Brigham Young University
BYU ScholarsArchive

All Theses and Dissertations

2009-08-07

Analysis of the Sediment Transport Capabilities of TUFLOW

Cameron G. Jenkins
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Civil and Environmental Engineering Commons

BYU ScholarsArchive Citation

Jenkins, Cameron G., "Analysis of the Sediment Transport Capabilities of TUFLOW" (2009). *All Theses and Dissertations*. 1889.
https://scholarsarchive.byu.edu/etd/1889

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in All Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.

ANALYSIS OF THE SEDIMENT TRANSPORT

CAPABILITES OF TUFLOW

By

Cameron G. Jenkins

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

December 2009

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Cameron G. Jenkins

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Rollin H. Hotchkiss, Chair
Date	Alan K. Zundel
Date	E. James Nelson

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Cameron G. Jenkins in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date

Rollin H. Hotchkiss
Chair, Graduate Committee

Accepted for the Department

E. James Nelson
Graduate Coordinator

Accepted for the College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

ANALYSIS OF THE SEDIMENT TRANSPORT

CAPABILITIES OF TUFLOW

Cameron G. Jenkins

Department of Civil and Environmental Engineering

Master of Science

The need to know how river morphology changes due to sedimentation is increasingly important as we attempt to predict future events. Engineers use numeric models to predict effects of changed morphology on river systems. The numerical model Two-dimensional Unsteady Flow (TUFLOW) has recently added, and is continually improving, its capability to model sediment transport in rivers and coastal systems. This paper evaluates the new tools for modeling sediment transport presently contained within TUFLOW and compares these tools with analytical and laboratory case studies.

Currently TUFLOW simulates combined bed and suspended load transport of noncohesive sediments under the effect of currents using the Van Rijn method. New TUFLOW capabilities which have not been extensively tested before include recognized sediment transport relationships such as those of Meyer-Peter and Mueller, Bagnold, and Ackers & White. It is important to note that the software evaluated herein is a snapshot

of a continuing software development process. The aim of the TUFLOW developers is to address any shortcomings outlined in this paper where feasible.

Eleven different test cases are modeled in the Surface-water Modeling System (SMS) software. The test cases are designed to examine how well TUFLOW simulates sediment transport modeling with channels of varying degrees of slope and contractions. Eight of the test cases are taken from Analysis of the Sediment Transport Capabilities of FESWMS. Three cases simulate a simple flume with varying midsection slopes. Four cases use a simple flume with no slope and different contractions: a short abrupt contraction, a long abrupt contraction, a long gradual contraction, and a wide contraction. Two of the test cases are from laboratory flume experiments that were performed at St. Anthony Falls Laboratory. The last test case consists of a river entering a reservoir.

The results show that TUFLOW is presently capable of representing sediment transport and morphology reasonably on moderate and shallow slopes and channels with contractions. However, more work is required to improve TUFLOW's morphological capabilities on steep slopes when hydraulic jumps are present.

The results show TUFLOW can handle long term simulations. The results show that TUFLOW is not capable at this time of recreating the lab flumes and more features need to be added to accurately portray the flumes.

TUFLOW did show perturbations, common for semi-coupled models, in the results for certain test cases. Filtering, a common way of removing perturbations was implemented and gave varying results. The developers are in the process of developing a more advanced scheme for filtering.

ACKNOWLEDGMENTS

I would like to thank my graduate advisors Dr. Rollin H. Hotchkiss, Dr. E. James Nelson, and Dr. Alan K. Zundel for watching over my shoulder to make sure this got done. I would like to thank Rusty Jones for helping me get the models to work run properly. I would like to thank David Wainwright for the help with the models and updating TUFLOW to allow for sediment transport, if it wasn't for him, I would not have had a thesis. I would like to thank my family for the support they have given me through school I lastly would like to show thanks and appreciation for my wife who had to put up with me during school and reading over everything to make sure all the t's were crossed and i's were dotted.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction and Background

There are several equations and models which can be used to simulate sediment transport, each with its simplifying assumptions and limitations. The need to know the limitations and proper usage of these equations and models is vital when computer modeling. TUFLOW (BMT-WBM 2008) is a model that recently added the capabilities of sediment transport and will be compared to simple hypothetical test cases and lab experiments.

TUFLOW uses well known equations such as Manning's, 2D Momentum, the 1D and 2D Continuity, and other equations, to calculate flow velocities, water depths, head, and sediment transport. The sediment transport equations will be the main focus of this study. The equations examined will come from selected the TUFLOW manual, Akers & White (1973), Bagnold (1966), Meyer-Peter & Muller (1948), and Van Rijn (1993).

Test cases are created to verify model capabilities. Hydrodynamic simulation files for each model are created in the Surface-water Modeling Systems (SMS). Because this software does not currently support the sediment transport capabilities of TUFLOW, the simulations are modified to add the sediment transport data. The test cases are based on previous tests done using hypothetical sediment transport models from Ipson (2006) and lab data from Seal et al. (1997), and Toro-Escobar et al. (2000). The results from each test case are compared to results found in their respective papers.

2 Numerical Models

2.1 TUFLOW

Two Dimensional Unsteady Flow or TUFLOW is a numerical model that simulates depth averaged, two and one dimensional free surface flow by solving the 2D Shallow Water Equations (SWE) using the Stelling Finite Difference Alternating Direction Implicit (ADI) scheme (Stelling 1984). TUFLOW incorporates the ESTRY 1D network or quasi-2D modeling system based on the full one dimensional free surface flow equations (BMT-WBM 2008).

The initial development of TUFLOW was a joint project between WBM Pty Ltd and the University of Queensland in 1990. Development has continued through to the present, including improvements that focus on hydraulic structures, flood modeling, advanced 2D/1D linking, GIS, and sediment transport (BMT-WBM 2008). TUFLOW is a proprietary program currently maintained by BMT-WBM Pty Ltd.

2.1.1 ADI Solver

TUFLOW incorporates the ADI solver (Stelling 1984) which has two stages. The stages are broken up into two steps that involve solving a tri-diagonal matrix. The first step of stage 1 solves the momentum equation in the Y-direction for the Y-velocities.

The equation is solved using a predictor/corrector method, which involves two iterations. For the first iteration, the calculation proceeds column by column in the Y-direction. The second step of stage 1 solves for the water levels and X-direction velocities by solving the equations of mass continuity and of momentum in the X-direction. A tri-diagonal equation is obtained by substituting the momentum equation into the mass equation and eliminating the X-velocity. The water levels are calculated and back substituted into the momentum equation to calculate the velocities. Stage 2 proceeds in a similar manner to stage 1 with the first step using the X-direction momentum equation and the second step using the mass equation and the Y-direction momentum equation (BMT-WBM 2008).

2.1.2 TUFLOW Equations

TUFLOW solves the 2D Shallow Water Equations (SWE) and sediment continuity. The shallow water equations are based on the assumption that the pressure distribution is hydrostatic. This is the case for long and shallow waves (i.e. waves with a wave length much larger than water depth), in which the vertical acceleration of fluid elements during the wave passage stays small. The 2D SWE in the horizontal plane and sediment continuity are described in the following partial differential equations

2D Continuity Equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \qquad \textbf{(2-1)}$$

Momentum Equations:

$$\frac{\partial u}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}-c_f v+g\frac{\partial \zeta}{\partial y}+gu\left(\frac{n^2}{h^{\frac{4}{3}}}+\frac{f_1}{2g\partial x}\right)\sqrt{u^2+v^2}-\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial x}=F_x$$

(2-2)

$$\frac{\partial x}{\partial t}+\frac{\partial x}{\partial x}+\frac{\partial x}{\partial y}-c_f u+g\frac{\partial \zeta}{\partial y}+gv\left(\frac{n^2}{h^{\frac{4}{3}}}+\frac{f_1}{2g\partial x}\right)\sqrt{u^2+v^2}-\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial x}=F_y$$

(2-3)

Sediment Continuity Equation:

$$(1\text{-}\eta)\frac{\partial z_b}{\partial t}+\frac{\partial q_{s1}}{\partial x}+\frac{\partial q_{s2}}{\partial y}=0 \qquad \textbf{(2-4)}$$

where: ζ = water surface elevation [L],u and v = depth averaged velocity in the X and Y directions [LT^{-1}], h = depth of water [L], t = time [T], x and y = distance in X and Y direction [L], c_f = Coriolis force coefficient, n = Manning's n, f_1 = form (energy) loss coefficient, μ = horizontal diffusion of momentum coefficient, p = atmospheric pressure [FL^2], ρ = density of water [ML^3], z_b = bed elevation [L], η = porosity, and q_{s1}, q_{s2} = volumetric total sediment transport rates in the X and Y directions [L^3T^{-1}], F_x and F_y = sum of the components of the external forces (eg. wind) in X and Y directions

2.1.3 Morphology Calculations

TUFLOW is a semi-coupled model, which means it calculates the hydrodynamic solution and inputs the values into the morphological calculations. With time, semi-coupled models generate harmonics with increasingly higher wave numbers that cannot be resolved in a finite difference scheme with a fixed grid spacing. The spatial harmonics will lead to noise and destroy the numerical solution if no spatial filtering is applied (Johnson and Zyserman 2002). The results of the harmonics tend to cause perturbations in the bed elevations, which can be seen in some of the results. The TUFLOW developers recently added code for filtering and are in the process of testing it.

The following information comes from personal communication with David Wainwright, a TUFLOW developer, on June 14th, 2009. The morphological calculations are broken up into seven distinct steps. Step one solves for the sediment flux at all four faces of the cell based on the velocities and depths from the hydrodynamic model. If the sediment transport method calculates bed load and suspended load, they are separated.

Step two reduces the sediment flux to the normal and parallel components. The normal component is only considered further.

Step three considers the sediment flux going in and out of the cell and calculates the amount of deposition. For bed load, this is a simple mass balance calculation.

Step four calculates suspended load deposition by using the Eysink & Vermaas (1983) equation to calculate how much settles in the cell and how much passes downstream. The calculations are undertaken in two directions to fully account for all deposition values.

Step five solves for the total amount of deposition and erosion for each cell. If the SMOOTH option is selected, the values are then smoothed using a four way filter before updating the bed elevations.

Step six involves updating the bed elevations and smoothing the bed if the SMOOTH BED option is selected. The SMOOTH BED option uses an enhanced four point spatial filter which depends on the limit value a user selects.

Step seven involves passing back the updated bed elevations into the hydrodynamic equations to get a new solution (David Wainwright, Personal Communication, June 14th, 2009)

2.1.4 Deposition

When considering deposition, suspended load and bed load are separated. Bed load is transferred from one cell to the next, with the difference between the bed load transport capacity from one cell to the next being deposited or picked up in that cell. With suspended load, deposition is smoothed out in accordance with the relationship of Eysink & Vermaas (1983) (David Wainwright, Personal Communication, February 6th, 2009). The EVA variable ranges from 0 to 1, 0 giving the most deposition.

$$q_{deposit} = (S_1 - S_2) * \left(1 - e^{-EVA\frac{x}{h}}\right) \quad \textbf{(2-5)}$$

where: $q_{deposit}$ = The deposition to the bed over distance x $[FL^{-1}]$, S_1= sediment transport into a control section $[FT^{-1}]$, S_2= equilibrium sediment transport potential within the control section $[FT^{-1}]$, x= distance of deposition in flow direction [L], and EVA= dimensionless constant depending on sediment characteristics and the hydraulic conditions in the channel

2.2 FESWMS

Finite Element Surface Water Modeling Software (FEWSMS) is a numerical model created by the Federal Highway Administration that has incorporated sediment transport into it (Froehlich 2003). FESWMS was created for the specific purpose of modeling the complexities of flow near highway river crossings. FEWSMS can solve for either steady-state or dynamic conditions and supports meshes consisting of six node triangles, eight node quadrilaterals, and nine node quadrilaterals (Froehlich 2003). FESWMS uses a different form of the 2D Shallow Water Equations than TUFLOW to solve for velocities and depth. FESWMS uses eight different sediment transport methods, but only Ackers & White and Meyer-Peter & Muller are used in both. The user's manual for FESWMS contains more information on hydrodynamic and morphological modeling (Froehlich 2003). FESWMS was recently tested by Ipson (2006) showing that it is not completely functional. The functional portion was tested and shown to give reasonable results and can be seen in Ipson (2006).

3 Sediment Equations

In 2004, WBM began to implement new code into TUFLOW adding sediment transport and morphological capabilities and a study was undertaken using these calculations (e.g. Wainwright et. al. 2004). The method of Van Rijn (as presented in Van Rijn (1993)) was the first to be added and includes both bed load and suspended load transport. Three methods are presently being added to TUFLOW: Ackers & White (1973), Bagnold (1966), and Meyer-Peter & Mueller (1948). Table 3-1 below shows the particle size limitations for each method.

Table 3-1: Sediment Particle Size Limitations for Each Method

Formula	Range of Particle Sizes [mm]	Material Description
Ackers-White (1973)	0.04 – 7.0	Sand, Fine Gravel
Bagnold (1966)	0.015 – 5.0	Sand, Fine Gravel
Meyer-Peter-Mueller (1948)	0.4 – 29.0	Sand, Gravel
Van Rijn (1993)	0.07 – 5.0	Sand, Fine Gravel

3.1 Ackers & White

In 1973, Ackers & White proposed a formula to estimate the total load transport with no distinction made between bedload and suspended load (Ackers 1973). This empirical formula is based on 925 sets of data from flume experiments in depths of flow up to 0.4m. The experiments use particle sizes ranging from 0.04mm to 4.0mm. This method cannot be used for particle sizes less than 0.04mm due to the cohesive properties of the soil. Sediment transport can be calculated by solving Equation 3-1.

$$\mathbf{q_t = \frac{qD_{35}C}{h}\left(\frac{\bar{u}}{u_*}\right)^n\left(\frac{F_{gr}}{A}-1\right)^m} \tag{3-1}$$

Table 3-2: Coefficients for the Ackers & White Formula

$D_* \geq 60$	$1 < D_* < 60$
$n = 0.0$	$n = 1.00 - 0.56 \log D_*$
$A = 0.17$	$A = \frac{0.23}{\sqrt{D_*}} + 0.14$
$m = 1.50$	$m = \frac{9.66}{D_*} + 1.34$
$C = 0.025$	$C = 10^{-3.53+2.86\log D_* - \log D_*^2}$

where: A, C, m, and n = coefficients found in Table 3-2, D_{35} = sediment diameter [L], D_*= dimensionless grain diameter (Rijn 1993), F_{gr}= sediment mobility number, $\bar{u}$= mean velocity [LT^{-1}], u_*= shear velocity, q_t= total sediment load [L^2T^{-1}], and q= flow [L^2T^{-1}]

3.2 Bagnold

Bagnold proposed an empirical sediment transport model for bedload and suspended load from over 100 flumes and rivers (Bagnold 1966). The experiments used both uniform and non-uniform particle sizes ranging from 0.015 to 5mm. Bagnold assumed that bedload particles primarily move because of saltations or jumps. Sediment transport can be calculated solving Equation 3-2. The bedload efficiency ranges from 0.1 to 0.2 and the suspended load efficiency is stated to be 0.015 (Bagnold 1966).

$$\mathbf{q_t} = \boldsymbol{\omega}\mathbf{g}\frac{\rho_s}{\rho_s\text{-}\rho}\left(\frac{\mathbf{e_b}}{\tan\boldsymbol{\alpha}} + \frac{\mathbf{e_s}\bar{\mathbf{u}}_\mathbf{s}}{\mathbf{w_s}}(\mathbf{1} - \mathbf{e_b})\right) \qquad \textbf{(3-2)}$$

where: q_t= total transport rate of solids by dry mass per unit width [$FT^{-1}L^{-1}$], ω= stream power per unit boundary [$FT^{-1}L^{-1}$], g= gravity [LT^{-2}] e_b= bedload efficiency, e_s= suspended load efficiency, α= coefficient of solid friction, and $\bar{u}_s$= mean transport of suspended solid [$FT^{-1}L^{-1}$], w_s= fall velocity [LT^{-1}]

3.3 Meyer-Peter & Muller

Meyer-Peter and Muller (1948) proposed an empirical sediment transport model for bedload from experimental research. The experiments used both uniform and non-uniform particle sizes ranging from 0.4 to 29 mm. Sediment transport can be calculated by solving Equation 3-3

$$\mathbf{q_b} = \mathbf{8}\left[\frac{\left(\frac{\mathbf{k}}{\mathbf{k'}}\right)^{\frac{3}{2}}\boldsymbol{\gamma}\mathbf{RS}}{(\boldsymbol{\gamma}_\mathbf{s}-\boldsymbol{\gamma})\mathbf{d_m}} - \mathbf{0.047}\right]^{\frac{3}{2}}\left(\boldsymbol{\gamma}_\mathbf{s}\sqrt{\left(\frac{\boldsymbol{\gamma}_\mathbf{s}}{\boldsymbol{\gamma}} - \mathbf{1}\right)\mathbf{g}\mathbf{d}_\mathbf{m}^\mathbf{3}}\right) \qquad \textbf{(3-3)}$$

where: k= total bed roughness [$L^{1/3}T^{-1}$], k'= grain roughness [$L^{1/3}T^{-1}$], R= hydraulic radius [L], γ_s= specific weight of solid [FL^3], γ= specific weight of fluid [FL^3], S= slope, d_m= arithmetic mean diameter [L], and q_b= bed load transport [$FT^{-1}L^{-1}$]

3.4 Van Rijn

The Van Rijn method breaks up the bed load and suspended load calculating each one separately before combining at the end of each time step (Rijn 1993). This method has the capability of calculating sediment transport due to waves and currents, but only the method using currents is incorporated into TUFLOW at the present time. Like Bagnold, Van Rijn assumes bedload particles move primarily due to saltations or jumps. Equation 3-4, 3-5, 3-6, and 3-7 are used to calculate sediment transport due to currents only.

$$q_t = q_b + q_s \tag{3-4}$$

$$q_b = 0.053(s\text{-}1)^{0.5} g^{0.5} d_{50}^2 D_*^{(-0.3)} T^{2.1} \ (T<3) \tag{3-5}$$

$$q_b = 0.1(s\text{-}1)^{0.5} g^{0.5} d_{50}^2 D_*^{(-0.3)} T^{1.5} \ (T>3) \tag{3-6}$$

$$q_s = F\bar{u}hc_a \tag{3-7}$$

where: q_s= suspended load transport [L^2T^{-1}], T= dimensionless bed shear parameter, c_a= volumetric reference concentration, D_{50}= sediment diameter, D_*= dimensionless grain diameter, and F= shape factor

4 Setup

4.1 Test Cases

Eleven different test cases are modeled in the Surface-water Modeling System (SMS) software. The test cases are designed to examine how well TUFLOW simulates sediment transport modeling with varying degrees of slope and contractions. The test cases are taken from Analysis of the Sediment Transport Capabilities of FEWSMS FST2DH (Ipson 2006). Three of the test cases are of a simple hypothetical flume with varying midsection slopes. Four of the test cases use a simple hypothetical flume with no slope and different contractions: a short abrupt contraction, a long abrupt contraction, a long gradual contraction, and a wide contraction. Two of the test cases are from Seal et al. (1997) and Toro-Escobar et al. (2000), which are laboratory flume experiments that were done in the St. Anthony Falls Laboratory. The last test case consists of a river entering a reservoir (Hotchkiss 1991). Table 4-1 only gives a brief overview of the models and their setup, more details are given in Appendix B.

