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

Benchmarking Hydraulic River Modelling Software Packages

Results – Test B (Looped System)

R&D Technical Report: W5-105/TR2B

defra
Department for Environment Food and Rural Affairs

Environment Agency

TECHNICAL REPORT W5-105/TR2B

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 ISBN: 1 8443 2290 4

Dissemination Status

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Statement of use

This document provides the results and findings from undertaking the Environment Agency's Benchmarking Test B (Looped System) 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, Split Flows, Looped System

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TECHNICAL REPORT W5-105/TR2B **Product code** SCHO0305BIXQ-E-P

EXECUTIVE SUMMARY

The test has successfully demonstrated that ISIS, MIKE 11 and HEC-RAS are all capable of modelling split flows (looped system) under both steady and quasi-steady flow regimes and by inference unsteady flow conditions. However, there are some notable nuances that need to be considered when undertaking split flow simulations with each of the software packages.

The results from each of the software packages have been compared to one another; however, there is no reference to either an analytical or experimental solution. As such, there is no definitive conclusion as to which software package is the most accurate.

When undertaking a steady state calculation with HEC-RAS notable differences have occurred for this test when using the split flow optimiser, which is not used in unsteady calculations. This has highlighted the need to assess the suitability of split flow calculation tolerances.

When undertaking a quasi-steady simulation and by inference an unsteady calculation each of the software packages uses a water level balance at the junctions. The results from each of the software packages for the quasi-steady calculations have shown a good correlation to one another.

The study has raised questions about the appropriateness of using a water level balance at junctions. Inspection of the unsteady results of the unsteady flow runs show an increase in energy and momentum from Reach A to Reach C, at junction 1, which is a physical impossibility, given the problem. The HEC-RAS steady flow solution is the only software package that considers conservation of energy or momentum, and continuity at the junction whereas both ISIS and MIKE 11 consider a water level balance at junctions. This has produced noticeably different results from the two approaches.

In MIKE 11 the use of either the resistance radius or hydraulic radius option for the cross section properties has a significant impact on the resultant split in flows and water levels. The resistance radius result has shown the closest correlation to the results obtained from ISIS.

For MIKE 11 the steady state and quasi-steady results are very similar, however, ISIS has shown that the downstream boundary condition can result in small differences in the predicted water levels. Conversely the steady state and quasi-steady results from HEC-RAS are notably different, which is a consequence of using the different methods of solution at the junction for steady and quasi-steady simulations.

The results of this test suggest that further work and research is needed into the numerical solution of split flows at junctions for both steady and unsteady calculations.

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1 INTRODUCTION

1.1 Background

This report presents the results and findings from Test B (Looped System) 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 B (Looped System), (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

1.2 Aim of Test

The aim of the test is to:

- assess the ability of each software package to calculate a diverging and converging flow scenario, i.e. a looped system; 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

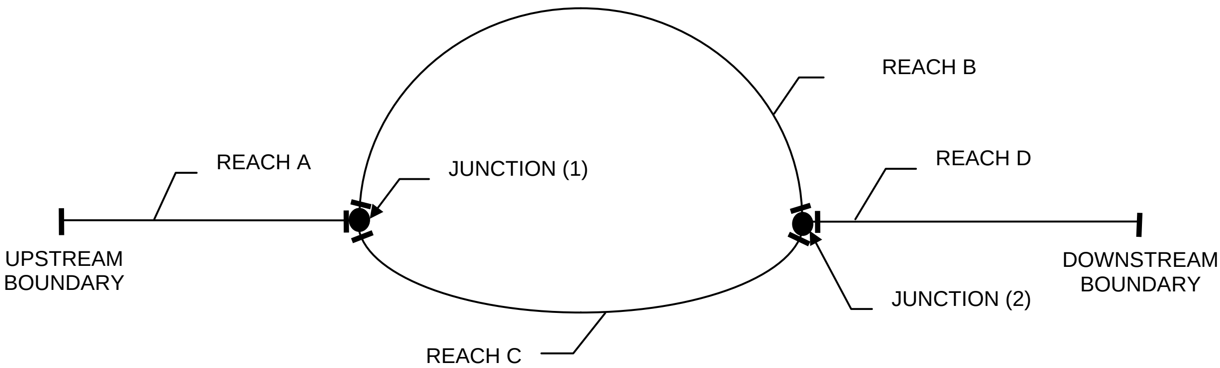
The test has been undertaken in accordance with the Benchmarking Test Specification - Test B (Crowder *et al*, 2004).

The test configuration is illustrated schematically in Figure 2.1. There are four reaches: Reach A, Reach B, Reach C and Reach D with a cross-section spacing of 25m, 375m, 100m and 25m respectively.

At the downstream end of Reach A the system diverges (splits) into Reaches B and C, which then converge to Reach D at their downstream sections.

A constant Manning's n roughness value of 0.012, 0.0125, 0.013 and 0.0135 has been used for Reaches A through to D respectively. It should be noted that Reach B is three times the length of Reach C with the same vertical drop between the two junctions.

Figure 2.1: TEST 2 - Schematic Illustration of Test Configuration



The configuration can be summarised as follows:

	Length (m)	Cross-Section Spacing (m)	Gradient	Manning's *n*
Reach A	100.0	25.0	1:2000.0	0.0120
Reach B	1500.0	375.0	1:2500.0	0.0125
Reach C	500.0	100.00	1:833.3	0.0130
Reach D	100.0	25.0	1:2000.0	0.0135

The software packages have been tested with two separate steady state flow boundary conditions as follows.

SS1: Upstream inflow boundary of $250m^3/s$
Downstream water level of 3.0m

SS2: Upstream inflow boundary of $250m^3/s$
Downstream water level of 1.6m

The software packages have also been tested under two separate quasi-steady boundary conditions: QS1 and QS2. The same conditions as specified for SS1 and SS2 have been used at 00:00hrs and extended through to 01:00hrs respectively.

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

The model build with ISIS, MIKE 11 and HEC-RAS was undertaken in accordance with the test specification, as defined by the dataset.

In ISIS the Junction unit was used to model the divergence (split) and the convergence in flow at the upstream and downstream junctions respectively. The equations used by ISIS to model junctions are:

Flow continuity: $Q1 + Q2 + Q3 + ... = 0$
Equality of water surface level: $h1 = h2 = h3 ....$

The "JUNCTION" unit in ISIS assumes that the cross-sections are all located directly at the junction. There is no ability to set a distance between the cross sections.

In HEC-RAS the Junction unit was used to model the divergence (split) and the convergence in flow at the upstream and downstream junctions respectively.

A distance between the upstream and downstream cross sections at a junction can be specified in HEC-RAS. This distance is only taken into account during a steady state, not unsteady state simulation. The test used a distance of 0.0m between the cross sections at the junction.

