



Graph 57 - Part B: NIKE 11 Implicit Weighting Comparison - Discharge v/s Time at Chainage 592.0m



Graph 62 - Part B : Comparison of Velocity vs Time at Chainage 269m - Inside Culvert Outlet



Graph 63 - Part B : Comparison of Velocity vs Time at Chainage 526.0m - Inside Culvert Inlet