The research includes setting up test cases 1- 8 in FESWMS and comparing them to the TUFLOW results. Because FESWMS offered only two of the same methods for sediment transport, Ackers & White and Meyer-Peter & Muller, only these methods will be compared. Each Program has different input options which caused the sediment simulations to differ slightly. The input parameters for FESWMS were chosen to best replicate the conditions that existed in TUFLOW.

Table 4-1: Test Case Parameters

(1) Test Case	(2) Width [m]	(3) Slope	(4) Length [m]	(5) Q [cms]	(6) Total Simulation Period [hr]
1	25	.00016,.0667,.00016	100,150,100	12.6	48
2	25	.00016,.0067,.00016	100,150,100	12.6	48
3	25	.00016,.0033,.00016	100,150,100	12.6	48
4	25,10,25	0	130,30,130	12.6	48
5	25,10,25	0	130,30,130	12.6	48
6	25,5,25	0	107.5,10,107.5	12.6	48
7	500,100,500	0	2412, 176, 2412	1000	48
8	varies,23,varies	Varies	varies	60	48
9	0.3	0.002	48.5	0.049	32.5
10	2.7	0.01	40	0.11	32.5
11	300	0.0075	150000	604	4320

Notes:
1. Test cases 1, 2, and 3 represent the sloped midsection models; test cases 4, 5, 6, and 7 represent models with contractions; test case 8 represents a river with a bridge contraction; test case 9 and 10 are lab flumes; test case 11 represents the deposition in a reservoir.
2. The three values represent upstream, contraction, downstream widths respectively.
3. The three values represent upstream, mid-reach, and downstream slopes.
4. The three values represent upstream, mid-reach, and downstream portions of the changing channel runs (1-7).

4.2 Model Setup

The model setup for each test case is shown in Table 4-2. The grid size and time step were selected to give a Courant number less than 10, which allows for a stable model and accurate results. A constant value for manning's n and the deposition coefficient EVA was used for all test cases.

Table 4-2: Initial Model Setup

(1) Test Case	(2) Manning's n [-]	(3) D [mm]	(4) EVA [-]	(5) Grid Cell Size [m]	(6) Time Step [T]
1	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
2	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
3	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
4	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
5	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
6	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
7	0.025	0.08, 0.2, 2.0, 4.0	0.00001	10	5
8	0.025	0.08, 0.2, 2.0, 4.0	0.00001	2.5	1
9	0.025	0.5, 1.14, 14, 32.0	0.00001	0.3	0.1
10	0.025	1.0, 5.6, 16.7, 32.0	0.00001	2.7	1
11	0.025	0.5	0.00001	50	10
Notes:	1. Test cases 1, 2, and 3 represent the sloped midsection models; test cases 4, 5, 6, and 7 represent models with contractions; test case 8 represents a river with a bridge contraction; test case 9 and 10 are lab flumes; test case 11 represents the deposition in a reservoir. 3. The values represent the particle size test cases 1 through 8 and 11 were run with. For test cases 10 and 11 they represent D35, D50, Dm, D90 respectively				

The sediment transport setup for each method is shown in Table 4-3. Each method requires different input parameters to run in TUFLOW. The Ackers & White method requires a D_{35} and roughness length 'k', calculated by D_{35} multiplied by 1.25. The Bagnold method requires a D_{90}, bed load efficiency coefficient which ranges from 0.1-0.2 and set to .15 for all test cases, suspended load efficiency coefficient which Bagnold states is 0.15, bedform height and length which is set to 0 for no bedforms, and fall velocity. The Meyer-Peter & Muller method requires a roughness factor which is set to 1 for no bedforms, a D_{90}, and D_m. The Van Rijn method requires a D_{50}, D_{90}, fall velocity, current roughness which is calculated by D_{90} multiplied by 3, reference level, and ratio of sediment and fluid mixing which is set to 1.

Table 4-3: Sediment Transport Method Setup

(1) Parameter	(2) 0.08mm	(3) 0.2mm	(4) 2.0mm	(5) 4.0mm
Roughness Length [m][a]	0.0001	0.00025	0.0025	0.005
Bed Load Efficiency [b]	0.15	0.15	0.15	0.15
Suspended Load Efficiency [b]	0.015	0.015	0.015	0.015
Bedform Height [m] [b]	0	0	0	0
Bedform Length [m] [b]	0	0	0	0
Roughness Factor [c]	1	1	1	1
Current Roughness [m] [d]	0.00024	0.0006	0.006	0.012
Reference Level [m] [d]	0.2	0.2	0.2	0.2
Ratio of Sediment and Fluid Mixing [d]	1	1	1	1
Notes:	[a] Ackers & White Input [b] Bagnold Input [c] Meyer-Peter & Muller Input [d] Van Rijn Input			

The laboratory experiments included an inflow sediment rate, but TUFLOW does not currently have that capability. Therefore, the model was modified by adding a steeper sloped extension to the upstream boundary. The same model setup was used in Ipson (2006) with a slope that gave approximately 20 kg/min (roughly two-thirds used in actual experiment) entered the grid. The 20kg/min was done to test if TUFLOW would give reasonable results and not cause a hydraulic jump.

5 Results and Discussion

5.1 Presentation of Results Qualitative Analysis

5.1.1 Sloped Midsection Simulations

The steady state, fixed bed hydrodynamic results, for all the test cases produce reasonable results and are shown in Appendix B. The flow in the test case with a steep slope has super critical flow that goes through a hydraulic jump to form subcritical flow. The other test cases have only subcritical flow.

When running the steep sloped midsection model with the Ackers & White, Bagnold, Meyer-Peter & Muller, and the Van Rijn method, the models exhibited instabilities or unrealistic results for all particle sizes. The instabilities are apparently caused by the presence of a hydraulic jump and the way these are presently being treated in the morphological code. The modeling of sediment transport on steep slopes is an ongoing area of research for the developers and further research will need to be done to learn the causes of the problem.

The results for all the moderate midsection models show oscillations after a certain run time if there is no filtering implemented. The bed smoothing procedures are an ongoing area of research for the TUFLOW developers and are frequently being updated. Most, but not all methods show similar results and only the Meyer-Peter & Muller results will be shown, for the complete results refer to the appendices.

The results for the moderate flume with and without bed smoothing using the Meyer-Peter & Muller method are shown in Figure 5-1 and Figure 5-2. All of the particle sizes show scouring at the knick-point that works its way upstream and shows deposition downstream of knick-point. The 0.08mm and 0.2mm particles in both figures show less scour than the larger particles which is not reasonable. This is due to how TUFLOW solves the Meyer-Peter & Muller method. As stated above, oscillations in the bed appeared partway through the run without bed smoothing due to harmonics (Johnson and Zyserman 2002). The smoothed results are comparable to Ipson (2006) and Brush et al (1960) which show scouring of the knick-point and deposition downstream of the break in slope. Figure 5-2 shows the finer particles moving farther downstream than the larger particles, Figure 5-3 does not. The TUFLOW developers need to investigate this change in results.

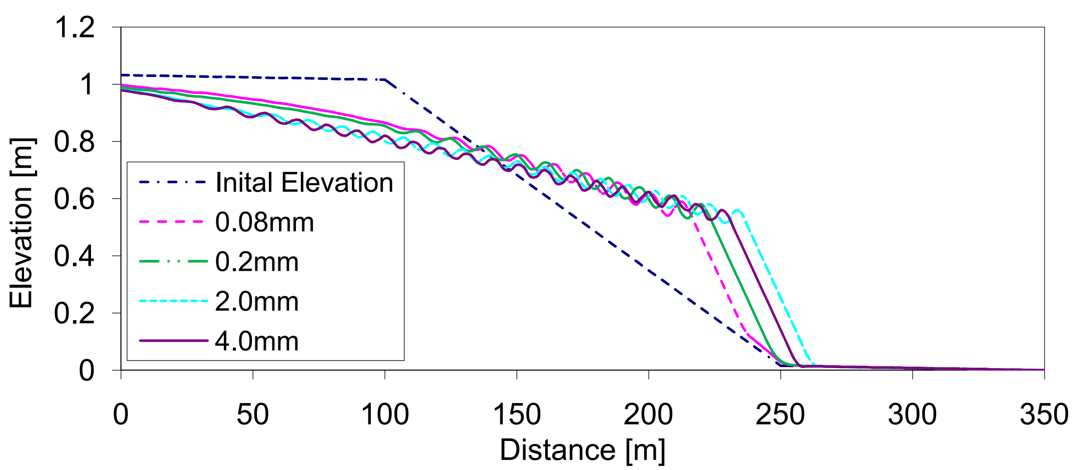

Figure 5-1: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW without Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

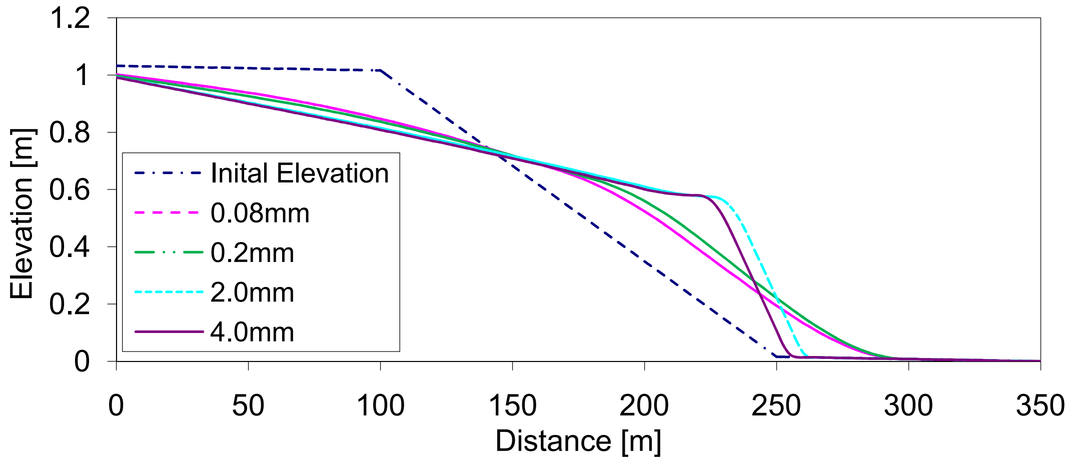

Figure 5-2: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW with Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Table 5-1 shows whether or not each test case finishes the hydrodynamic run, each morphology method finishes, there is reasonable scour, and reasonable deposition. Reasonable scour and deposition in Table 5-1 is based on the scour and deposition pattern relative to each different particle size.

5.1.2 Contraction Simulations

For the contraction simulations, the steady state, fixed bed hydrodynamic results, for all test cases show subcritical flow throughout the entire model. The depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and decelerates. All test cases except the short abrupt contraction produce reasonable hydrodynamic results. The short abrupt contractions results show the velocity after the contraction curved to one side of the flume which was not expected and was investigated further. The TUFLOW developers stated that the cause of this irregularity was due to the numerical solver. The developers are aware of this and are working on a solution. The short abrupt contraction test cases were still tested to give an idea of how sediment transport is handled.

Table 5-1: Results for the Sloped Midsection Test Cases with Bed Smoothing for each Morphology Method

Test Cases	Particle Size	Hydrodynamic Finished	Morphology Finished	Reasonable Scour	Reasonable Deposition
Shallow Midsection	0.08	Yes	A, B, M, V	A, B, V	A, B, M, V
	0.2	Yes	A, B, M, V	A, B, V	A, B, M, V
	2.0	Yes	A, B, M, V	A, M, V	A, M, V
	4.0	Yes	A, B, M, V	A,B, V	A, B, M, V
Moderate Midsection	0.08	Yes	B, M, V	B	B, M, V
	0.2	Yes	A, B, M, V	A, B, V	A, B, M, V
	2.0	Yes	A, B, M, V	A, B, M, V	A, B, M, V
	4.0	Yes	A, B, M, V	A, B, M, V	A, B, M, V
Steep Midsection	0.08	Yes			
	0.2	Yes			
	2.0	Yes			
	4.0	Yes			
Notes:	A= Ackers & White B= Bagnold M= Meyer-Peter & Muller V= Van Rijn				

As with the sloped midsection models only the Meyer-Peter & Muller method will be shown, for all results refer to appendix C. The results show that as the particle size increases, the location of scour remains constant, the location of deposition moves upstream and the magnitude of transport increases. The general shape of the regions of scour and deposition are reasonable when no bed smoothing is turned on and is shown in Figure 5-3. Some of the test cases show odd bed formations that can be seen in the plan view of the results found in Appendix C. They show a diagonal pattern that is not correct and needs to be addressed with the oscillations.

Once this option is enabled the scour and deposition patterns are an order of magnitude less than without smoothing and are shown in Figure 5-4. Most of the scouring in the test cases occurs along the center of the channel where the highest velocities are observed. Not all particle sizes had proper scour or deposition and need to be investigated further to understand whether it is a deficiency in the code or a limitation of the equation.

As with the midsection models, the results for some of the contraction test cases show oscillations or waves forming after a certain run time. The smoothing function removed all perturbations, but the scour and deposition was not reasonable. The results for the gradual contraction with and without smoothing using the Meyer-Peter& Muller method are shown in Figure 5-3 and 5-4. All particle sizes show a similar pattern of scour and deposition. The 0.08mm and 0.2mm particle sizes show less scour than the larger particle sizes which was not expected.

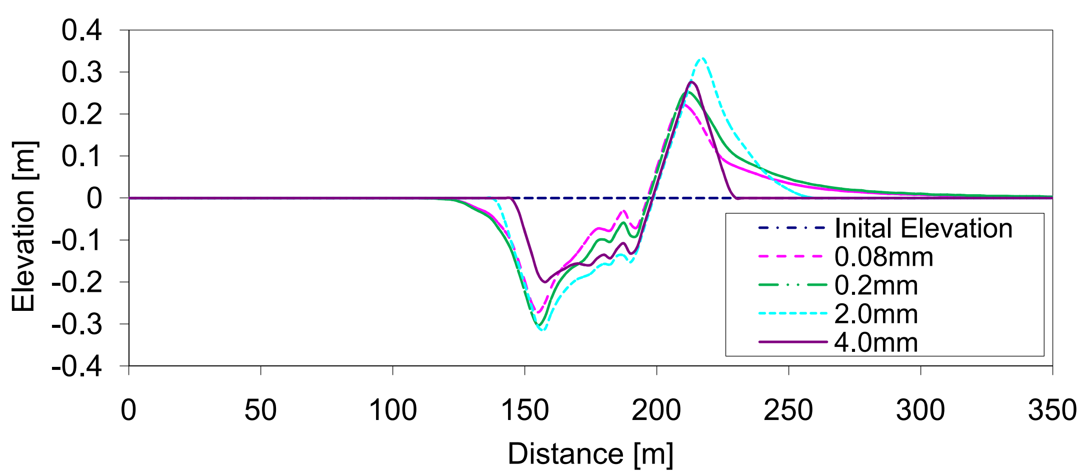

Figure 5-3: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case without Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

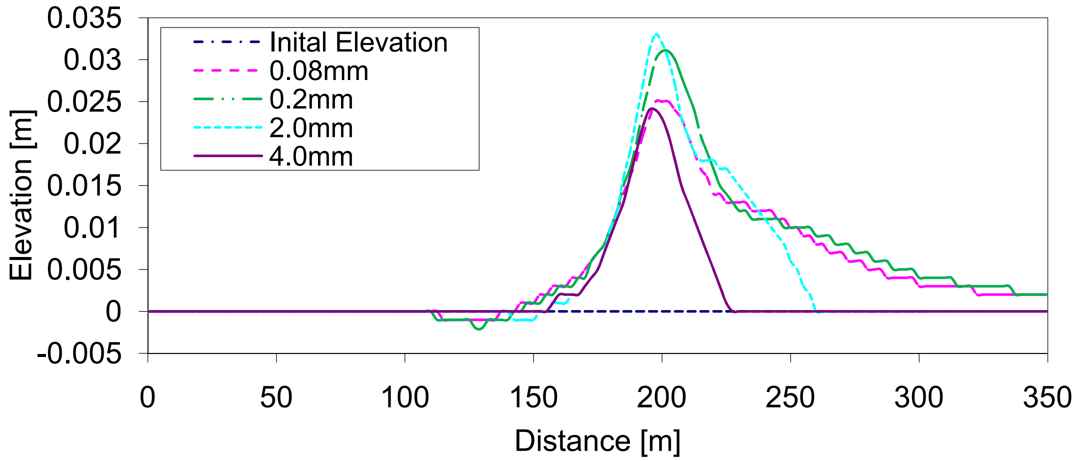

Figure 5-4: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case with Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Table 5-2 shows whether or not each contraction test case finishes the morphology method, the test case has oscillations, and is there reasonable scour and reasonable deposition.