When undertaking a steady state calculation in HEC-RAS the junction unit can calculate the water surface profile through the junction with either conservation of energy and continuity, or using conservation of momentum and continuity. It is the only software package of the three tested that has this capability. The momentum and continuity approach can consider the angle of a tributary and also (if specified) friction and weight forces. By inference the energy and continuity approach takes neither of these into account.

When undertaking an unsteady flow calculation in HEC-RAS a water surface balance is applied at the junction unit and hence, flows are computed by mass continuity.

In MIKE 11 a reach (referred to as a branch in MIKE 11) is directly connected to another reach without the use of a specific junction unit. For each reach an upstream and downstream connection needs to be defined unless it is a connected to a boundary. The connection is specified between the reaches upstream/downstream node (cross-section) and any other node in the model. MIKE 11 then performs a water level balance at the connected nodes and hence a flow balance.

3 RUNNING THE MODEL

3.1 Running the Model in ISIS

ISIS was first run with the default run options in steady state mode using the SS1 and SS2 boundary conditions. It should be noted that this employs the 'direct method' solution method.

When running the test with the SS1 boundary conditions the diagnostics file warned that the direct method had automatically added cross sections at chainages 50.0m and 75.0m in reach D. In addition when running the SS1 and SS2 boundary conditions the diagnostics file indicated that the simplified method had been used to compute the solution at the following chainages:

SS1:	Reach C	500.0m	SS2:	Reach C	500.0m
	Reach C	375.0m		Reach C	375.0m
	Reach C	250.0m		Reach C	250.0m
	Reach C	125.0m		Reach C	125.0m
	Reach C	0.0m		Reach C	0.0m
	Reach D	75.0m		Reach D	100.0m
	Reach D	50.0m		Reach D	75.0m
	Reach D	25.0m		Reach D	50.0m
	Reach D	0.0m		Reach D	25.0m
				Reach D	0.0m

ISIS was run in unsteady mode with a time step of 20s for both the QS1 and QS2 boundary conditions. The results from the respective steady state simulations were used as initial conditions in each instance. It was found that ISIS would crash if initial conditions were not specified.

The diagnostics file (zzd) for the unsteady state runs provided no errors or warnings for either of the test conditions.

3.2 Running the Model in MIKE 11

The test version/release of MIKE 11 did not provide the facility to undertake a steady state calculation; hence to obtain a result MIKE11 was run in unsteady mode with the quasi-steady boundary conditions and the type of initial condition set as steady state. This forced MIKE 11 to undertake a steady state calculation at t = 0s and then subsequently use the steady state result as an initial condition for the quasi-steady simulation. The result at t = 0s was then taken as the steady state solution. For both parts of the test a time step of 20s was used.

No errors or warnings were reported in the log report file for any of the test conditions.

In addition to undertaking the test with the default "Resistance Radius" resistance factor (set in the cross-section editor) the test has been repeated using the alternative "Hydraulic Radius (Effective Area)" option for the SS1 and QS1 boundary conditions.

The Manuals supplied with the tested version of MIKE 11 do not provide advice on the most appropriate choice of resistance factor to use or any technical information on the two options. However, it is noted that the HD Reference Manual for version 3.01, as used in the previous Benchmarking Study (Crowder *et al*, 1997) does provide technical information, which the reader is directed to for further information.

3.3 Running the Model in HEC-RAS

When running HEC-RAS in steady state mode an initial estimate of the split flows is required by the user. This is specified in the 'steady flow data reach boundary conditions'. The junction optimisation option can then be used to refine these split flows. The split flow optimization routine solves the split flow junction problem by iterating on the energy gradelines of the cross sections below the junction.

To assess the performance of the flow optimiser several split flows ratios have been investigated for both the SS1 and SS2 boundary conditions.

When HEC-RAS was run in steady state mode with the SS1 boundary the following warnings were given:

Reach: A Chainage 0.0m	The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections. A flow split was encountered. The program first calculated the momentum of both channels below the junction. An energy balance was performed across the junction from the stream with the highest momentum downstream to the section upstream.
Reach: C Chainage 0.0m	The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

When HEC-RAS was run in steady state mode with the SS2 boundary the following warnings were given:

Reach: A Chainage 0.0m	The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections. A flow split was encountered. The program first calculated the momentum of both channels below the junction. An energy balance was performed across the junction from the stream with the highest momentum downstream to the section upstream.
Reach: B Chainage 0.0m	The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections.
Reach: C Chainage 0.0m	The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections. The conveyance ratio (upstream conveyance divided by downstream

	conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections.

In an attempt to reduce/eliminate the number of warnings for both the SS1 and SS2 boundary conditions additional cross sections were added at a spacing of 5.0m using the interpolation feature within HEC-RAS. However, this had no effect and as such interpolations were not used in the test.

When using the QS1 and QS2 boundary conditions HEC-RAS was set-up to automatically generate the initial conditions at each of the computational nodes (cross sections). The procedure employed by HEC-RAS is a steady state calculation based on the boundary conditions at t = 0s and the unsteady flow data reach boundary conditions. For QS1 the split in flow between reaches B and C was assumed to be 50:50, however, to obtain a satisfactory result with QS2 the initial split was set at 48:52 (see section 4).

For the QS1 boundary conditions a time step of 20s was used, however, to avoid instabilities with the QS2 boundary conditions, which were presumably caused by poor initial conditions and/or high Froude numbers, the test was run with a time step of 60s and the 'mixed flow' option selected.

When HEC-RAS was run in unsteady mode with both the QS1 and QS2 boundary conditions the following warnings messages were given in the dialogue summary box:

Reach: A Chainage 0.0m	The velocity head has changed by more than 0.5 ft (0.15 m). This may indicate the need for additional cross sections. The conveyance ratio (upstream conveyance divided by downstream conveyance) is less than 0.7 or greater than 1.4. This may indicate the need for additional cross sections. A flow split was encountered. The program first calculated the momentum of both channels below the junction. An energy balance was performed across the junction from the stream with the highest momentum downstream to the section upstream.

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 the SS1 and SS2 boundary conditions additional analysis has been undertaken with HEC-RAS that compares results when using different estimates for the initial split in flow between reaches B and C.

For MIKE 11, with each of the boundary conditions, additional analysis has been undertaken which compares results when using the default ‘Resistance Radius’ cross section option with the alternative ‘Hydraulic Radius (Effective Area)’ option.

For both the steady state and quasi-steady simulations results for discharge and water level results have been reported upon in tabular form at each of the cross sections defined by the dataset. In addition, water level results are presented in graphical form.

4.2 Analysis of HEC-RAS Results – Initial Estimate of Split Flow

The results from HEC-RAS for the SS1 boundary conditions when using the flow optimiser have been found to be dependant upon the initial estimate of the split flow between reaches B and C. As can be seen from Table 4.1, which provides a summary of the results for a range of split flows, HEC-RAS is inconsistent in the results that it produces.