5.2 Presentation of Results: Quantitative Analysis

This section provides comparisons between the results from TUFLOW and FESWMS. It also gives the results from the TUFLOW test cases built with data from previous research with laboratory flumes and comments on those results. The last test case in this section reviews the results from a TUFLOW simulation modeling the deposition of sediment at a river's entrance into a reservoir.

5.2.1 FESWMS

To help evaluate the sediment transport capabilities of TUFLOW, the test cases were compared to the results from FESWMS. The results illustrate that for most test cases the general pattern of scour is consistent with FESWMS, but FESWMS shows more deposition. Due to the results, the TUFLOW developers will need to verify they are calculating equilibrium transport and deposition correctly. The only two sediment transport methods TUFLOW and FESWMS have in common are Ackers & White and Meyer-Peter & Muller. Because of this, only these methods will be tested in FESWMS and compared to TUFLOW.

5-2: Results for the Contraction Test Cases without Bed Smoothing

Test Cases	Particle Size	Morphology Finished	Oscillations	Reasonable Scour	Reasonable Deposition
Gradual Contraction	0.08	A, B, M, V	A, B	A, B, V	A, B, M, V
	0.2	A, B, M, V	A, B, V	A, B	A, B, M
	2.0	A, B, M, V	A, B	B, M, V	B, V
	4.0	A, B, M, V	B	A, B, M, V	A, B, M
long Contraction	0.08	A, B, M, V	A, B	A, B, M	B, M, V
	0.2	A, B, M, V	B, M, V	A, B	A, B, M
	2.0	A, B, M, V	B	A, B, M	A, B, M, V
	4.0	A, B, M, V	B	A, B, M	A, B, M, V
Short Contraction	0.08	A, B, M, V	A, B, M, V	A, B	A, B, V
	0.2	A, B, M, V	A, B, M, V	A, B	A, B
	2.0	A, B, M, V	A, B, M, V	A, B, M, V	A, B, V
	4.0	A, B, M, V	A, B, M, V	A, B, M, V	A, B, V
Wide Flume Short Contraction	0.08	A, B, M, V		A, B	A, B, M
	0.2	A, B, M, V		A, B	A, B, M
	2.0	A, B, M, V	A	A, B, M, V	A, B, M, V
	4.0	A, B, M, V		A, B, M, V	A, B, M, V
River Model with Contraction	0.08	A, B, M, V	A, B, M, V	A, B	A, M, V
	0.2	A, B, M, V	A, B, M, V	A, B, V	A, M, V
	2.0	A, B, M, V	A, B, M, V	A, B, M, V	A, B, V
	4.0	A, B, M, V	A, B, M, V	A, B, M, V	A, B, M, V
Notes:	A= Ackers & White B= Bagnold M= Meyer-Peter & Muller V= Van Rijn				

Neither model successfully simulated the steep sloped midsection test case. Due to these instabilities this case was dropped. The Ackers & White method was unstable for all test cases in FESWMS and could not be compared. As with the previous section, not all test cases will be presented. Only the test cases that provide insight will be presented, for complete results refer to Appendix D.

Figure 5-5 shows the results for the 0.08mm particle size run for both TUFLOW and FESWMS. The scour of the knick-point for both models looks similar with scour stopping at the inflow boundary and reaching an equilibrium slope. FESWMS shows far more deposition than TUFLOW and transport rates need to be verified. Some of the contraction test cases using Meyer-Peter & Muller in FESWMS were either unstable or show deeper scour holes the larger the particle size and can be seen in Figure 5-6. Because of this, only the scour and deposition location could be compared.

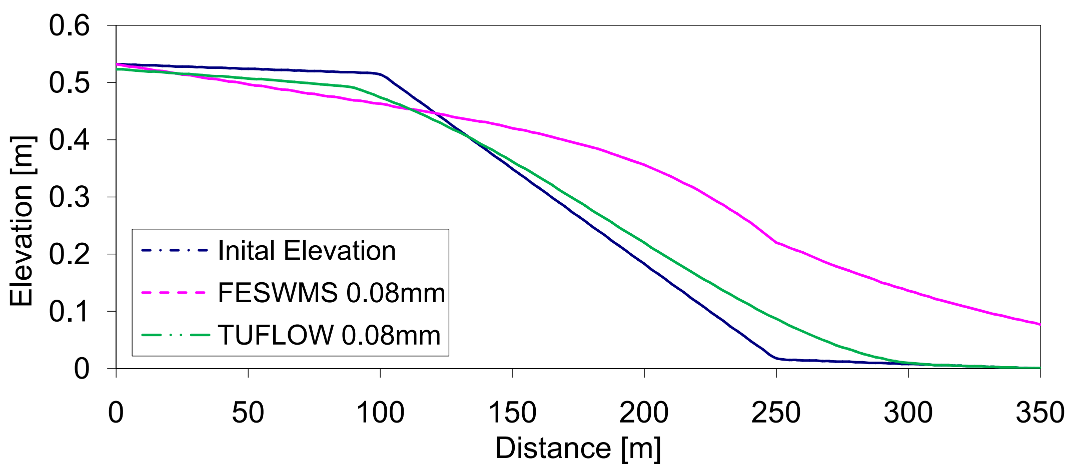

Figure 5-5: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

As with Ipson (2006), one of the main difficulties when modeling the small laboratory flumes was the size of the model. The small size of the grid cells cause the hydrodynamic runs to give unrealistic results with wide fluctuations in velocity and water surface elevation. Run time is another issue with the small grid cell sizes. The initial setup for the models creates run times of two weeks, which caused difficulties in correcting errors found in the model. Others have experienced difficulties in modeling small channels with small grid cell sizes (Barton 2001). An attempt was made to scale the flume to a larger size to determine if the results would be realistic and not have oscillations. The larger model did give reasonable results and smaller run times. While scaling the flumes could be done, it would not represent the actual conditions.

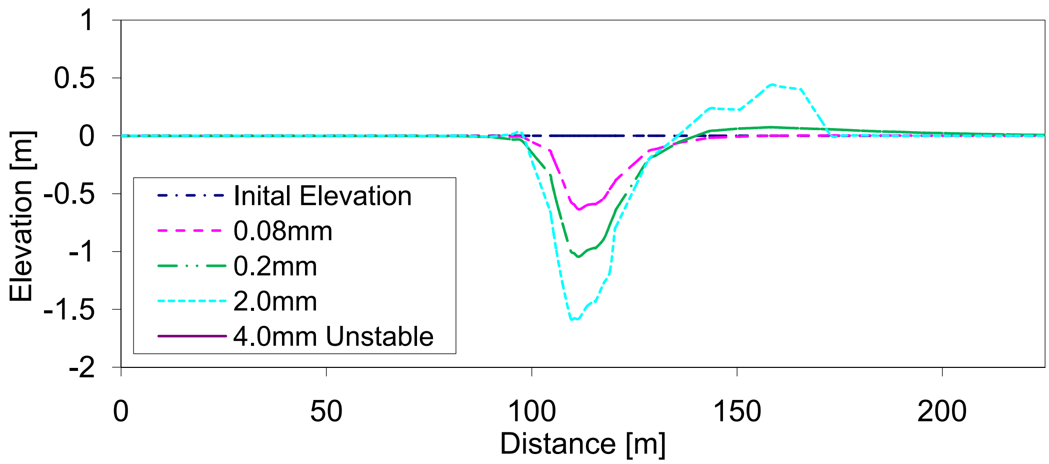

Figure 5-6: Initial and Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter and Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Another main difficulty was the limitation of the current functionality of the sediment capabilities in TUFLOW. The two laboratory flumes use sediment concentration as inflow rates. TUFLOW currently only allows equilibrium inflow of sediment. A solution to this was to replicate an inflow transport rate by applying an equilibrium flowrate to an extended sloped upstream addition to the flume as in Ipson (2006). Because of the limitations of TUFLOW, the exact laboratory conditions could not be replicated. The test cases did illustrate patterns of deposition that one would expect.

Because of the difficulties expressed above the narrow flume with downstream fining did not give valid results due to invalid hydrodynamic results. The wide flume with downstream fining only gave valid results for the Bagnold and Meyer-Peter & Muller sediment transport methods. The other two methods did not show any sediment transport which was initially thought to be due to size of particles. Adjusting particle size values within a valid range for the equations still gave no change in bed elevation. Only the Meyer-Peter & Muller method will be presented, for complete setup and results refer to Appendix C.

Figure 5-7 shows the change in bed elevation over time for the modified wide flume with downstream fining test case using the Meyer-Peter & Muller method for sediment transport. The pattern of deposition begins upstream the actual flume due to the decelerating velocity. The amount of deposition increases over time and extends downstream as expected. Due to the sediment inflow limitation, the model could not fully replicate actual conditions causing the results to differ. The observed data shows that more sediment was being added to the flume than the water could carry causing it to deposit where it was added.

5.2.2 Deposition into a Reservoir

The test case for the flume entering the reservoir completed all 180 days for the hydrodynamic run and each method of sediment transport. All of the test cases show similar results except the Ackers & White method. The Ackers & White method shows a delta forming with a sharper drop, which has similar results as Hotchkiss and Parker

(1991). The other methods do not show a sharp drop but show deposition in the correct area. Only the Meyer-Peter & Muller method will be presented below, for complete setup and results refer to Appendix E.

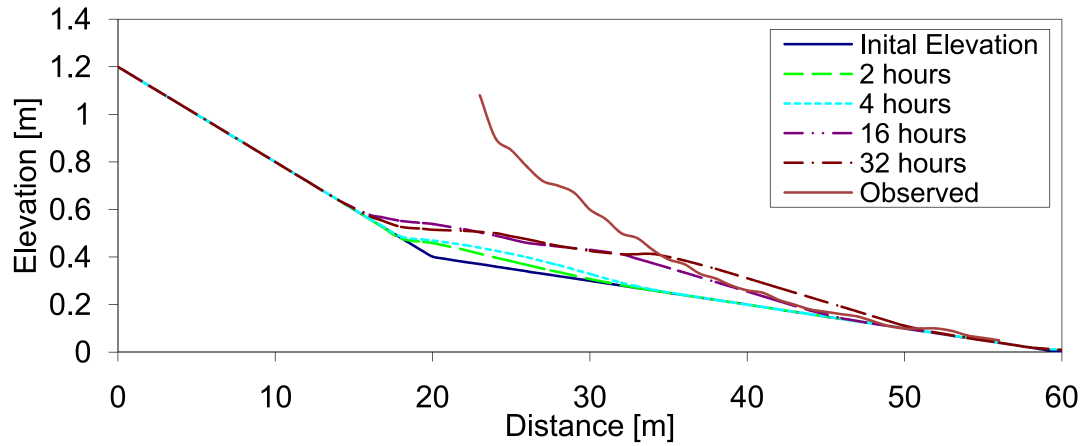

Figure 5-7: Centerline Profile and Plan View of the Final Elevations over a 48 Hour Simulation of the Wide Flume using the Meyer-Peter & Muller Method and Final Observed Elevation

Figure 5-8 shows the change in bed elevation over time for the deposition in a reservoir test case using the Meyer-Peter & Muller method for sediment transport. The pattern of deposition begins around the 142,000 m from the inflow boundary where the velocity begins to decelerate due to the backwater. The amount of deposition increases over time and extends downstream but does not form a delta as in Hotchkiss and Parker (1991).

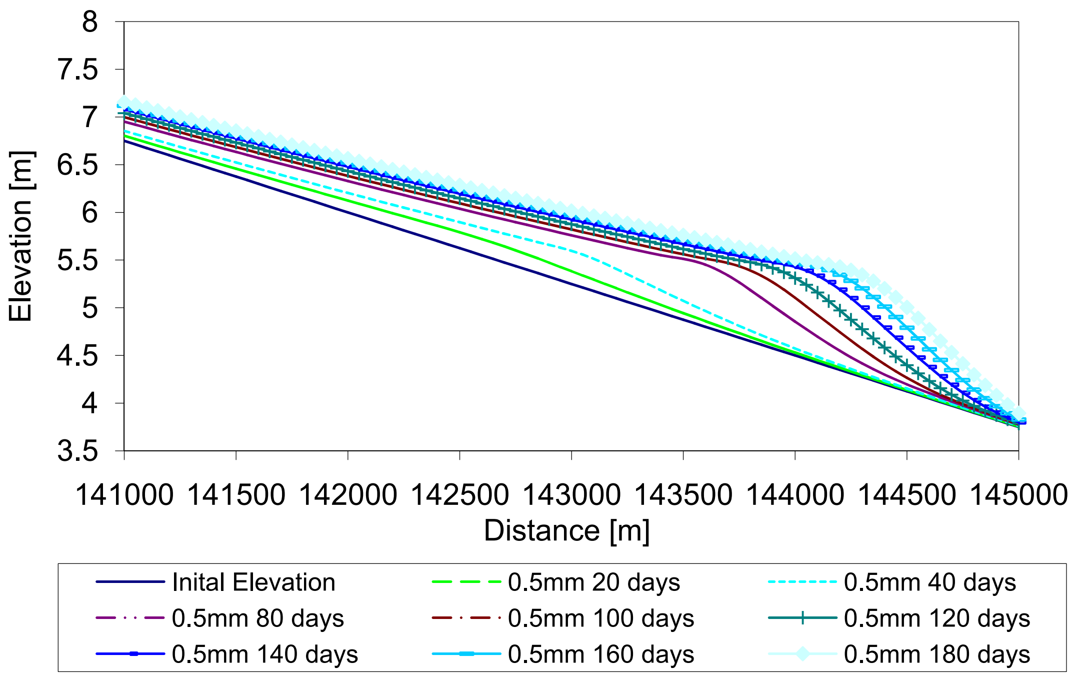

Figure 5-8: Profiles for Original Elevation, and Bed Elevations over 180 Days using the Meyer-Peter & Muller Method with Bed Smoothing

6 Conclusions

The following sections give an overview of the results and provide suggestions for possible future research of the sediment capabilities of TUFLOW.

6.1 Conclusions

At its present stage of development, TUFLOW shows reasonable results for models that have shallow to moderate slopes with subcritical flow. The steep slope models show that TUFLOW can handle supercritical flow with a hydraulic jump without a sediment transport method. The model also shows that once a sediment transport method is introduced when there is a hydraulic jump, difficulties can arise.

The results show that after certain models are run for a period of time, oscillations in the bed appear. This appears to be a computational artifact that may be resolved with a smoothing function in the numerical code (Johnson and Zyserman 2002). Further research is being done by the developers to fully understand the reason for oscillations and effective ways of handling them.

The results show that some of the contraction test cases form odd bed formations that have a diagonal pattern. The reason for this is unknown and needs to be investigated by the TUFLOW developers.

The results from the TUFLOW and FESWMS comparison show that all of sediment transport methods in TUFLOW run to completion and not all methods work in FESWMS. TUFLOW usually gives less deposition and both models need to be checked to see if the equilibrium inflow boundary condition is calculated correctly. Both have problems with scour in contractions with the 0.08mm and 0.2mm particle size, and both give more reasonable results the 2.0mm and 4.0mm particle sizes. Both models predicted similar shapes and locations of scour.

The laboratory flume test cases showed that TUFLOW has some difficulty in modeling laboratory flumes. One main difficulty for modeling the laboratory flumes includes TUFLOW giving unrealistic results due to size of grid cells. The other main difficulty was accurately representing conditions seen in the laboratory because of limited functionality of the sediment options in TUFLOW.

The test case for the flume representing deposition at the entrance of a reservoir only appropriately represented the formation of a delta due to backwater with the Ackers & White method. The other methods did not from deltas, but did show deposition in the location where flow decelerated.

6.2 Suggested Improvements for TUFLOW and Future Work

While many of the sediment transport options in TUFLOW are functional, the implementation of new sediment inflow options such as inflow concentrations or flow rates is needed. Other changes should be implemented to make TUFLOW more stable for models with smaller grid sizes and models with hydraulic jumps.

The files TUFLOW writes take large amounts of disk space which may be an issue. The developers could look into finding more efficient ways of writing files or different formats that would decrease the large size of the current files.

TUFLOW is still in the process of adding new equations and updates and the results from this research will help the TUFLOW developers find areas where TUFLOW can be improved. Once the updates are made, the tests should be undertaken again by the developers to see if the issues have been resolved. Other tests that are more complex should be undertaken once the simple test case problems are fixed to determine TUFLOW's full applicability. These tests should include more laboratory flumes and models of real world situations.

References

Ackers, P. White, W.R. "Sediment Transport: A New Approach and Analysis." *Journal of Hydraulics Division*, 1973: 2041-2060.

Bagnold, R. A. "An Approach to the Sediment Transport Problem from General Physics." *U. S. Geological Survey Professional Paper*, 1966: 422-I.

Barton, C. L. "Flow Through an Abrupt Constriction- 2D Hydrodynamic Model Performance and Influence of Spatial Resolution." Thesis, School of Environmental Engineering, Griffith University, 2001.

BMT-WBM Australia. *User's Manual for TUFLOW.* Spring Hill: WBM Oceanics Australia, 2008.

Brush, L. M., JR., and M. G. Wolman. "Knickpoint Behavior in Noncohesive material: A Laboratory Study." *Bulletin of the Geological Society of America* 41 (1960): 59-74.

Eysink, W. D. and H. Vermaas. "Computational Methods to Estimate the Sedimentation in Dredged Channels and Harbour Basins in Estuarine Environments." Coastal and Port Engineering in Developing Countries. Colombo, Sri Lanka, 1983.

Froehlich, D. C. *User's Manual for FESWMS FST2DH, Two-Dimensional Depth Averaged Flow and Sediment Transport Model.* U.S. Department of Transportation, McLean: Federal Highway Administration, 2003.

Hotchkiss, R. H. and Parker, G. "Shock Fitting of Aggradational Profiles Due to Backwater." *Journal of Hydraulic Engineering* 117, no. 9 (1991): 119-1144.

Ipson, M. "Analysis of the Sediment Transport Capabilities of FEWSMS FST2DH." Master Thesis, Department of Civil & Environmental Engineering, Brigham Young University, 2006.

Johnson, H. K. and J. A. Zyserman. "Controlling spatial oscillations in bed level update schemes." Coastal Engineering (2002): 109-126.

Meyer-Peter, E. and Muller, R. "Formulas for Bed-Load Transport." *Report on Second Meeting of IAHR.* Stockholm, Sweden, 1948. 39-64.

Rijn, V. L. C. *Principles of Sediment Transport in Rivers, Estuaries and Coastal seas.* The Netherlands: Aqua Publications, 1993.

Seal, R. Paola, C., Parker, G., Southard, J. B., and Wilcock, P. R. "Experiments on Downstream Fining of Gravel I: Narrow-Channel Runs." *Journal of Hydraulic Engineering* 124, no. 10 (1997): 874-884.

Stelling, G.S. *On the Construction of Computational Methods for Shallow Water Flow Problems.* Hague, Netherlands: Rijkswaterstaat Communications, 1984.

Toro-Escobar, C. M., Paola, C., Parker, G., Wilcock, P. R., and Southard, J.B. "Experiments on Downstream Fining of Gravel II: Wide and Sandy Runs." *Journal of Hydraulic Engineering* 126, no. 3 (2000): 198-208.

Wainwright, D.J., P. Vienot, and W.J. Syme. "Dynamic Modelling of the Impace of Entrance Scour on Flood Behaviour in Coastal Lakes and Estuaries." *NSW Coastal Conference.* 2004.

A List of Notations

A, C, m, and n = coefficients found in table 3-2

c_a= volumetric reference concentration

c_f = Coriolis force coefficient

D, D_{35}, and D_{50}=sediment diameter [L]

D_*= dimensionless grain diameter

D_m= arithmetic mean diameter [L]

EVA= dimensionless constant depending on sediment characteristics and the hydraulic conditions in the channel

e_b= bedload efficiency

e_s= suspended load efficiency

f_l = form (energy) loss coefficient

F= shape factor

F_{gr}= sediment mobility number

F_x and F_y = sum of the components of the external forces in X and Y directions

g= acceleration due to gravity [LT^{-2}]

h = depth of water [L]

k= total bed roughness [$L^{1/3}T^{-1}$]

k'= grain roughness [$L^{1/3}T^{-1}$]

n = Manning's n

p = atmospheric pressure [FL^2]

q_t= total sediment load [L^2T^{-1}]

q= flow [L^2T^{-1}]

$q_{deposit}$ = The deposition to the bed over distance x [FL^{-1}]

q_t= total transport rate of solids by dry mass per unit width $[FT^{-1}L^{-1}]$

q_{s1}, q_{s2} = volumetric total sediment transport rates in the X and Y directions $[L^3T^{-1}]$

q_b= bed load transport $[L^2L^{-1}]$

q_s= suspended load transport $[L^2T^{-1}]$

R= hydraulic radius [L]

s= specific density, $\bar{u}$= mean velocity $[LT^{-1}]$

S= slope

S_1= sediment transport into a control section $[FT^{-1}]$

S_2= equilibrium sediment transport potential within the control section $[FT^{-1}]$

T= dimensionless bed shear parameter

t = time [T]

u_*= shear velocity

$\bar{u}_s$= mean transport of suspended solid $[FT^{-1}L^{-1}]$

u and v = depth averaged velocity in the X and Y directions $[LT^{-1}]$

x and y = distance in X and Y direction [L]

z_b = bed elevation [L]

ω= stream power per unit boundary $[FT^{-1}L^{-1}]$

α= coefficient of solid friction

μ = horizontal diffusion of momentum coefficient

ρ = density of water $[ML^3]$

η = porosity

ν= kinematic viscosity coefficient $[L^2T^{-1}]$

γ_s= specific weight of solid $[FL^3]$

γ= specific weight of fluid $[FL^3]$

ζ = water surface elevation [L]

B Data Set Up

The remaining sections of this appendix describe the different test cases created for TUFLOW sediment transport analysis. Section B.1 outlines the basic input parameters needed for each method of sediment transport. Section B.2 details the flumes with varied midsection slopes and Section B.3 provides the parameters used to create flumes with different types of contractions. The flumes with varying slopes, widths, and input parameters all provide details about the current functionality of the sediment transport in TUFLOW. Section B.4 provides parameters for the river with a contraction test case found in the appendix of Ipson (2006). Section B.5 provides the input parameters for the models that are created in FESWMS and to be compared with TUFLOW. The last two sections (Section A.6 and Section A.7) give details about the test cases created from physical flume data and a test case built to examine the deposition of sediment water flows into a reservoir.

B.1 Input Parameters

Each sediment transport method uses different parameters for the model to run. The Ackers & White method needs only two input parameters to run in TUFLOW, the Nikuaradse roughness length “k” is used to determine shear stress and the D_{35} as the representative particle size.

The Bagnold method input parameters are D_{50}, D_{90}, bed load efficiency coefficient, suspended load efficiency coefficient, bedform length and height (for shear stress calculations), and fall velocity. The fall velocity is calculated the same way as the Van Rijn (1993) method and values shown in Table B-1. The bed load and suspended load efficiency is set to 0.15 and 0.015 for each run.

The Meyer-Peter & Muller method input parameters are roughness factor, D_{90}, and Dm. The roughness factor was set to 1, meaning that the total roughness is equal to the bed roughness.

The Van Rijn method uses D_{50}, D_{90}, fall velocity, current related roughness, reference level, ratio of sediment and fluid mixing. The fall velocity is calculated for each particle size from Van Rijn (1993) and is shown in Table B-1. The current related roughness and reference level is set to 0.05 m and 0.2 m respectively for each run.

Table B-1: Fall Velocity using Van Rijn (1993)

Particle Size [mm]	Fall Velocity [m/s]
0.08	0.00514
0.2	0.0238
2	0.198
4	0.280

The Eysink & Vermass deposition method is used for all test runs. There is only one parameter input for this method and it is the “EVA” coefficient. For the models in this study it was set to 0.00001, which will cause the most deposition.

B.2 Straight Flume with Varying Midsection Slopes

The velocity for the flatter upstream and downstream segments is selected to be 0.5 m/s, which would cause most of the sediment movement to happen around the more steeply sloped midsection. Parameters for the length, width, and depth are arbitrarily chosen, resulting in a flow rate of 12.6 cms and for a normal slope of 0.00016 for the upstream and downstream segments. The parameters for the different flumes are given below in Table B-2.

Table B-2: Parameters for Flumes with Varying Midsection Slopes

Parameter	Upstream and Downstream Segments
Flow rate [cms]	12.6
Width [m]	25.0
Downstream Depth [m]	1.0
Segment Length [m]	100.0
Manning's n	0.025
Grid Cell Size [m]	2.5
Time Step Length [s]	1
Total Length of Run [hr]	48.0

The slopes for the midsection of the three flumes were chosen to produce various water depths and velocities and are given in Table B-3 below. Each sloped midsection length is150 meters long and Figure B-1 shows a plot of the initial elevations for each of the three flumes.

Table B-3: Slopes for the Midsection Flumes

Flume	Slope [m/m]
Steep Midsection	0.0667
Moderate Midsection	0.0067
Shallow Midsection	0.0033

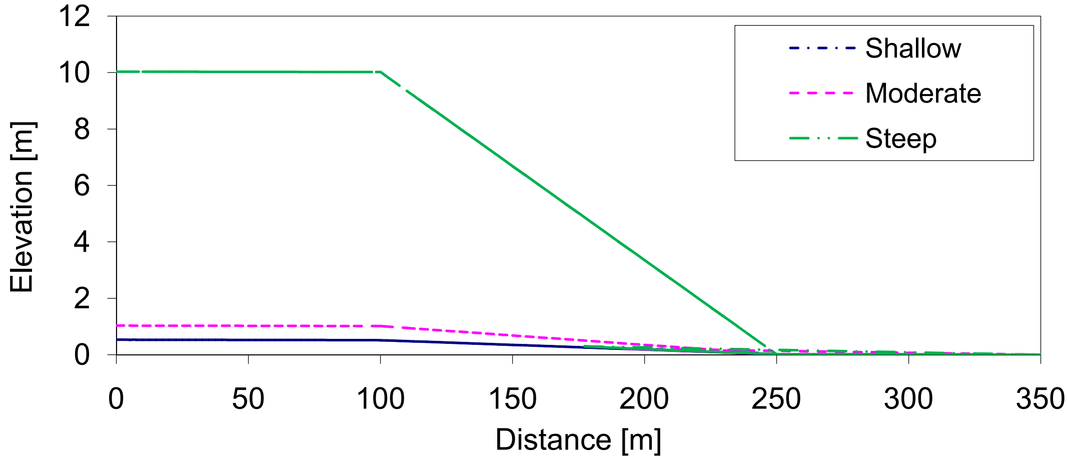

Figure B-1: Profile of the Three Flumes with Varying Midsection Slope

The flumes are set up to run for a 48 hour period with bed elevation changes written every 15 minutes with a 1 second time step. Each flume run was evaluated with particle grain size D50 and D90 equal to 0.08mm, 0.2mm, 2.0mm, and 4.0mm, respectively. The sizes were chosen to be within the range limits of the sediment transport methods.

B.3 Flumes with Contractions

The creation of four simple flumes with contractions allowed for further analysis of the sediment trends represented by TUFLOW when the width of a channel changed in different ways. All three flumes with contractions had 0% slope. The first flume contained a gradual contraction shown in Figure B-2. Its dimensions were chosen to match Ipson (2006). It had a total length of 350 meters and upstream and downstream widths of 30 meters. The contraction started 130 meters downstream from the inflow boundary. The narrowest portion measured 30 meters in length and 10 meters in width. The transitions to and from the contraction to the upstream and downstream widths of the channel each measured 30 meters in length. The parameters for the flume are given below in Table B-4.

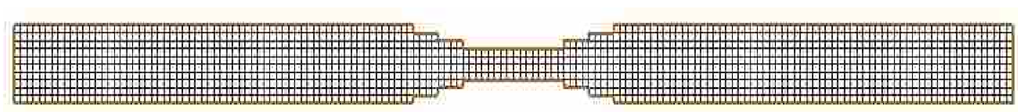

Figure B-2: Plan View of the Flume with a Gradual Contraction

Table B-4: Parameters for the Flume with a Gradual Contraction

Parameter	Upstream and Downstream Segments
Flowrate [cms]	12.6
Width [m]	25.0
Downstream Depth [m]	1.0
Cross-Sectional Area [m^2]	25.0
Segment Length [m]	130.0
Manning's n	0.025
Grid Cell Size [m]	2.5
Timestep Length [s]	1
Total Length of Run [hr]	48.0

The second set of test cases for contractions, modeled a flume with a long abrupt contraction. This flume followed the same general description as the one described above, except that the contraction began and ended abruptly. The parameters given above in Table B-4 applied to this set of test cases in addition to those of the flume with a gradual contraction. Figure B-3 provides a plan view of the flume with a long abrupt contraction.

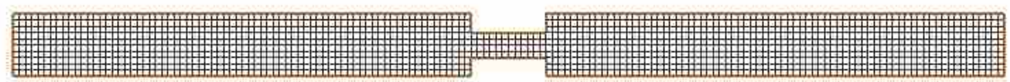

Figure B-3: Plan View of the Flume with a Long Abrupt Contraction

The third set of test cases for a flume with a contraction, modeled a channel that contained a short abrupt contraction, similar to a bridge contraction. The test case for the flume with an abrupt contraction represented a hypothetical channel. The flowrate, depth, and widths for the main channel and the contraction, and other related parameters were again chosen arbitrarily with the intent of providing a reasonable velocity of 0.5 m/s both upstream and downstream of the contraction. Table B-5 lists the main parameters applied to this test case and Figure B-4 provides a plan view of the flume with a short, abrupt contraction.

The fourth set of test cases for a flume with a contraction, modeled a wide channel that contained an abrupt contraction, similar to a bridge contraction. The test case for the flume with an abrupt contraction represented a hypothetical channel. The flowrate, depth, widths for the main channel and the contraction, and other related parameters were again chosen arbitrarily with the intent of providing a reasonable velocity of 0.5 m/s both upstream and downstream of the contraction. Table B-6 lists the main parameters applied to this test case and Figure B-5 provides a plan view of the wide flume with an abrupt contraction.

Table B-5: Parameters for a Flume with a Short Abrupt Contraction

Parameter	Upstream and Downstream Segment	Contraction
Flowrate [cms]	12.5	--
Width [m]	25.0	5.0
Downstream Depth [m]	1.0	--
Cross-Sectional Area [m^2]	25.0	--
Segment Length [m]	107.5	10.0
Manning's n	0.025	0.025
Grid Cell Size [m]	2.5	2.5
Timestep Length [s]	1.0	1.0
Total Length of Run [hr]	48.0	48.0

Table B-6: Parameters for a Wide Flume with an Abrupt Contraction

Parameter	Upstream and Downstream Segment	Contraction
Flowrate [cms]	1000.0	--
Width [m]	500.0	100.0
Downstream Depth [m]	4.0	--
Cross-Sectional Area [m^2]	2000.0	--
Segment Length [m]	2412.0	176.0
Manning's n	0.025	0.025
Grid Cell Size [m]	10.0	10.0
Timestep Length [s]	5.0	5.0
Total Length of Run [hr]	48.0	48.0

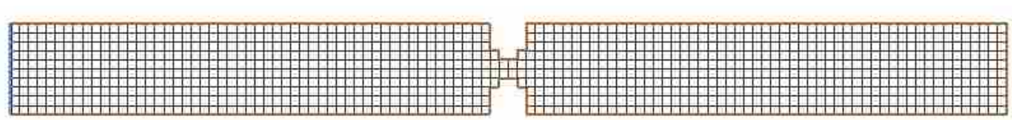

Figure B-4: Plan View of the Flume with a Short Abrupt Contraction

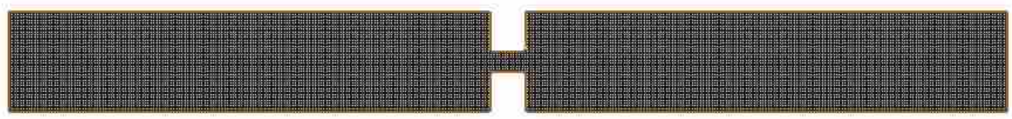

Figure B-5: Plan View of the Wide Flume with an Abrupt Contraction

B.4 River with a Contraction

A Simple river model with a contraction in the middle representing a highway crossing is created and is based on a sediment transport model found in the appendix of Ipson (2006). The purpose of the models is to test how well TUFLOW handles sediment transport in a river model. The flowrate, depth, widths for the main channel and the contraction, and other related parameters were again chosen to match Ipson (2006). Table B-7 lists the main parameters applied to this test case and Figure B-6 provides a plan view of the wide flume with an abrupt contraction.

B.5 FESWMS

The research included setting up the test cases found in sections B.1, B.2, and B.3 in FESWMS and comparing them to the TUFLOW results. Because FESWMS offered only two of the same methods for sediment transport, Ackers & White and Meyer-Peter & Muller, only these methods will be compared. Each Program has different input options which caused the sediment simulations to differ slightly. The input parameters for FESWMS were chosen to best replicate the conditions that existed in TUFLOW.

Table B-7: Parameters for the River with a Contraction

Parameter	Upstream and Downstream Segment	Contraction
Flowrate [cms]	60.0	--
Width [m]	--	23.0
Downstream Depth [m]	1.7	--
Manning's n	0.025	0.025
Grid Cell Size [m]	2.5	2.5
Timestep Length [s]	1.0	1.0
Total Length of Run [hr]	48.0	48.0

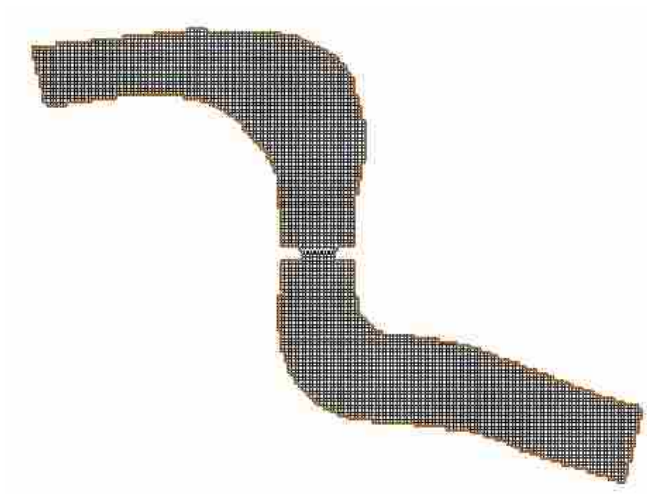

Figure B-6: Plan View of the River with a Contraction

B.6 Laboratory Models

The research included two model runs based on data given for previous sediment transport research completed with laboratory flumes. The small sizes of the flume in the experiments are not ideal for TUFLOW and presented difficulties in setting up the models and are shown in Figures 5-7 and 5-8. The test cases included the following TUFLOW models found in articles describing previous research:

- A narrow flume demonstrating downstream fining (Seal et al. 1997)
- A wide flume demonstrating downstream fining (Toro-Escobar et al. 2000)

The flowrate, depth, widths for the flumes, and other related parameters were chosen to match their respective papers. Tables B-8 and B-9 lists the main parameters applied to the test cases.