As can be seen from Table 4.1 the flow optimiser has not changed the initial estimate of the split in flow when a 50:50 ratio is used. Reducing the initial estimate of flow in Reach B to 120 m3/s results in Reach B carrying 49.2% of the flow, and conversely increasing the initial estimate of flow to 130 m3/s results in Reach B carrying 50.2% of the flow. The impact of the initial estimate of split flows on water levels is marginal in each reach.

Table 4.1: TEST A - Comparison of HEC-RAS (SS1) results using the split flow optimiser with different initial estimates of split flow

		INITIAL ESTIMATE OF SPLIT BETWEEN REACH B & C					
		50:50		48 : 52		52 : 48	
Reach	Chainage (m)	Flow (m^3/s)	Stage (m)	Flow (m^3/s)	Stage (m)	Flow (m^3/s)	Stage (m)
A	0.000	250.000	3.203	250.000	3.199	250.000	3.204
B	0.000	125.000	3.237	122.925	3.236	125.407	3.237
C	0.000	125.000	3.101	127.075	3.097	124.593	3.102
D	0.000	250.000	3.013	250.000	3.013	250.000	3.013

* Values are for the upstream cross-section of each reach

The results from HEC-RAS for the SS2 boundary conditions when using the flow optimiser have also been found to be dependant upon the initial estimate of the split flow between reaches B and C. However, as can be seen from Table 4.2, which provides a summary of the results for a range of split flows, the inconsistencies observed for SS1 are not as pronounced for SS2.

As can be seen from Table 4.2 the flow optimiser has changed the initial estimate of the split in flow when a 50:50 ratio is used. Either reducing or increasing the initial estimate of flow in Reach B to 120 m3/s or 130 m3/s respectively has only a marginal impact on the resultant split flows and water levels.

Table 4.2: TEST B – Comparison of HEC-RAS (SS2) results using the split flow optimiser with different initial estimates of split flow

		INITIAL ESTIMATE OF SPLIT BETWEEN REACH B & C					
		50:50		48 : 52		52 : 48	
Reach	Chainage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	0.000	250.000	2.593	250.000	2.594	250.000	2.592
B	0.000	132.246	2.625	132.410	2.625	132.076	2.624
C	0.000	117.754	2.353	117.590	2.353	117.924	2.353
D	0.000	250.000	1.887	250.000	1.887	250.000	1.887

* Values are for the upstream cross-section of each reach

Further to the above finding a ratio of 48:52 for the initial estimate of split flow has been used for both the SS1 and SS2 boundary conditions when comparing the results of HEC-RAS with ISIS and MIKE 11.

Using the SS1 boundary conditions the optimised split flow results (48:52 ratio split) have been compared in Graph 3, Appendix A and Table 4.3 to those when using a defined split flow (ISIS and MIKE 11 results) without the use of the split flow optimiser. As can be seen from these results a decrease in the flow in reach B increases the water levels and vice versa for reach C, as would be expected given that HEC-RAS carries out an energy level balance. However, the impact on the water level results in reach A shows a significant degree of variability.

Table 4.3: TEST B – HEC-RAS: Optimised and Defined Split Flow Results (SS1)

		Optimised Split		Defined Split No.1		Defined Split No.2	
Reach	Chainage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100.000	250.000	3.199	250.000	3.401	250.000	3.156
B	1500.000	122.925	3.236	80.621	3.224	93.315	3.227
C	500.000	127.075	3.097	169.379	3.049	156.790	3.059
D	100.000	250.000	3.013	250.000	3.013	250.000	3.013

* Values are for the upstream cross-section of each reach
Split flows No's. 1 and 2 are those as determined by ISIS and MIKE 11 using the SS1 boundary conditions

Consultation with the developers of HEC-RAS has provided an explanation for the performance of the split flow optimiser for this test, which is discussed in Section 5.

4.3 Comparison of ISIS, MIKE 11 and HEC-RAS Results – SS1 and QS1

Table 4.4 and 4.5 provide a summary of the results from each of the software packages for the simulations with the SS1 and QS1 boundary conditions respectively. A complete set of results is presented in Tables 1 and 2, and Graphs 1 and 2, Appendix A.

A comparison of the results obtained from the three software packages when undertaking a steady state calculation shows notable differences.

ISIS and MIKE 11 (resistance radius), both of which undertake a water level balance at the junctions, show a good correlation to each other with respect to water level and split flows. At junction 2 MIKE 11 predicts a water level that is slightly lower than that calculated by ISIS, however, at junction 1 this trend is reversed.

HEC-RAS, which undertakes an energy level balance at junctions, calculates a significantly higher water surface profile along the length of reaches A and B and a notably different result for the split flow when compared to ISIS and MIKE 11. For reach C, at junction 2, HEC-RAS calculates a water level that is lower than that calculated by the other two software packages, however, this is reversed at junction 1. This higher water level in reach B is transferred through to reach A.

The quasi-steady result for HEC-RAS, which is based on a water level balance, is notably different to the steady state result and shows a good correlation to the results obtained by ISIS and MIKE 11 (resistance radius). At junction 2 MIKE 11 predicts a water level that is slightly lower than that calculated by ISIS and HEC-RAS, however, at junction 1 this trend is reversed. The split flows calculated by HEC-RAS are within 4% of those calculated by ISIS and 16% of those calculated by MIKE 11 (resistance radius).

For both the steady state and quasi-steady boundary conditions the hydraulic radius option in MIKE 11 increases the water levels throughout the system when compared to the resistance radius result. In addition, the hydraulic radius option causes a shift of flow of approximately 10 cumecs towards reach B from reach C.

The results in Table 1, Appendix A, appear to show a timestepping or convergence problem with the MIKE11 steady state result, as the flows are not quite constant. Investigation of this problem has not been undertaken as part of the test as it was considered to be beyond the scope of the study. Comment on this observation is made in Section 5.

Table 4.4: TEST B – Summary of SS1 Flow and Stage Results

		HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
Reach	Chainage	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100.000	250.000	3.199	250.000	3.066	250.000	3.073	250.000	3.101
B	1500.000	122.925	3.236	80.621	3.053	93.181	3.060	102.910	3.087
C	500.000	127.075	3.097	169.379	3.053	156.790	3.060	147.035	3.087
D	100.000	250.000	3.013	250.000	3.015	250.021	3.012	249.822	3.014

* Values are for the upstream cross-section of each reach, (RR) – Resistance Radius, (HR) – Hydraulic Radius

Table 4.5: TEST B – Summary of QS1 Flow and Stage Results

Reach	Chainage	HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
		Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100.000	250.000	3.065	250.000	3.066	250.000	3.072	250.000	3.100
B	1500.000	78.150	3.052	80.993	3.053	92.949	3.060	102.696	3.086
C	500.000	171.850	3.052	169.007	3.053	157.051	3.060	147.304	3.086
D	100.000	250.000	3.012	250.000	3.015	250.000	3.011	250.000	3.014

* Values are for the upstream cross-section of each reach, (RR) – Resistance Radius, (HR) – Hydraulic Radius

4.4 Comparison of ISIS, MIKE 11 and HEC-RAS Results – SS2 and QS2

Tables 4.6 and 4.7 provide a summary of the results for the simulations with the SS2 and QS2 boundary conditions respectively. A complete set of results is presented in Tables 3 and 4, and Graphs 4 and 5, Appendix A.