B.1 Deposition in a Reservoir

The final test case is based on a journal article by Hotchkiss and Parker (1991), which describes how aggradation occurs due to backwater when a dam is placed across a river. The test case matches Ipson (2006) and parameters found in table B-10. The test case had a slope of 0.00075 m/m, and an upstream normal depth of 1.44 meters

Table B-8: Parameters for the Seal Flume

Parameter	Values
Flowrate [cms]	0.049
Width [m]	0.3
Downstream Depth [m]	0.9
Length [m]	48.5
Manning's n	0.009
Grid Cell Size [m]	0.3
Timestep Length [s]	0.1
Total Length of Run [hr]	32.5

Table B-9: Parameters for the Toro-Escobar Flume

Parameter	Values
Flowrate [cms]	0.11
Width [m]	2.7
Downstream Depth [m]	0.45
Length [m]	40.0
Manning's n	0.025
Grid Cell Size [m]	2.7
Timestep Length [s]	1.0
Total Length of Run [hr]	32.5

Table B-10: Parameters for the Flume Showing Deposition at the Entrance to a Reservoir

Parameter	Values
Flowrate [cms]	604.0
Width [m]	300.0
Downstream Depth [m]	7.0
Length [m]	150000
Manning's n	0.025
Grid Cell Size [m]	50.0
Timestep Length [s]	10.0
Total Length of Run [days]	180.0

C QUALITATIVE RESULTS

The purposes of this report include identifying the areas of functionality within the sediment transport portion of TUFLOW and determining the accuracy of the model in representing the movement of sediment. This chapter provides and interprets the sediment results from TUFLOW for each of the test cases. The next Appendix of this report gives a comparison of results from TUFLOW to FESWMS and also explains the sediment results from TUFLOW models of real laboratory flumes.

C.1 Varying Midsection Slopes

C.1.1 Steep Midsection Slope

The steep midsection steady state hydrodynamic solution produces supercritical flow conditions followed by a hydraulic jump at the downstream section. The results of the hydrodynamic run are similar to Ipson (2006) and are shown in Figure C-1.

When running the model with the Ackers & White, Bagnold, Meyer-Peter & Muller, and the Van Rijn method, the models exhibited instabilities or unrealistic results with all of the different particle sizes. The instabilities are apparently caused by the presence of a hydraulic jump and the way these are presently being treated in the morphological code. The modeling of sediment transport on steep slopes is an ongoing area of research for the developers.

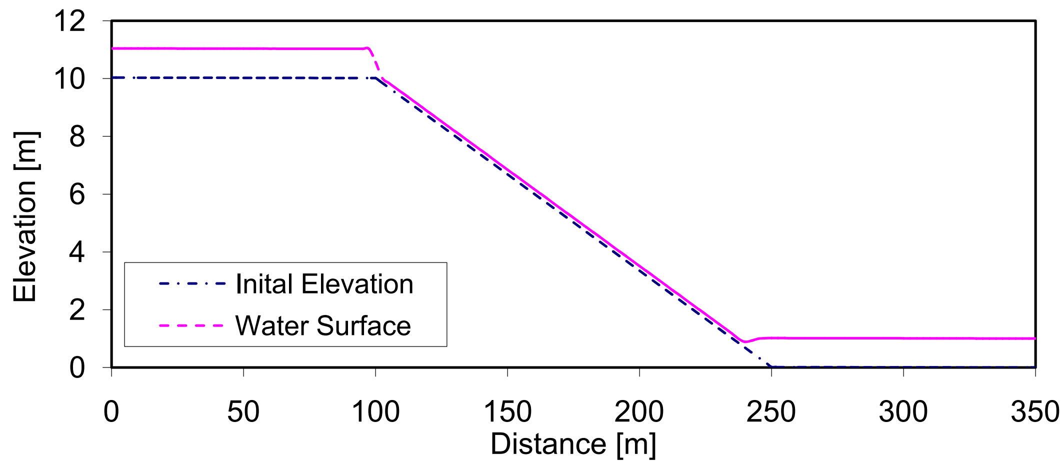

Figure C-1: Initial Bed Elevation and Water Surface for a Flume with a Steep Midsection Slope

C.1.2 Moderate Midsection Slope

The steady state hydrodynamic results show sub critical flow throughout the entire model and is reasonable and is shown in Figure C-2. The solution shows that the flow remains subcritical throughout the entire channel and a backwater curve extends up beyond the inflow boundary.

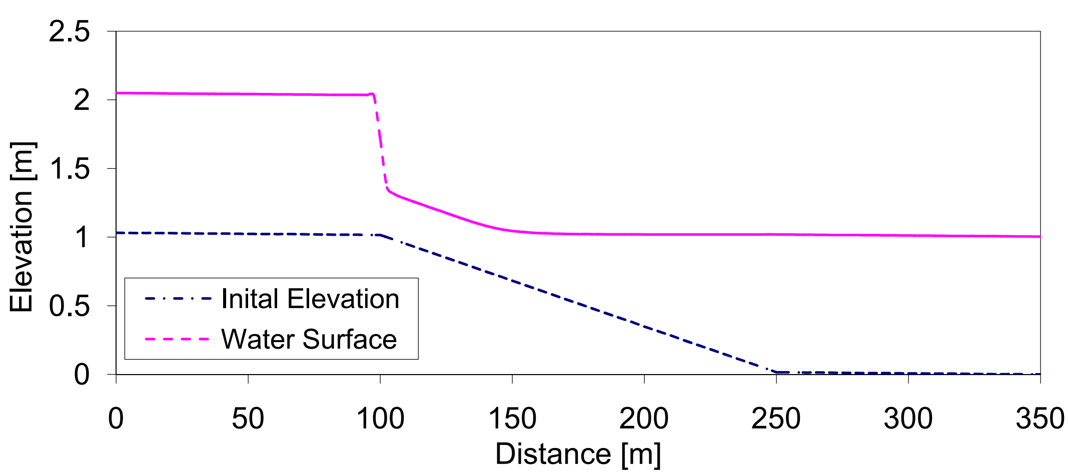

Figure C-2: Initial Bed Elevation and Water Surface for a Flume with a Moderate Midsection Slope

The results for the moderate flume for all methods are shown in Figure C-3, C-4, C-5, and C-6. All of the test cases ran to completion except the 0.08mm Ackers & White test case. The test cases show scouring that starts at the knick point and works its way upstream with deposition downstream. The test cases are comparable to Ipson (2006) and Brush et al (1960) which show scour upstream and deposition downstream.

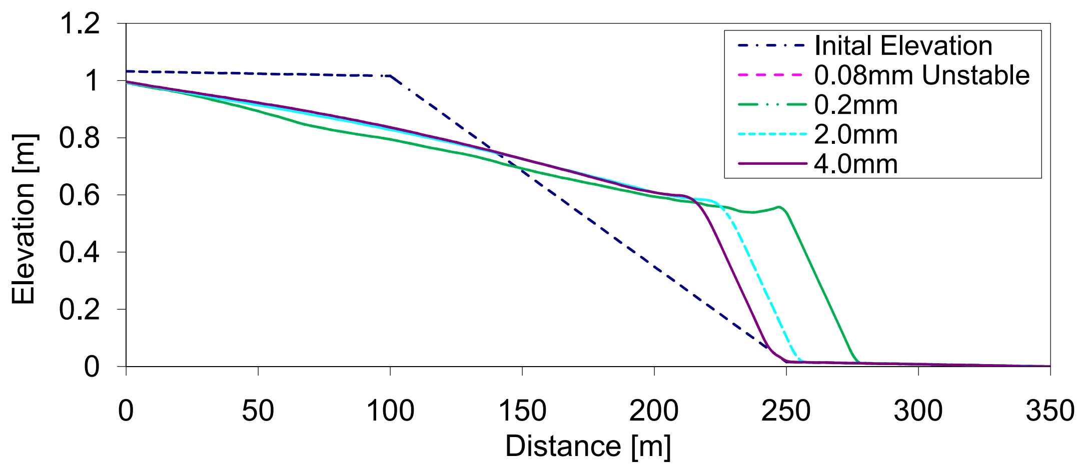

Figure C-3: Initial and Final Bed Elevations using Ackers & White for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW with Bed Smoothing using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

C.1.1 Shallow Midsection Slope

The steady state hydrodynamic results show subcritical flow throughout the entire mode, is reasonable, and is shown in Figure C-7. The solution shows that the flow remains subcritical throughout the entire channel and a backwater curve extends up beyond the inflow boundary.

The results for the shallow for all methods are shown in Figure C-8, C-9, C-10, and C-11. All test cases ran to completion with sediment transport and produced results similar to those of the moderate midsection test case. Scouring for each of the test cases began at the break in slope and progressed upstream while depositing downstream. The results for all of the particle sizes are comparable to Brush et al (1960), which show scour upstream of knick point and deposition downstream. The Bagnold 2.0mm test case shows less scour than the 4.0mm which is not reasonable.

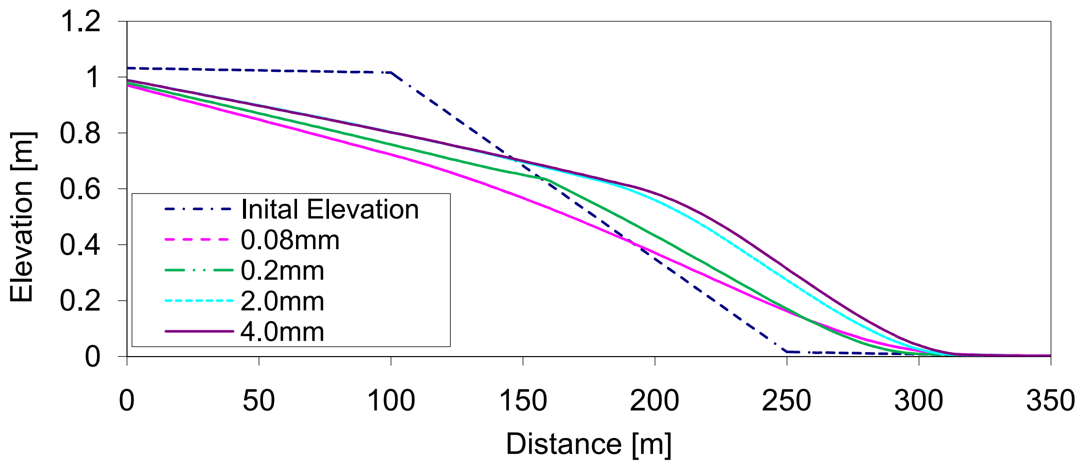

Figure C-4: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW with Bed Smoothing using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

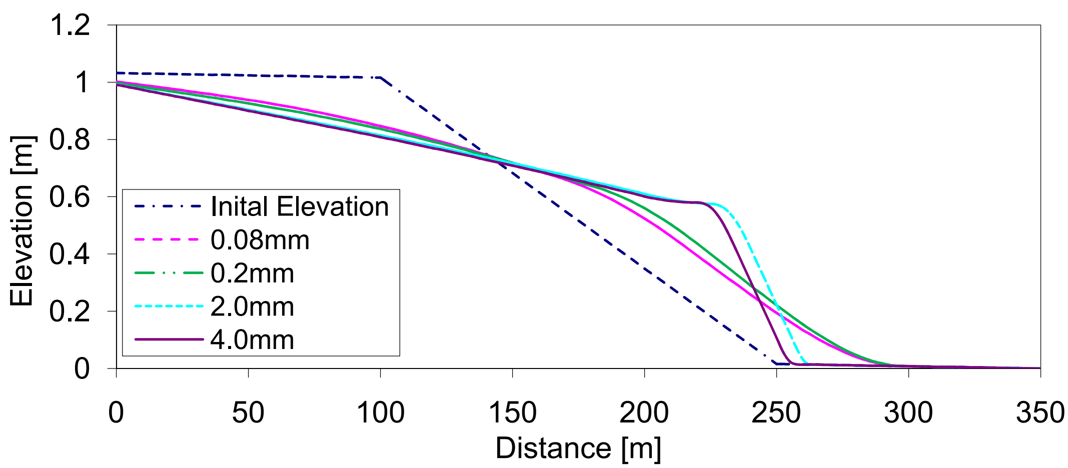

Figure C-5: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW with Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

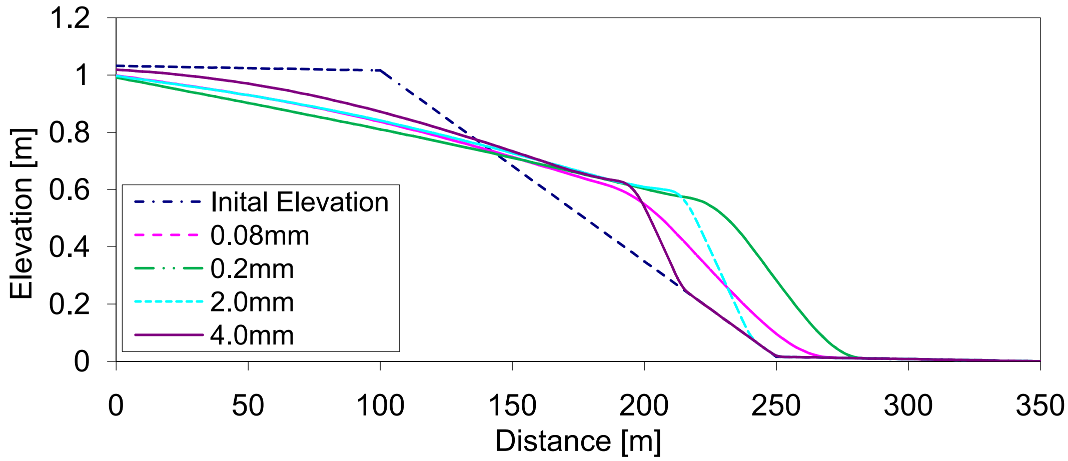

Figure C-6: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume in TUFLOW with Bed Smoothing using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

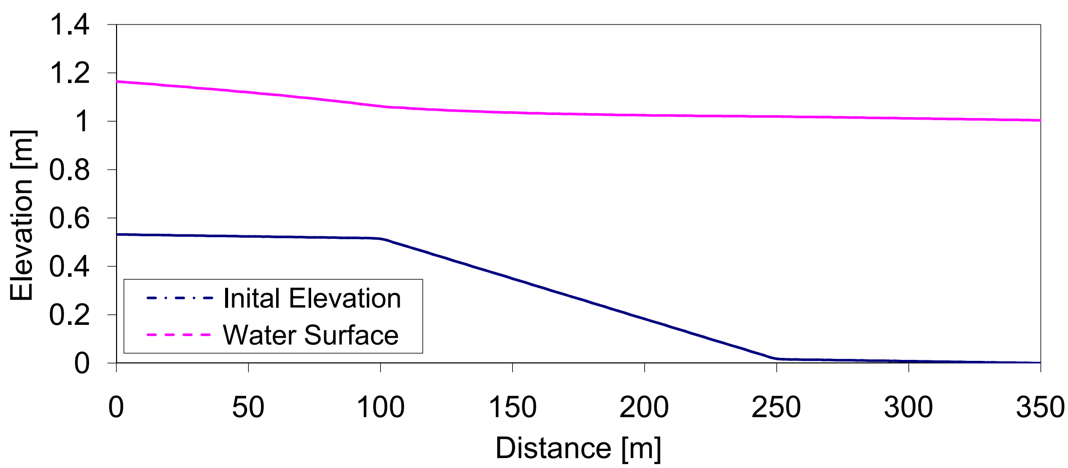

Figure C-7: Initial Bed Elevation and Water Surface for a Flume with a Shallow Midsection Slope

C.1 Flumes with Contractions

C.1.1 Gradual Contraction

The steady state hydrodynamic results show subcritical flow throughout the entire model are reasonable and are shown in Figure C-12, C-13, C-14, and C-15. The depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and slows down.