As with the SS1 results, a comparison of the SS2 results shows a notable difference in results obtained from the three software packages.

ISIS and MIKE 11 (resistance radius), both of which undertake a water level balance at the junctions, show a similar correlation to each other with respect to water level and split flows. However, ISIS notably calculates a rapid increase in the water level along reach D and consequently a higher water level at junction 2. At junction 1 the difference in water levels between ISIS and MIKE 11 is reduced.

HEC-RAS, which undertakes an energy level balance at junctions, calculates a significantly higher water surface profile along the length of reaches A and B and a notably different result for the split flow when compared to ISIS and MIKE 11. At junctions 1 and 2 HEC-RAS calculates a water level that is significantly higher than that calculated by the other two software packages. This higher water level is transferred through to reach A.

Although not presented, a test with HEC-RAS was undertaken with a 48:52 and 52:48 ratio in the initial estimate of split flows. The results from this test produced less than 0.01% difference in the calculated split flow and water levels.

The quasi-steady result for HEC-RAS, which is based on a water level balance, is notably different to the steady state result and again, as for the QS1 result, shows a good correlation to the results obtained by ISIS and MIKE 11 (resistance radius). ISIS consistently calculates a water level higher than that of MIKE 11 and similarly HEC-RAS higher than ISIS. This trend is not repeated in the split flows, which are within 3% of each other.

For both the steady state and quasi-steady boundary conditions the hydraulic radius option in MIKE 11 increases the water levels throughout the system when compared to the resistance radius result. This increase is not as pronounced as that observed when using the SS1 and QS1 boundary conditions. In addition the hydraulic radius option causes a shift of flow of approximately 10m^3/s towards reach B from reach C. Similarly this shift is not as pronounced as that observed when using the SS1 and QS1 boundary conditions.

As with the SS1 results the SS2 results, Table 3, Appendix A, appear to show a timestepping or convergence problem since the flows are not quite constant. Investigation of this problem has not been undertaken as part of the test as it was considered to be beyond the scope of the study.

Table 4.6: TEST B – Summary of SS2 Flow and Stage Results

Reach	Chainage	HEC-RAS Flow	HEC-RAS Stage	ISIS Flow	ISIS Stage	MIKE 11 (RR) Flow	MIKE 11 (RR) Stage	MIKE 11 (HR) Flow	MIKE 11 (HR) Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100.000	250.000	2.593	250.000	2.413	250.000	2.370	250.000	2.413
B	1500.000	132.246	2.625	119.241	2.343	116.795	2.305	117.720	2.350
C	500.000	117.754	2.353	130.759	2.343	133.184	2.305	132.288	2.350
D	100.000	250.000	1.887	250.000	1.826	250.569	1.735	250.680	1.741

* Values are for the upstream cross-section of each reach, (RR) – Resistance Radius, (HR) – Hydraulic Radius

Table 4.7: TEST B – Summary of QS2 Flow and Stage Results

Reach	Chainage	HEC-RAS Flow	HEC-RAS Stage	ISIS Flow	ISIS Stage	MIKE 11 (RR) Flow	MIKE 11 (RR) Stage	MIKE 11 (HR) Flow	MIKE 11 (HR) Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100.000	250.000	2.420	250.000	2.407	250.000	2.370	250.000	2.412
B	1500.000	117.613	2.355	120.497	2.334	116.852	2.305	117.802	2.349
C	500.000	132.387	2.355	129.503	2.334	133.148	2.305	132.198	2.349
D	100.000	250.000	1.778	250.000	1.743	250.000	1.734	250.000	1.740

* Values are for the upstream cross-section of each reach, (RR) – Resistance Radius, (HR) – Hydraulic Radius

4.5 Summary of Spilt Flows

Table 4.8 provides a summary of the ratio of split flows between channel B and channel C for the SS1, QS1, SS2 and QS2 boundary conditions.

Table 4.8: TEST B – Summary of Ratio's of Split Flows

		Boundary Condition			
		SS1	QS1	SS2	QS2
	Reach	B:C	B:C	B:C	B:C
Software	HEC-RAS	49:51	32:68	53:47	47:53
	ISIS	32:68	32:68	48:52	48:52
	MIKE 11 (RR)	37:63	37:63	47:53	47:53
	MIKE 11 (HR)	41:59	41:59	47:53	47:53

5 DISCUSSION AND CONCLUSIONS

It has been possible to set up the test for each of the software packages as specified by the test specification without the need for any adjustments in the configuration. However, in order to obtain steady state results with MIKE 11 an unsteady simulation (QS1 and QS2) had to be undertaken with the initial conditions determined by a steady state calculation. The steady state results have then been taken from the unsteady simulation at t = 0s. This approach is not considered to be a hindrance.

The steady state results from HEC-RAS have shown that differences can occur when using the split flow optimiser. An appropriate estimation of the initial split flow when using the SS1 boundary conditions is clearly important for this test configuration as it can influence both the split flow and water level results. When using the SS2 boundary conditions, which use a lower downstream water level boundary, the differences are not as pronounced.

The use of the split flow optimiser in HEC-RAS and its method of solution/operation should be considered in context when undertaking steady state simulations of this type. As such the carrying out of a sensitivity analysis on the initial estimate of split flows and assessing the importance of calculation tolerances (see below) is recommended if confidence in the results is to be achieved.

Through consultation with the developers of HEC-RAS an understanding of the operation of the split flow optimiser has been attained. When used the water surface profiles are calculated and energies are compared. Flow is adjusted in the reaches based on the energy gradelines, water surface profiles are recalculated, and energies are compared again. This process continues until the energies of the receiving streams are within a tolerance. The default tolerance is 0.006m. Considering the results from this test for the comparison starting with a 50:50 split, and then trying 48:52, and finally 52:48, there are some differences in the resulting flows in each reach. However, the water surfaces and energies are balanced to within the default tolerance of 0.006m. This would suggest that HEC-RAS is performing to within the default level of accuracy and that the differences observed in this test are a consequence of the test configuration. The test configuration produces significant changes in flows for the reaches based on very small changes in the water surface elevations and energies. For test SS1 the difference in the resulting water surfaces from the three trials is less than 0.001m for reach B, 0.005m for reach C, and 0.005m for reach A (i.e. a very small difference in stage). Reducing the default tolerance for the solution of a split flow at a junction to 0.001m should produce a stage and energy that was within the 0.001 tolerance and thence reduce the flow differences. This test has not been tested as part of this study as it is considered to be beyond the scope of the study; however, it is recommended that this be assessed for modelling studies.

The study has raised questions about the appropriateness of using a water level balance at junctions in a steady state calculation. The HEC-RAS steady flow answer is the only one that is preserving conservation of energy or momentum, and continuity whereas both ISIS and MIKE 11 consider a water level balance at junctions.

From the steady state results it can be seen that the approach adopted by HEC-RAS has resulted in significantly higher water levels along the upstream reach when compared to the results obtained from ISIS and MIKE 11.

The MIKE 11 steady state solutions appear to show a timestepping or convergence problem, as the flows are not quite constant. It could perhaps be concurred from this that MIKE 11 is not undertaking a true backwater calculation but is instead undertaking a quasi-steady calculation, which in this case has not yet converged.

The results obtained with ISIS and MIKE 11, when using the SS1 and QS1 boundary conditions, show only a marginal difference in the resultant split flow and calculated water surface profile throughout the system. However, when using the SS2 and QS2 boundary conditions only the results from MIKE 11 show close agreement for both split flow and water levels. The results from ISIS show close agreement for the split in flow; however, there is a 0.08m reduction in the predicted water levels at junction 2 and a marginal reduction at junction 1.

The results obtained from each of the software packages when undertaking the simulations with the QS1 and QS2 boundary conditions have shown a good correlation to one another. The results from ISIS, MIKE 11, and HEC-RAS (unsteady flow) all assume a constant water surface across the junction at all three cross-sections i.e. these simulations are not preserving conservation of energy or conservation of momentum, only continuity. This assumption is an approximation of what is really happening at a stream junction. The assumption may be considered to be representative for flat sloping streams that move at lower velocities. However, as the stream slope increases, and thus the velocity increases, this assumption will begin to produce an error in both the estimate of flow going into each reach and the resulting upstream water surface elevation. This error becomes even greater when one of the receiving streams has a much greater bed slope than the other, as is the case in this test. It is recommended that further study and software development be made with respect to considering this issue.

Listed in the Tables 5.1 and 5.2 for SS1 and SS2 respectively, are the energy levels as calculated from first principles (i.e. area, average velocity, velocity head, and then the energy grade line).

Table 5.1: TEST B - ISIS Results for Test SS1

Reach	Chainage (m)	Stage (m)	Discharge (m^3/s)	Flow Area (m^2)	Velocity (m/s)	Velocity Head (m)	Energy (m)
A	0.0	3.053	250.000	125.920	1.985	0.201	3.254
B	1500.0	3.053	80.621	77.864	1.035	0.055	3.108
C	500.0	3.053	169.379	53.834	3.146	0.505	3.558

Table 5.2: TEST B - ISIS Results for Test SS2

Reach	Chainage (m)	Stage (m)	Discharge (m^3/s)	Flow Area (m^2)	Velocity (m/s)	Velocity Head (m)	Energy (m)
A	0.0	2.343	250.000	87.516	2.857	0.416	2.759
B	1500.0	2.343	119.241	53.651	2.223	0.252	2.595
C	500.0	2.343	130.759	36.726	3.560	0.647	2.990

Inspection of the unsteady results of the unsteady flow runs show an increase in energy and momentum from Reach A to Reach C, at junction 1, which is a physical impossibility, given the problem. Consideration of the ISIS results for both the SS1 and SS2 tests illustrates this.

As shown in both Tables 5.1 and 5.2, the energy is increasing in the downstream direction through the junction to reach C, and decreasing in the downstream direction through the junction to reach B. The increase in energy at reach C is the greatest for test SS1, but is also significant for test SS2. This increase in energy is physically impossible. The same calculations could be made for conservation of momentum by calculating specific force at each cross section. If this were done then we find a dramatic increase in momentum for reach C. The increase in momentum would be large enough that there would be such that conservation of momentum could not be conserved across the junction, given these results. What this suggests is that all three software packages, ISIS, MIKE 11, and HEC-RAS (unsteady flow), are putting too much flow into reach C and not enough flow into reach B.

As observed in Test A for this Benchmarking Study the use of either the resistance radius or hydraulic radius cross-section option in MIKE 11 can have a notable impact on the water level results. For this test there is a similar finding, however, the impact is not only on the water levels but also on the calculated split flow. Considering the results when using the QS1 and QS2 boundary conditions it is clear that the resistance radius option provides a better match to the results obtained from ISIS and HEC-RAS.

6 RECOMMENDATIONS

The test has run each of the software packages under a range of boundary conditions and in some instances with a number of calculation settings. The results have then been compared to one another with no reference to either an analytical or experimental solution. As such there is no definitive conclusion as to which software package is the most accurate. Hence, it is recommended that either one or both of the following be considered for future investigation:

- undertake a physical model study which is dimensionally similar to the configuration investigated in this test or alternatively identify a suitable existing study that investigates the principles of the test. Then compare flow and level measurements to results obtained from each of the software packages with the appropriate configuration changes; and/or
- identify a field situation that has a similar split flow characteristic/principle to that investigated by this test and to obtain appropriate cross section, flow and level data. This data could then to be used to construct a numerical model and a comparison of the physical and numerical results made.

The study has raised questions about the appropriateness of using a water level balance at junctions in a steady state or unsteady calculation and has produced interesting steady results from HEC-RAS, which is the only software package that considers the conservation of energy or momentum, and continuity. Both ISIS and MIKE 11 consider a water level balance at junctions in this instance. Further work and research is required to investigate these approaches and determine the most appropriate method for engineering problems and to asses the modelling risks (i.e. confidence in results) associated with the current approaches.

Logic would suggest that a T-junction is likely to have different characteristics to a shallow Y-junction and different bed slopes both upstream and downstream of the junction will have some impact. Hence, it is recommended that the geometry and orientation of the junction be considered when evaluation split flows. Clearly physical modelling would help to resolve the issue. Once resolved the development of clear practical guidance to the modeller would be appropriate.

The timestepping or convergence problems identified with MIKE 11 for the steady state result should be investigated and an appropriate explanation sought.

The spacing of cross sections at or across a junction and their orientation has not been considered as part of this study. Furthermore, the approach and impact of these important features has not been considered for both the steady and unsteady flow regime. Hence, it is recommended that further study be undertaken in the area.