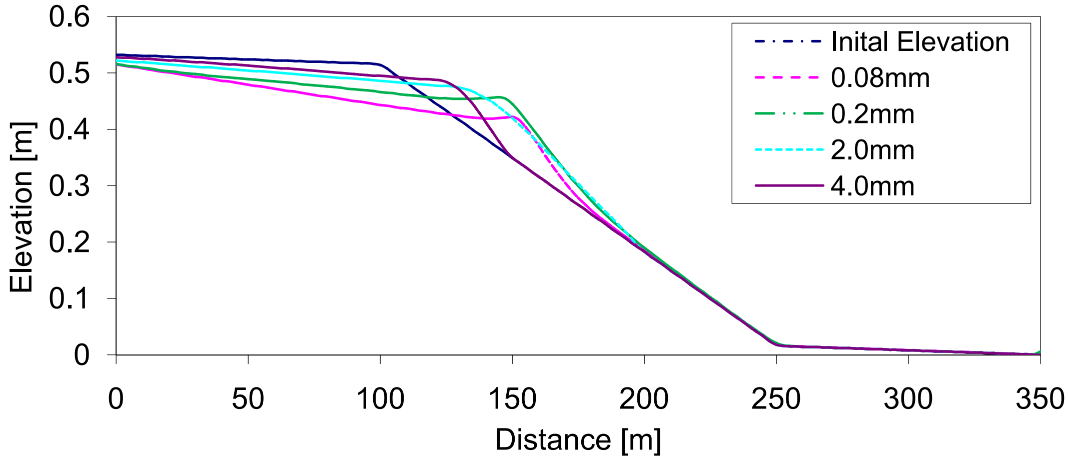

Figure C-8: Initial and Final Bed Elevations using for a 48 Hour Simulation of the Shallow Midsection Slope Flume in TUFLOW with Bed Smoothing using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

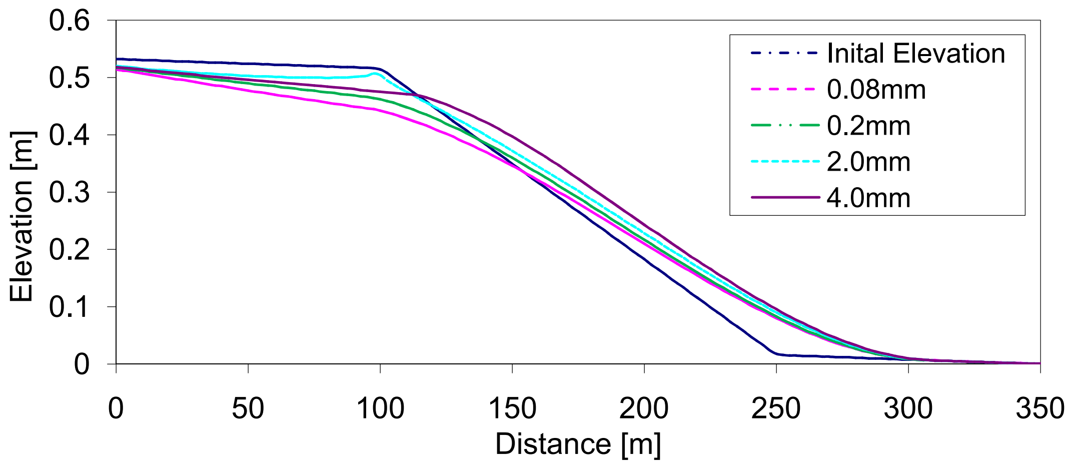

Figure C-9: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume in TUFLOW with Bed Smoothing using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

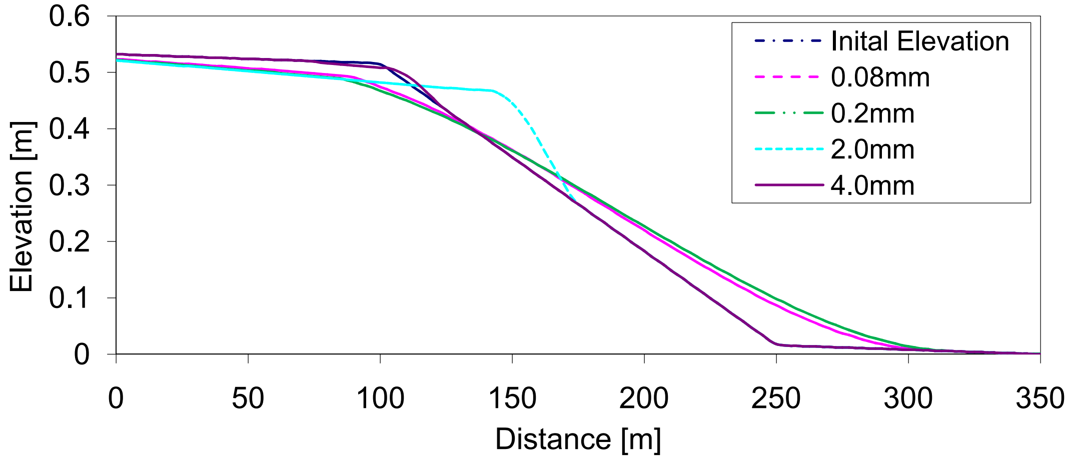

Figure C-10: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume in TUFLOW with Bed Smoothing using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

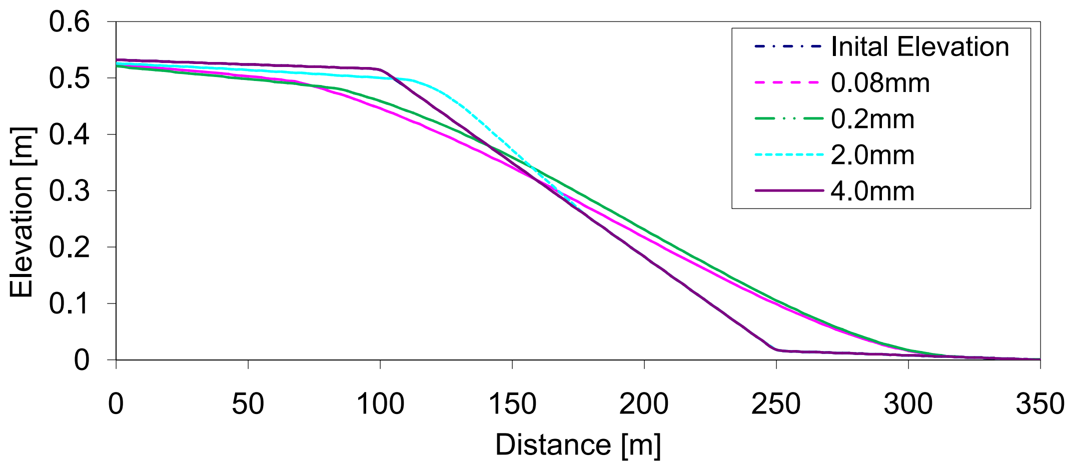

Figure C-11: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume in TUFLOW with Bed Smoothing using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

The results show that as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases. The general shape of the regions of scour and deposition appear to be valid. Most of the scouring happens along the center of the channel where the highest velocities are observed.

As with the midsection model, the results for some of the contraction models show oscillations after a certain run time. When bed smoothing was implemented to remove the oscillations, the results became unrealistic. The results shown below are the models without bed smoothing. Some of the results show odd bed formations in a diagonal pattern and needs to be investigated by the developers.

The results for all of the test cases are shown in Figure C-16 through C-23. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the contraction and progressed downstream until depositing downstream of the contraction.

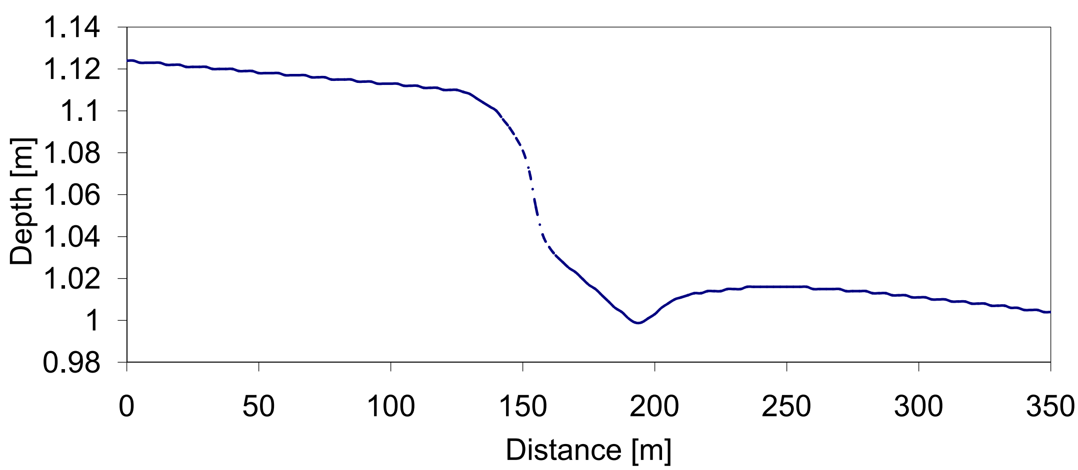

Figure C-12: Steady-State Solution for Water Depth in the Flume with a Gradual Contraction

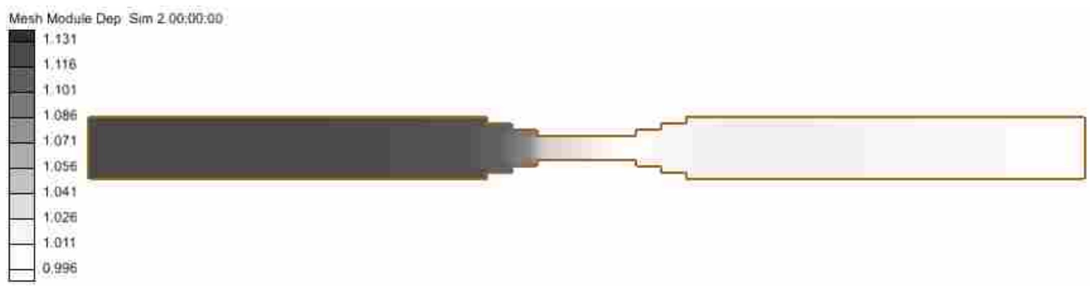

Figure C-13: Plan View of Steady-State Solution for Water Depth in the Flume with a Gradual Contraction

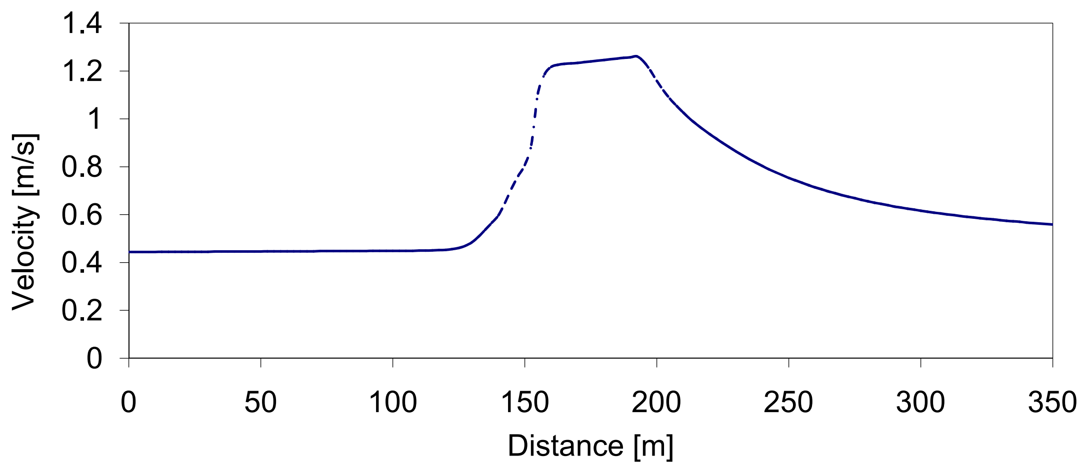

Figure C-14: Steady-State Solution for Velocity Magnitude for the Flume with a Gradual Contraction

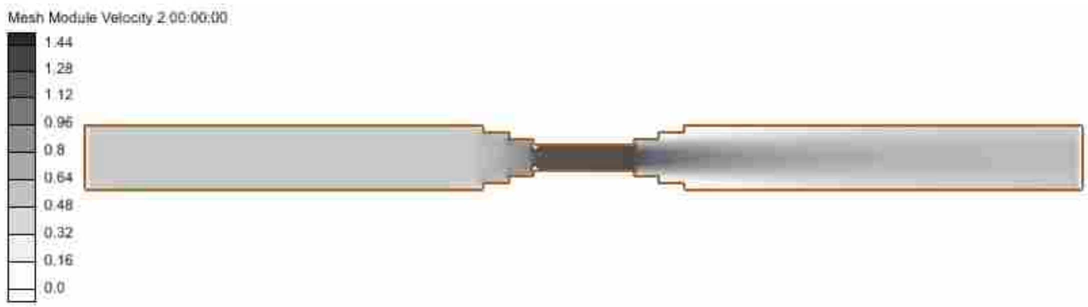

Figure C-15: Plan View of Steady-State Solution for Velocity Magnitude for the Flume with a Gradual Contraction

Each particle size shows a similar pattern of scour and deposition. The results show that as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases. The results show that some sediment transport methods create oscillations.

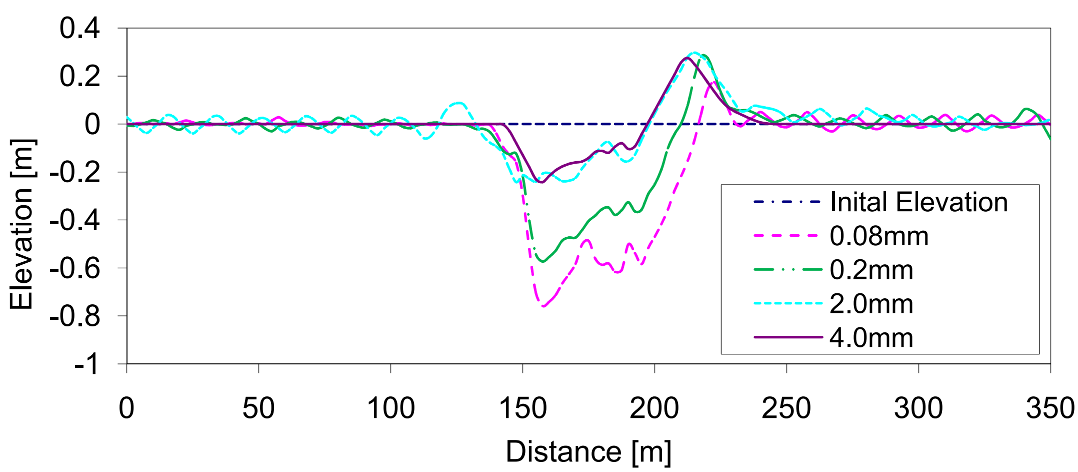

Figure C-16: Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

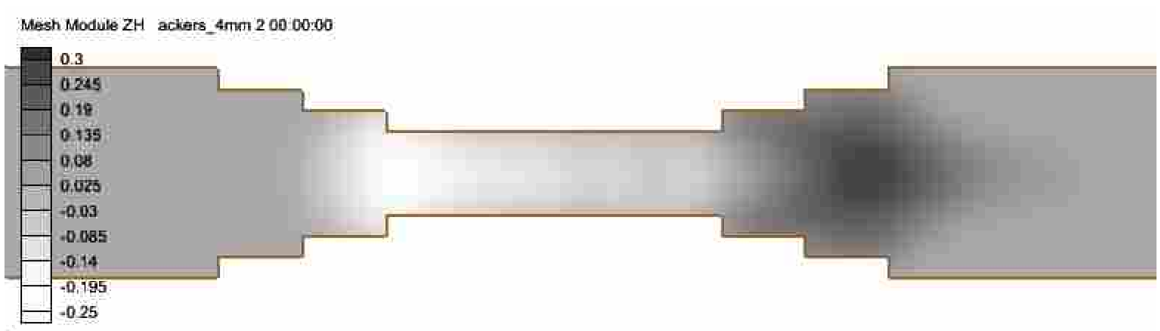

Figure C-17: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Ackers & White Method with the 4.0mm Particle Size

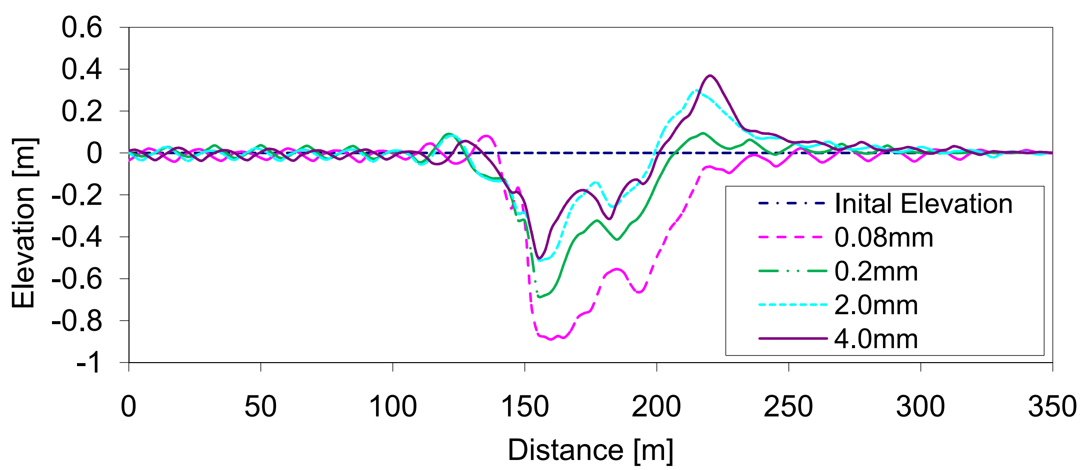

Figure C-18: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

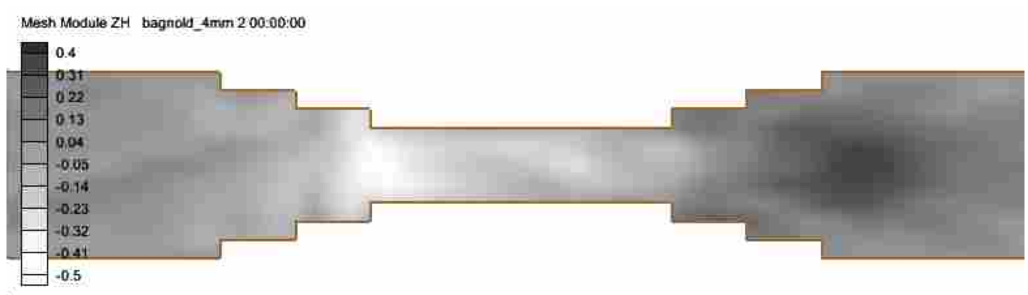

Figure C-19: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Bagnold Method with the 4.0mm Particle Size