7 REFERENCES

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

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

APPENDIX A RESULTS

Table 1: TEST B – SS1 Flow and Stage Results

Reach	Chaiange	HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
		Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100	250.000	3.199	250.000	3.066	250.000	3.073	250.000	3.101
	75	250.000	3.196	250.000	3.062	249.998	3.069	249.987	3.097
	50	250.000	3.193	250.000	3.059	249.989	3.066	249.970	3.094
	25	250.000	3.190	250.000	3.056	249.978	3.063	249.955	3.090
	0	250.000	3.187	250.000	3.053	249.971	3.060	249.945	3.087
B	1500	122.925	3.236	80.621	3.053	93.181	3.060	102.910	3.087
	1125	122.925	3.207	80.621	3.040	93.231	3.044	102.891	3.063
	750	122.925	3.181	80.621	3.030	93.311	3.031	102.919	3.044
	375	122.925	3.160	80.621	3.022	93.315	3.020	102.953	3.028
	0	122.925	3.141	80.621	3.015	93.232	3.012	102.822	3.014
C	500	127.075	3.097	169.379	3.053	156.790	3.060	147.035	3.087
	375	127.075	3.080	169.379	3.037	156.829	3.038	147.085	3.058
	250	127.075	3.067	169.379	3.027	156.909	3.025	147.188	3.039
	125	127.075	3.056	169.379	3.020	156.877	3.016	147.136	3.025
	0	127.075	3.048	169.379	3.015	156.790	3.012	147.001	3.014
D	100	250.000	3.013	250.000	3.015	250.021	3.012	249.822	3.014
	75	250.000	3.010	250.000	3.011	250.020	3.009	249.818	3.010
	50	250.000	3.007	250.000	3.007	250.019	3.006	249.824	3.007
	25	250.000	3.003	250.000	3.004	250.011	3.003	249.823	3.003
	0	250.000	3.000	250.000	3.000	250.010	3.000	249.825	3.000

(RR) – Resistance Radius, (HR) – Hydraulic Radius

Table 2: TEST B – QS1 Flow and Stage Results

Reach	Chainage	HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
		Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100	250.000	3.065	250.000	3.066	250.000	3.072	250.000	3.100
	75	250.000	3.062	250.000	3.063	250.000	3.069	250.000	3.096
	50	250.000	3.059	250.000	3.060	250.000	3.066	250.000	3.093
	25	250.000	3.056	250.000	3.057	250.000	3.063	250.000	3.089
	0	250.000	3.052	250.000	3.053	250.000	3.060	250.000	3.086
B	1500	78.150	3.052	80.993	3.053	92.949	3.060	102.696	3.086
	1125	78.150	3.039	80.993	3.041	92.949	3.044	102.696	3.063
	750	78.150	3.028	80.993	3.030	92.949	3.031	102.696	3.043
	375	78.150	3.019	80.993	3.022	92.949	3.020	102.696	3.027
	0	78.150	3.012	80.993	3.015	92.949	3.011	102.696	3.014
C	500	171.850	3.052	169.007	3.053	157.051	3.060	147.304	3.086
	375	171.850	3.036	169.007	3.038	157.051	3.038	147.304	3.058
	250	171.850	3.025	169.007	3.027	157.051	3.024	147.304	3.039
	125	171.850	3.017	169.007	3.020	157.051	3.016	147.304	3.025
	0	171.850	3.012	169.007	3.015	157.051	3.011	147.304	3.014
D	100	250.000	3.012	250.000	3.015	250.000	3.011	250.000	3.014
	75	250.000	3.009	250.000	3.011	250.000	3.009	250.000	3.010
	50	250.000	3.006	250.000	3.007	250.000	3.006	250.000	3.007
	25	250.000	3.003	250.000	3.004	250.000	3.003	250.000	3.003
	0	250.000	3.000	250.000	3.000	250.000	3.000	250.000	3.000

(RR) – Resistance Radius, (HR) – Hydraulic Radius

Table 3: TEST B – SS2 Flow and Stage Results

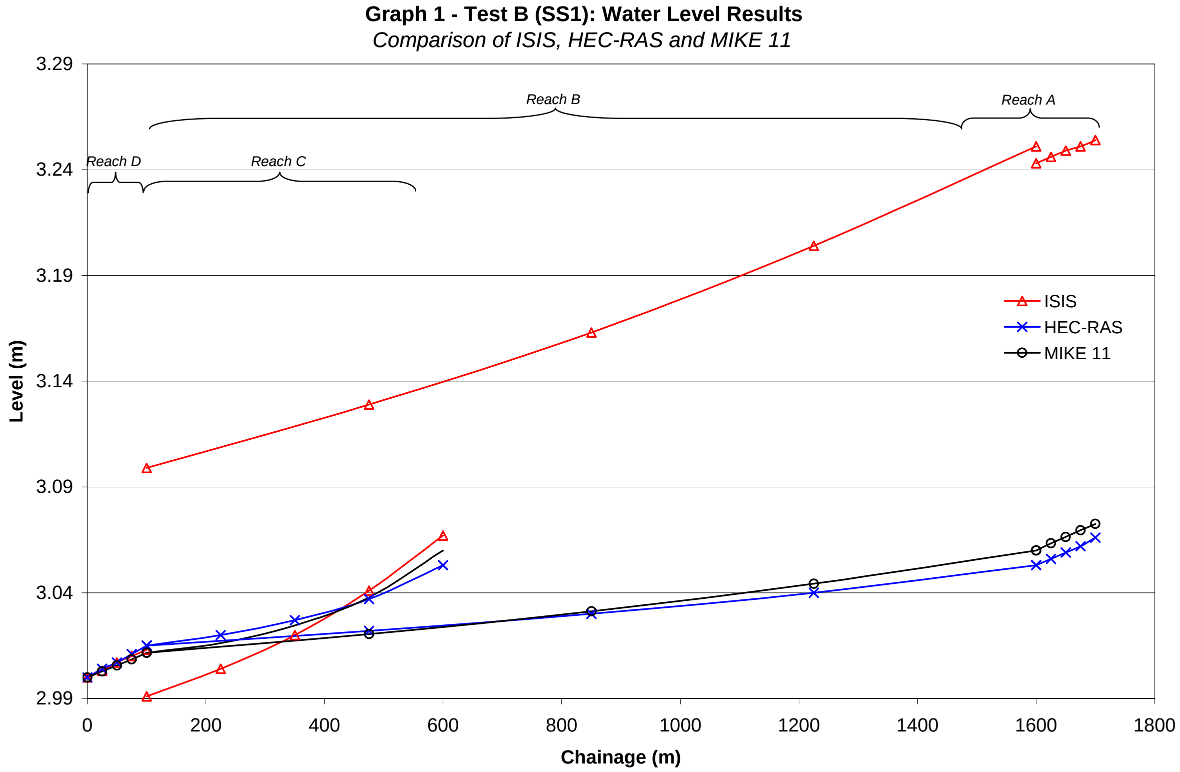
		HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
Reach	Chainage	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100	250.000	2.593	250.000	2.413	250.000	2.370	250.000	2.413
	75	250.000	2.583	250.000	2.396	250.013	2.355	250.020	2.398
	50	250.000	2.572	250.000	2.379	250.004	2.339	250.017	2.383
	25	250.000	2.562	250.000	2.362	249.991	2.323	250.012	2.367
	0	250.000	2.551	250.000	2.343	249.979	2.305	250.007	2.350
B	1500	132.246	2.625	119.241	2.343	116.795	2.305	117.720	2.350
	1125	132.246	2.522	119.241	2.204	116.960	2.161	117.912	2.200
	750	132.246	2.430	119.241	2.070	117.127	2.017	118.067	2.048
	375	132.246	2.348	119.241	1.944	117.160	1.875	118.086	1.896
	0	132.246	2.277	119.241	1.826	117.274	1.735	118.236	1.741
C	500	117.754	2.353	130.759	2.343	133.184	2.305	132.288	2.350
	375	117.754	2.268	130.759	2.196	133.191	2.160	132.312	2.199
	250	117.754	2.202	130.759	2.052	133.199	2.016	132.333	2.047
	125	117.754	2.151	130.759	1.922	133.238	1.874	132.376	1.895
	0	117.754	2.111	130.759	1.826	133.295	1.735	132.445	1.741
D	100	250.000	1.887	250.000	1.826	250.569	1.735	250.680	1.741
	75	250.000	1.851	250.000	1.757	250.601	1.702	250.709	1.707
	50	250.000	1.809	250.000	1.688	250.641	1.669	250.705	1.672
	25	250.000	1.758	250.000	1.640	250.668	1.635	250.662	1.636
	0	250.000	1.600	250.000	1.600	250.675	1.600	250.636	1.600

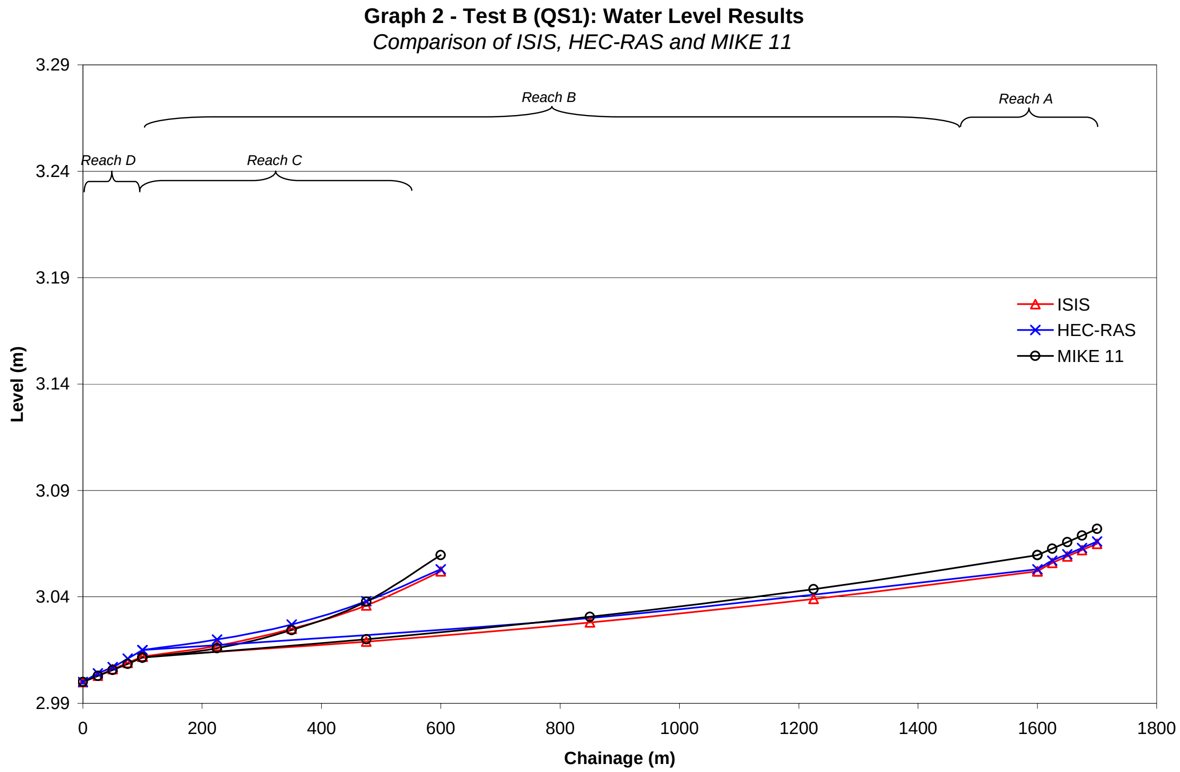
(RR) – Resistance Radius, (HR) – Hydraulic Radius

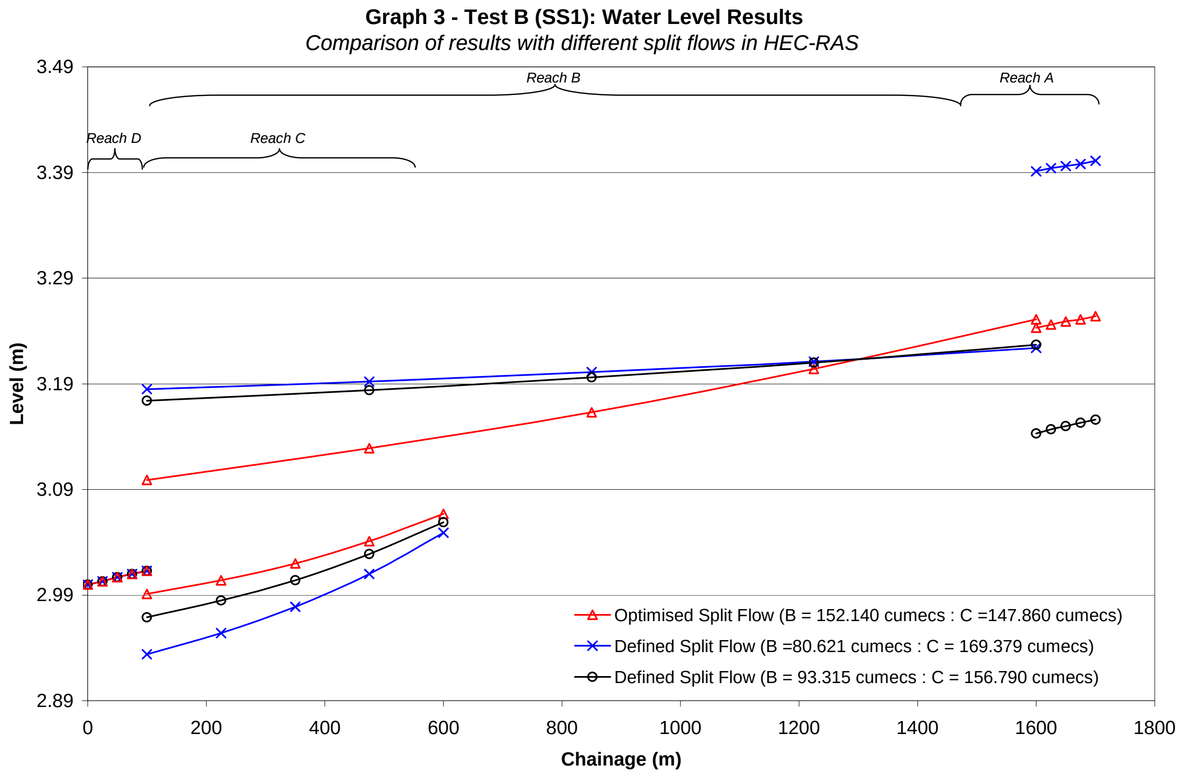
Table 4: TEST B – QS2 Flow and Stage Results