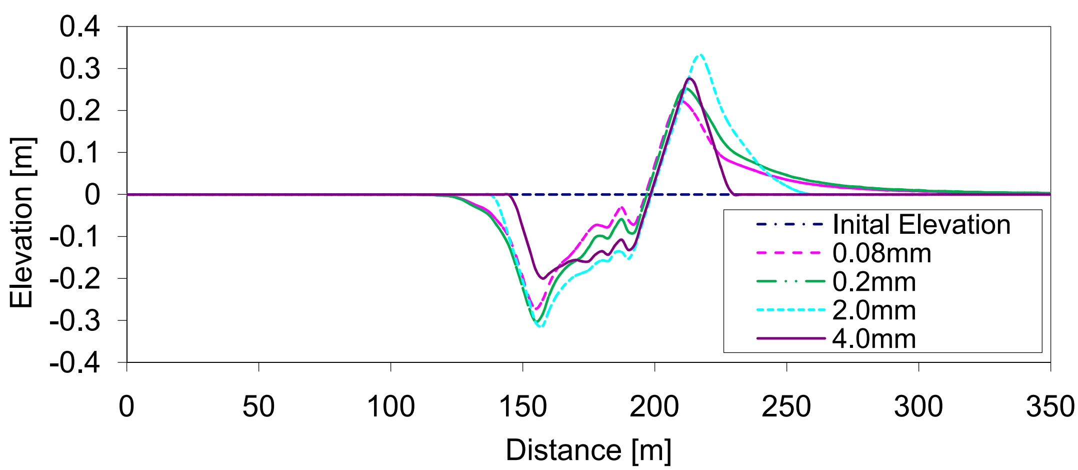

Figure C-20: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

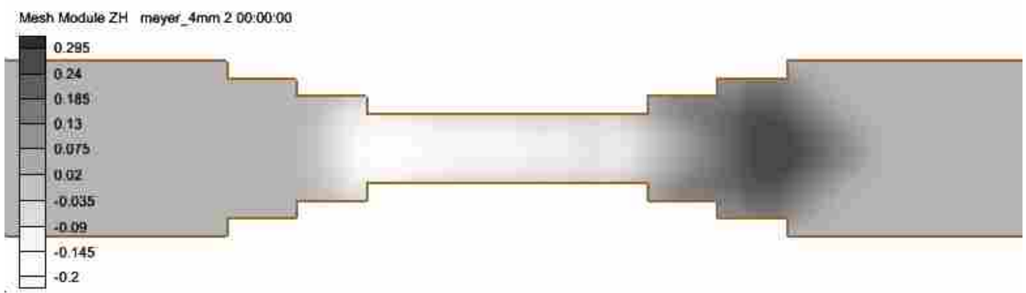

Figure C-21: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Meyer-Peter & Muller Method with the 4.0mm Particle Size

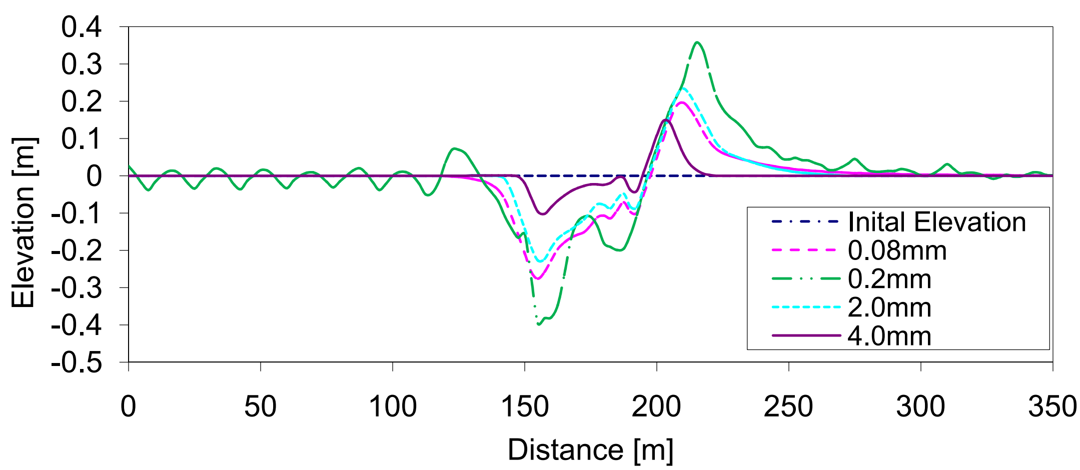

Figure C-22: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

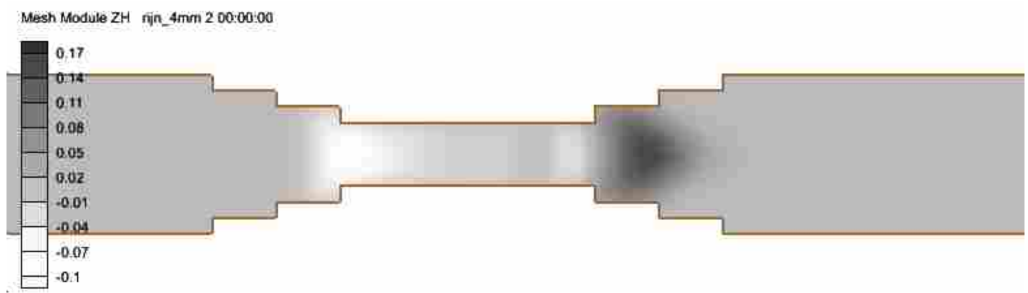

Figure C-23: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Van Rijn Method with the 4.0mm Particle Size

C.1.2 Long Abrupt Contraction

The steady state hydrodynamic results show subcritical flow throughout the entire model is reasonable and are shown in Figure C-24 through C-27. As with the gradual contraction, the depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and slows down. The velocities upstream and downstream are quite small compared to the max velocity of 1.55 cfs in the contraction.

As with the gradual contraction test cases, the results show that as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases. The general shape of the regions of scour and deposition appear to be valid. Most of the scouring happens along the center of the channel where the highest velocities are observed.

The long abrupt test cases predict two main locations of scour within the contraction. The first scour hole is near the beginning of the contraction, extends slightly upstream, and is contained mostly in the center of the channel. The second location occurs near the end of the contraction. Some of the results show odd bed formations in a diagonal pattern and needs to be investigated by the developers.

As with the gradual contraction test cases, the results for some of the contraction models show oscillations after a certain run time and bed smoothing gave unrealistic results.

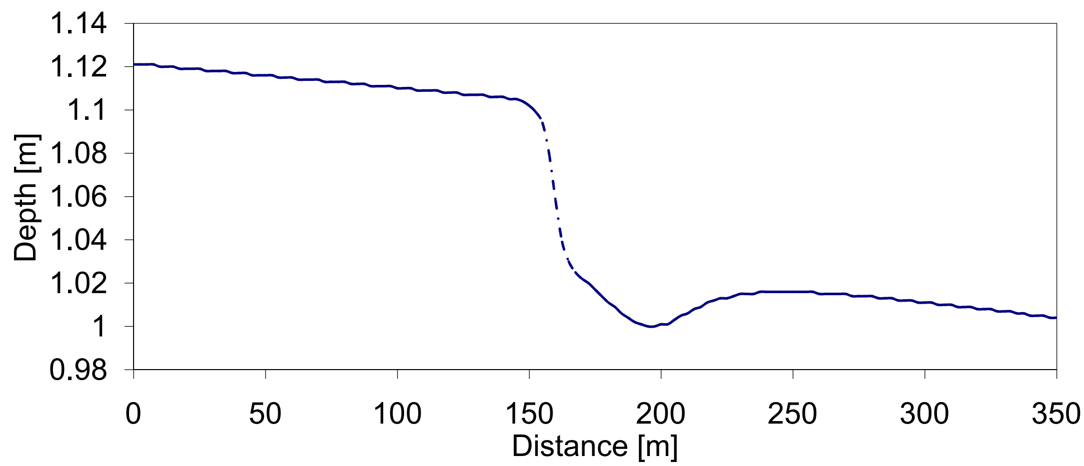

Figure C-24: Steady-State Solution for Water Depth in the Flume with a Long Abrupt Contraction

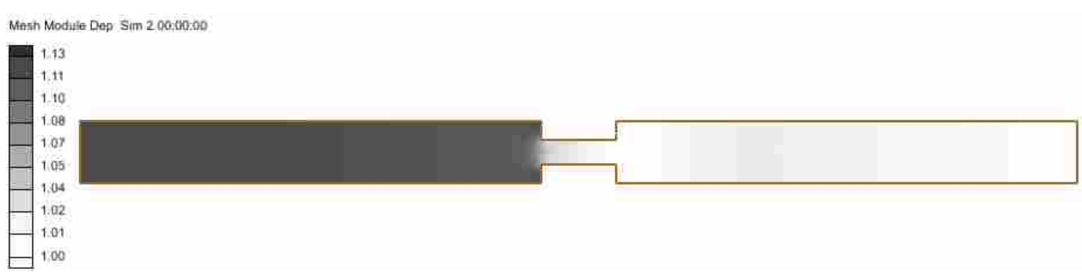

Figure C-25: Plan View of Steady-State Solution for Water Depth in the Flume with a Long Abrupt Contraction

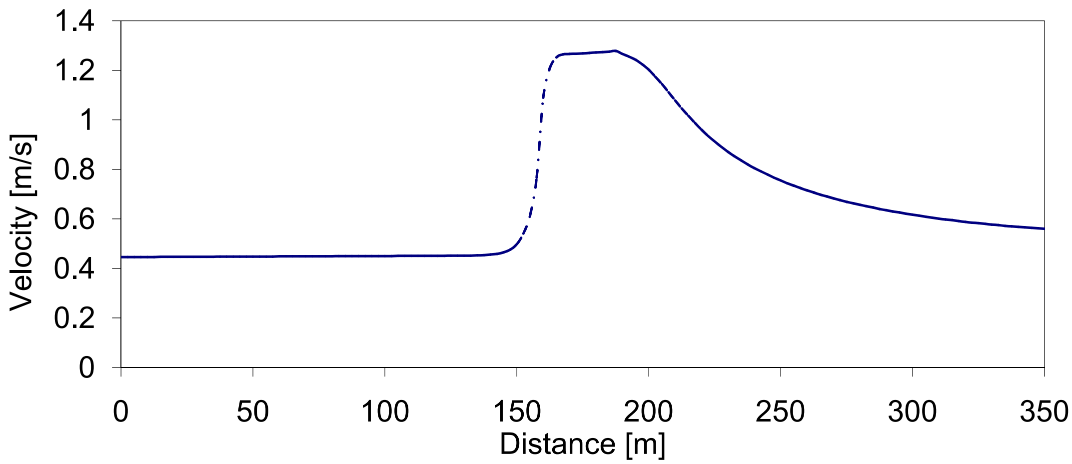

Figure C-26: Steady-State Solution for Velocity Magnitude for the Flume with a Long Abrupt Contraction

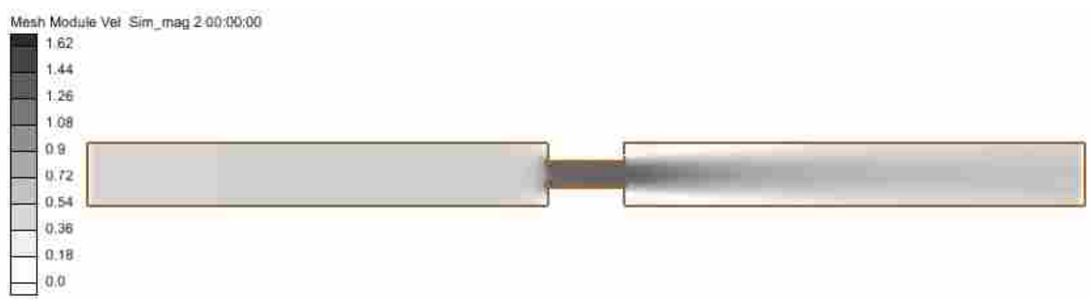

Figure C-27: Steady-State Solution for Velocity Magnitude for the Flume with a Long Abrupt Contraction

The results for the all the test cases are shown in Figures C-28 through C-35. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the contraction and progressed downstream until depositing downstream of the contraction.

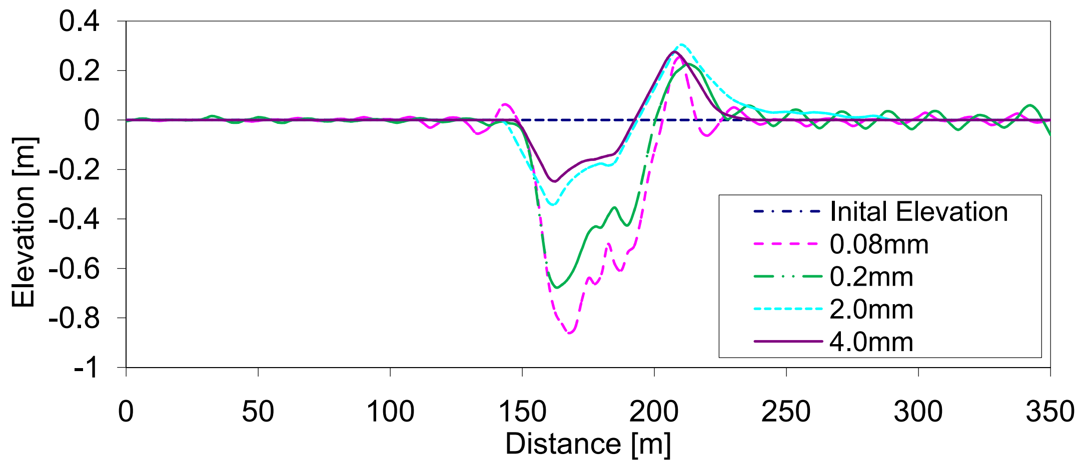

Figure C-28: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

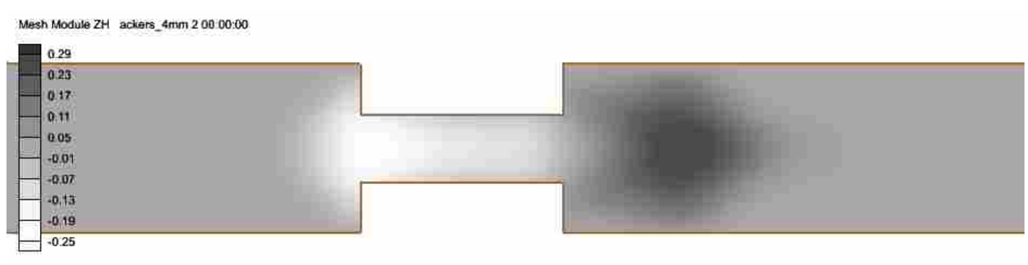

Figure C-29: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Ackers & White Method with the 4.0mm Particle Size

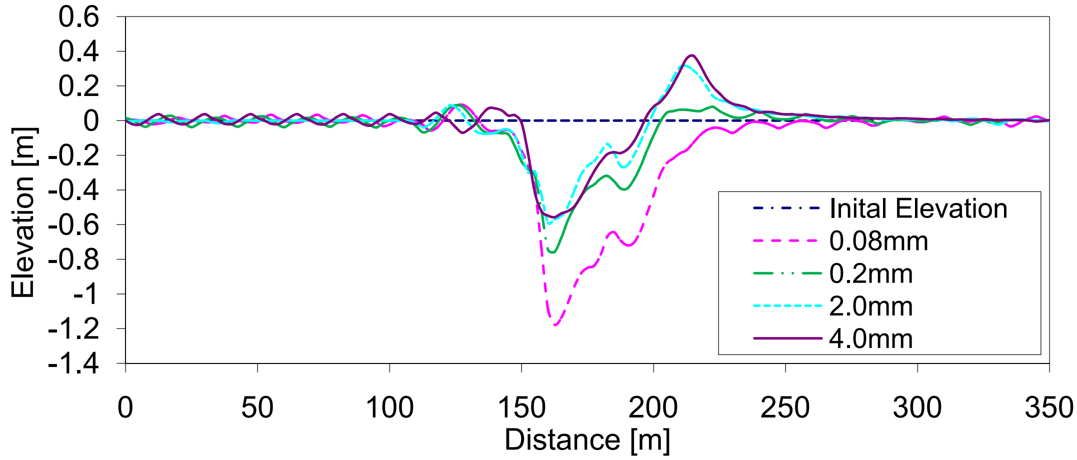

Figure C-30: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

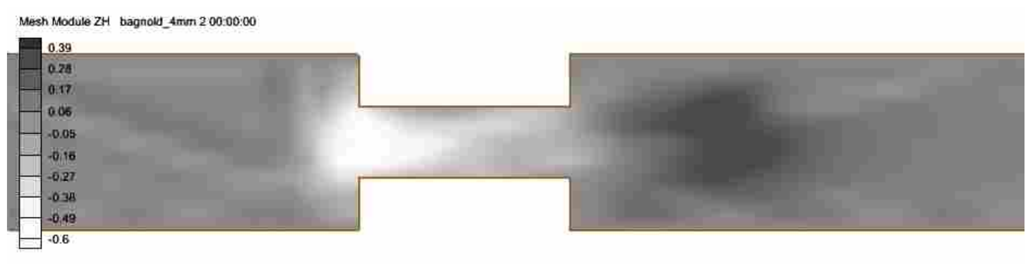

Figure C-31: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Bagnold Method with the 4.0mm Particle Size

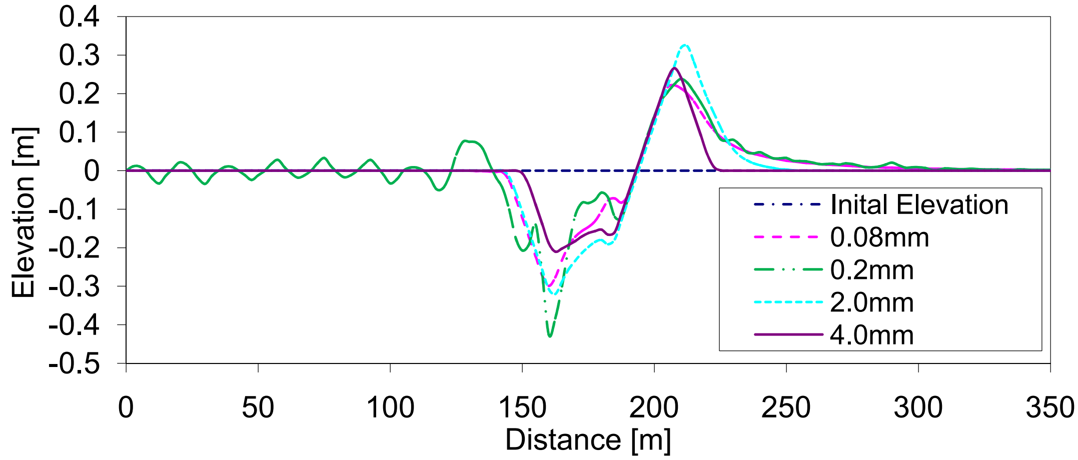

Figure C-32: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

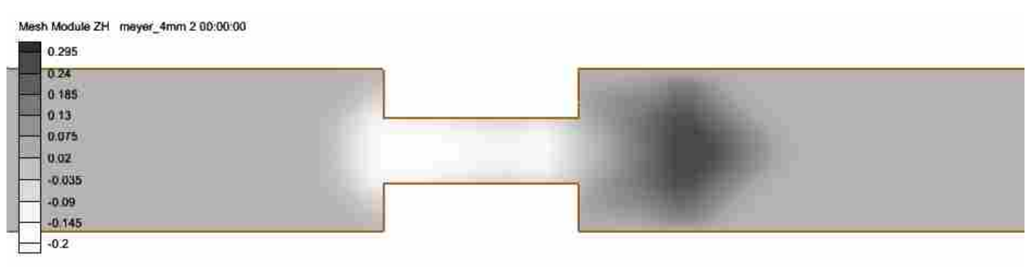

Figure C-33: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with the 4.0mm Particle Size