		HEC-RAS		ISIS		MIKE 11 (RR)		MIKE 11 (HR)	
Reach	Chainage	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)	(m^3/s)	(m)
A	100	250.000	2.420	250.000	2.407	250.000	2.370	250.000	2.412
	75	250.000	2.405	250.000	2.389	250.000	2.354	250.000	2.396
	50	250.000	2.389	250.000	2.371	250.000	2.338	250.000	2.381
	25	250.000	2.372	250.000	2.354	250.000	2.321	250.000	2.365
	0	250.000	2.355	250.000	2.334	250.000	2.305	250.000	2.349
B	1500	117.613	2.355	120.497	2.334	116.852	2.305	117.802	2.349
	1125	117.613	2.208	120.497	2.185	116.852	2.159	117.802	2.198
	750	117.613	2.062	120.497	2.037	116.852	2.014	117.802	2.046
	375	117.613	1.918	120.497	1.889	116.852	1.873	117.802	1.894
	0	117.613	1.778	120.497	1.743	116.852	1.734	117.802	1.740
C	500	132.387	2.355	129.503	2.334	133.148	2.305	132.198	2.349
	375	132.387	2.207	129.503	2.186	133.148	2.159	132.198	2.197
	250	132.387	2.060	129.503	2.037	133.148	2.015	132.198	2.046
	125	132.387	1.915	129.503	1.890	133.148	1.873	132.198	1.893
	0	132.387	1.778	129.503	1.743	133.148	1.734	132.198	1.740
D	100	250.000	1.778	250.000	1.743	250.000	1.734	250.000	1.740
	75	250.000	1.733	250.000	1.709	250.000	1.702	250.000	1.707
	50	250.000	1.687	250.000	1.675	250.000	1.669	250.000	1.672
	25	250.000	1.642	250.000	1.638	250.000	1.635	250.000	1.636
	0	250.000	1.600	250.000	1.600	250.000	1.600	250.000	1.600

(RR) – Resistance Radius, (HR) – Hydraulic Radius

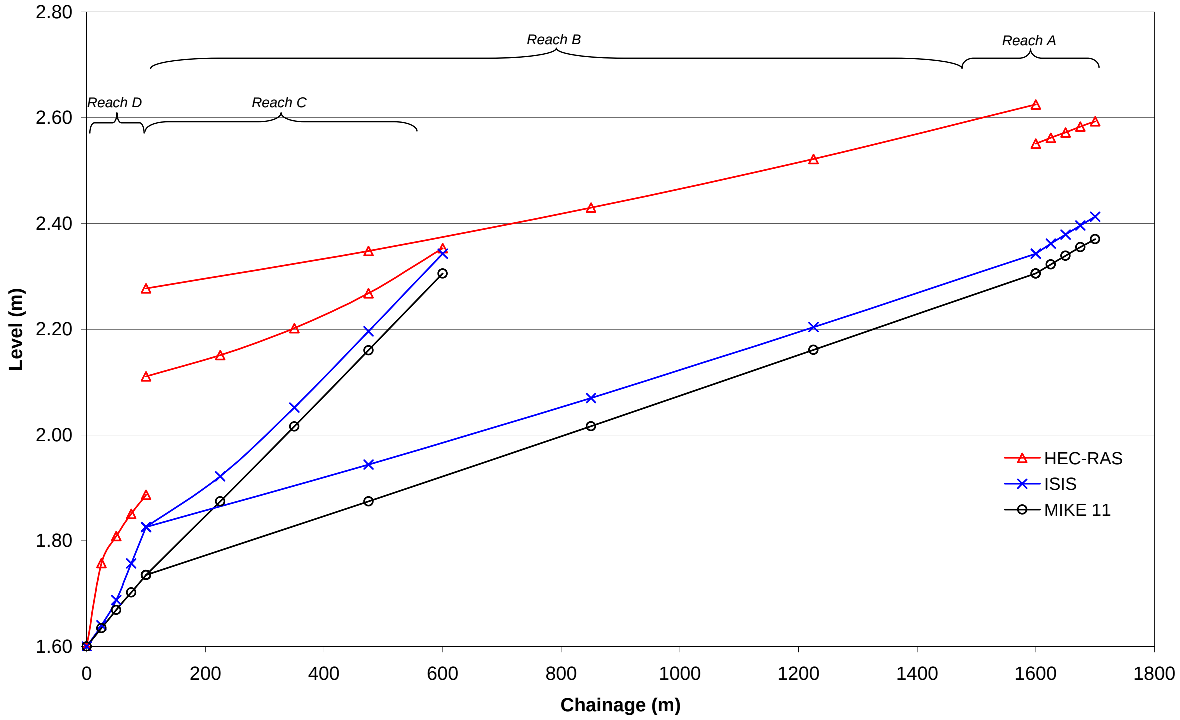

Graph 1 - Test B (SS1): Water Level Results
Comparison of ISIS, HEC-RAS and MIKE 11
Reach B
Reach A
Reach D
Reach C
ISIS
HEC-RAS
MIKE 11
Level (m)
Chainage (m)
3.29
3.24
3.19
3.14
3.09
3.04
2.99
0
200
400
600
800
1000
1200
1400
1600
1800


Graph 2 - Test B (QS1): Water Level Results
Comparison of ISIS, HEC-RAS and MIKE 11
Reach B
Reach A
Reach D
Reach C
ISIS
HEC-RAS
MIKE 11
Level (m)
Chainage (m)
3.29
3.24
3.19
3.14
3.09
3.04
2.99
0
200
400
600
800
1000
1200
1400
1600
1800



Graph 3 - Test B (SS1): Water Level Results
Comparison of results with different split flows in HEC-RAS
Reach A
Reach B
Reach C
Reach D
Level (m)
3.49
3.39
3.29
3.19
3.09
2.99
2.89
0
200
400
600
800
1000
1200
1400
1600
1800
Chainage (m)
Optimised Split Flow (B = 152.140 cumecs : C =147.860 cumecs)
Defined Split Flow (B =80.621 cumecs : C = 169.379 cumecs)
Defined Split Flow (B = 93.315 cumecs : C = 156.790 cumecs)

Graph 4 - Test B (SS2): Water Level Results
Comparison of ISIS, HEC-RAS and MIKE 11



Graph 5 - Test B (QS2): Water Level Results
Comparison of ISIS, HEC-RAS and MIKE 11