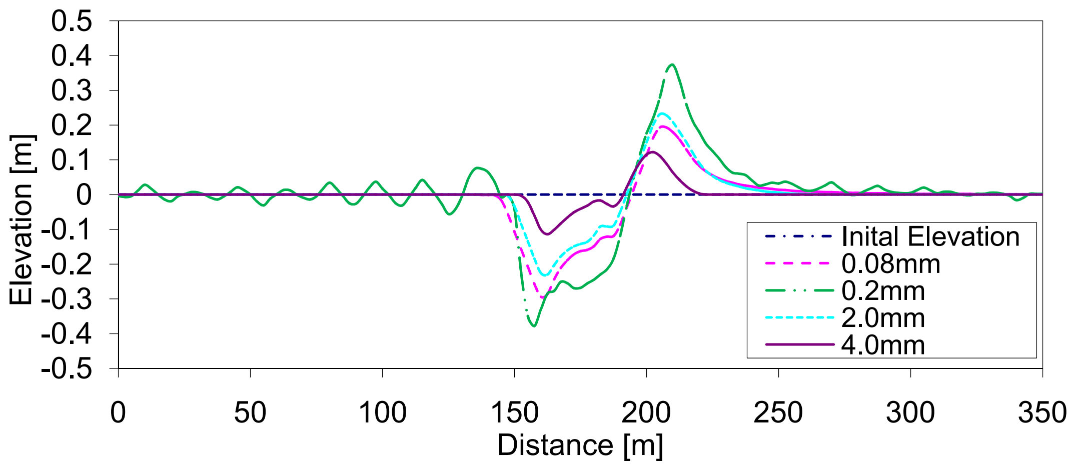

Figure C-34: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

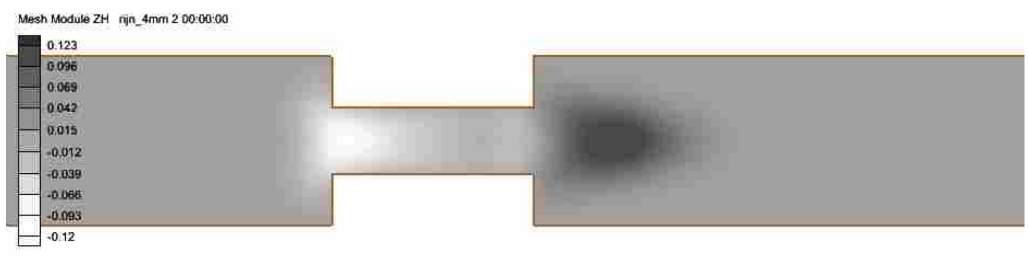

Figure C-35: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Van Rijn Method with the 4.0mm Particle Size

C.1.3 Short Abrupt Contraction

The steady state hydrodynamic results show subcritical flow throughout the entire model and are shown in Figure C-36 through C-39. The velocities after the contraction curved to one side of the flume which was not expected and investigated. The TUFLOW developers stated that the cause of this irregularity was due to the numerical solver and how it works. The developers are going to investigate this further and figure out a solution.

Although the velocities don't match what is expected, the models were still set up with sediment transport to give a general idea of scour and deposition.   As with the gradual contraction, the depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and slows down.

As with the gradual contraction test cases, in most cases as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases.

As with the gradual contraction test cases, the results for some of the contraction models show oscillations after a certain run time and if bed smoothing was implemented the results became unreasonable. Some of the results show odd bed formations in a diagonal pattern and needs to be investigated by the developers.

The results for all the test cases are shown in Figures C-40 through C-47. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the contraction and progressed downstream until depositing downstream of the contraction.

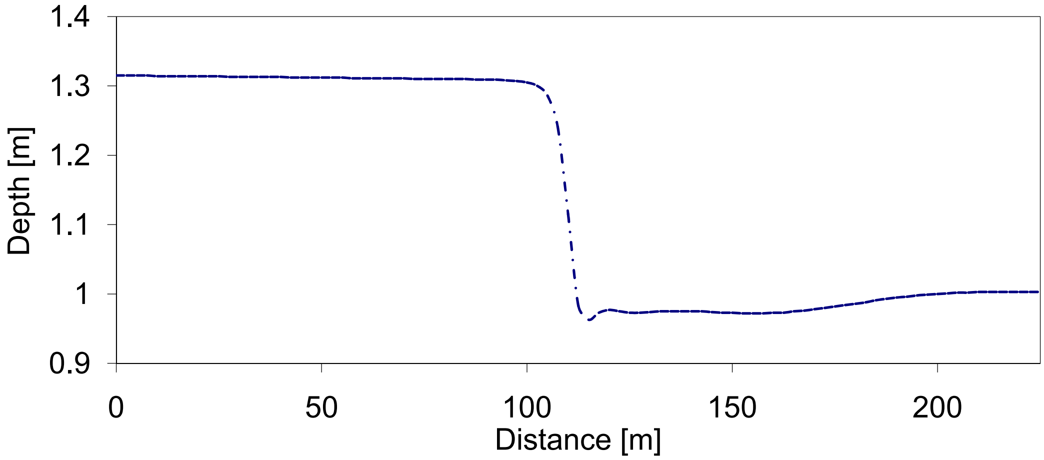

Figure C-36: Steady-State Solution for Water Depth in the Flume with a Short Abrupt Contraction

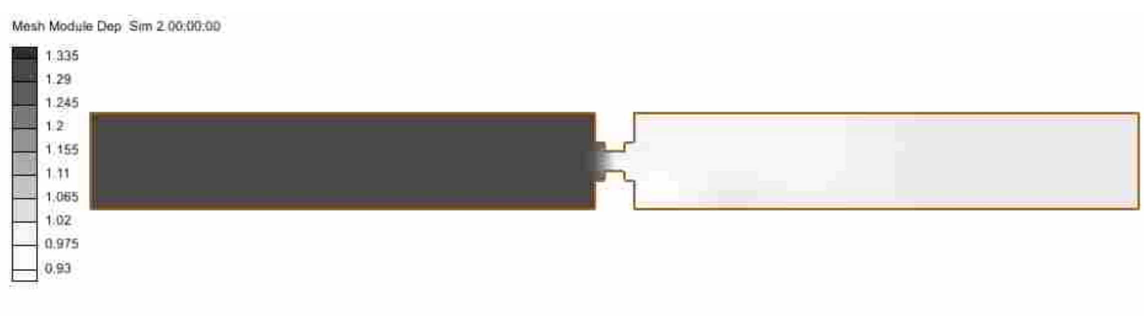

Figure C-37: Plan View of Steady-State Solution for Water Depth in the Flume with a Short Abrupt Contraction

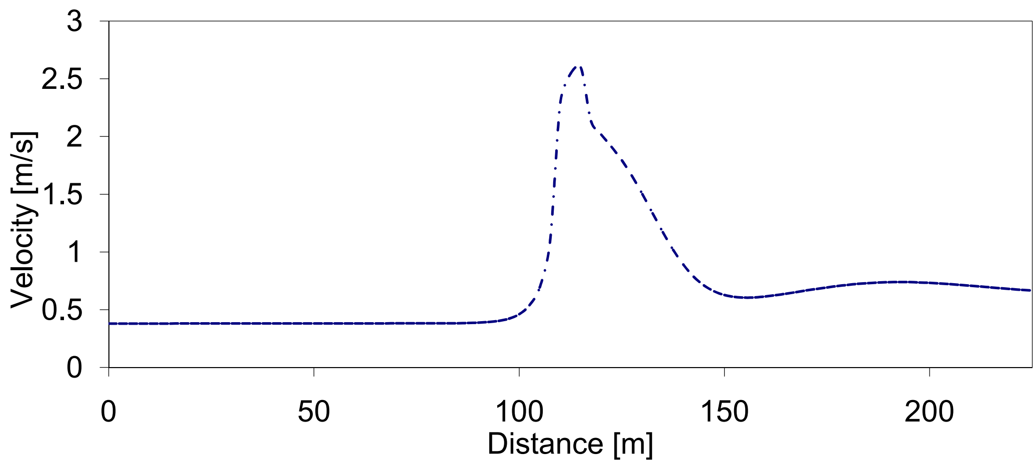

Figure C-38: Steady-State Solution for Velocity Magnitude for the Flume with a Short Abrupt Contraction

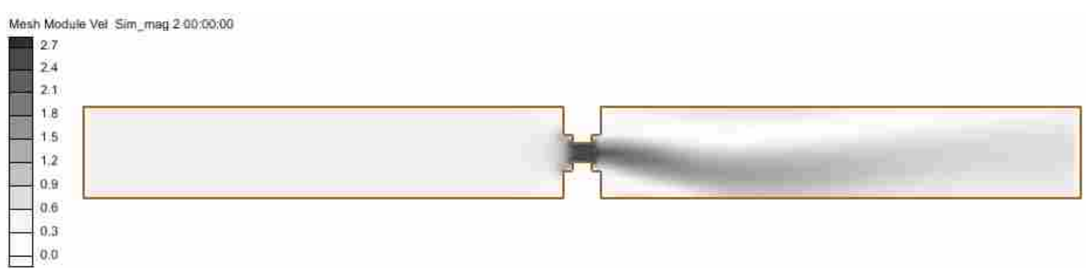

Figure C-39: Plan View of Steady-State Solution for Velocity Magnitude for the Flume with a Short Abrupt Contraction

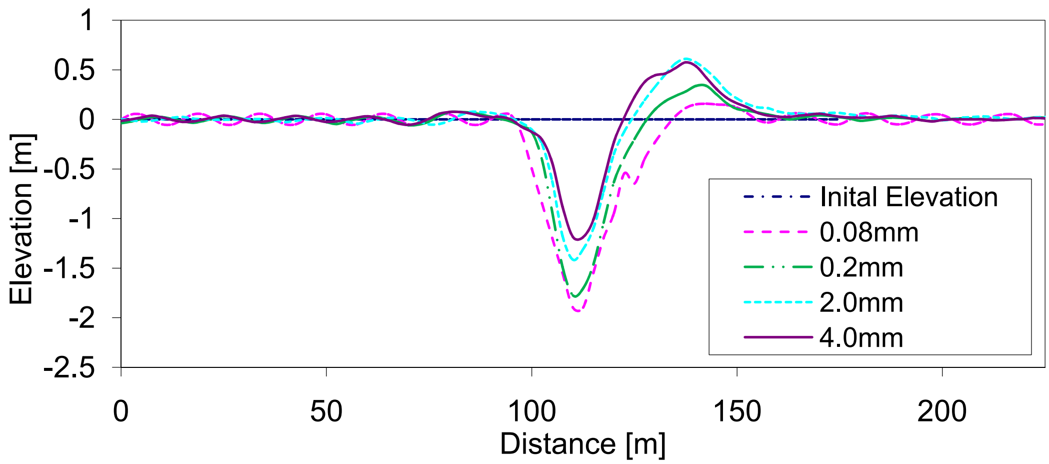

Figure C-40: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

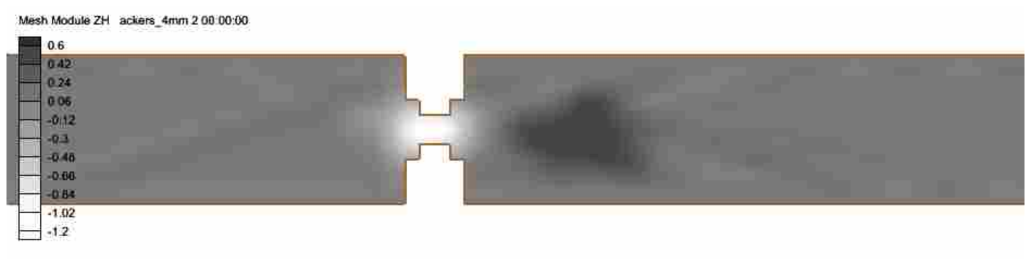

Figure C-41: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Ackers & White Method with the 4.0mm Particle Size

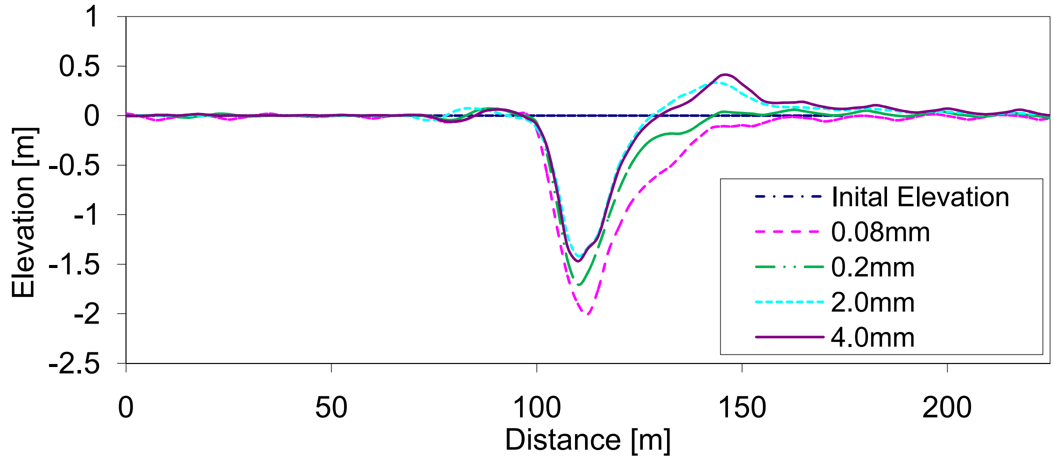

Figure C-42: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

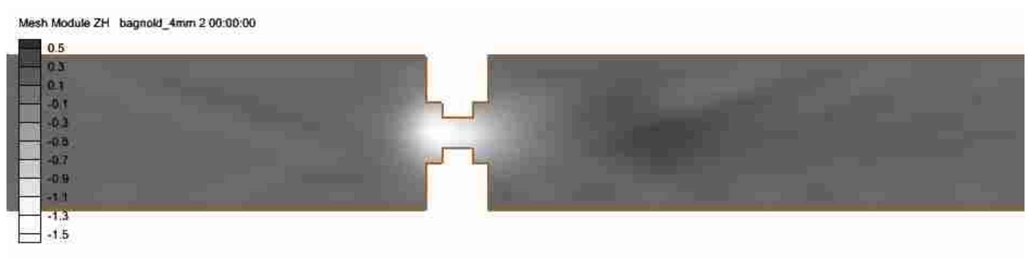

Figure C-43: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Bagnold Method with the 4.0mm Particle Size

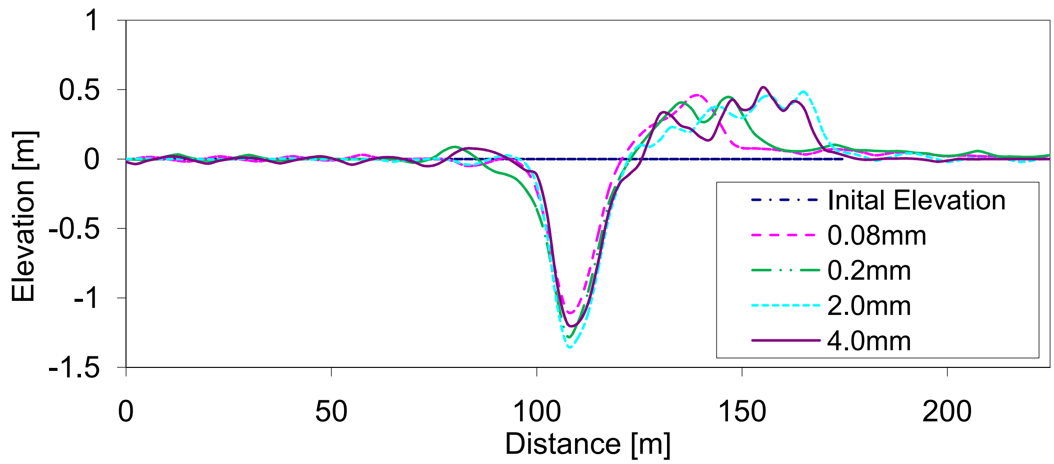

Figure C-44: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

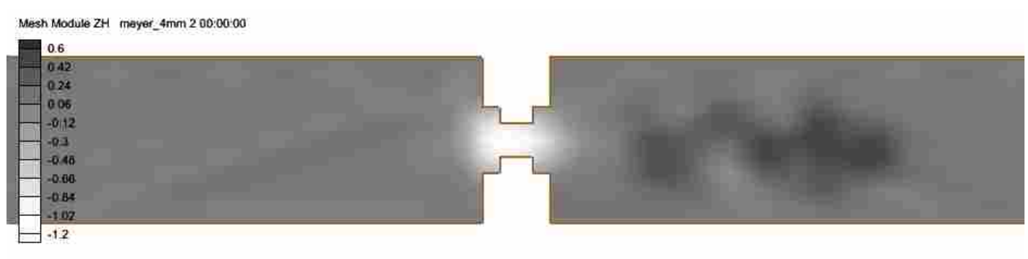

Figure C-45: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with the 4.0mm Particle Size

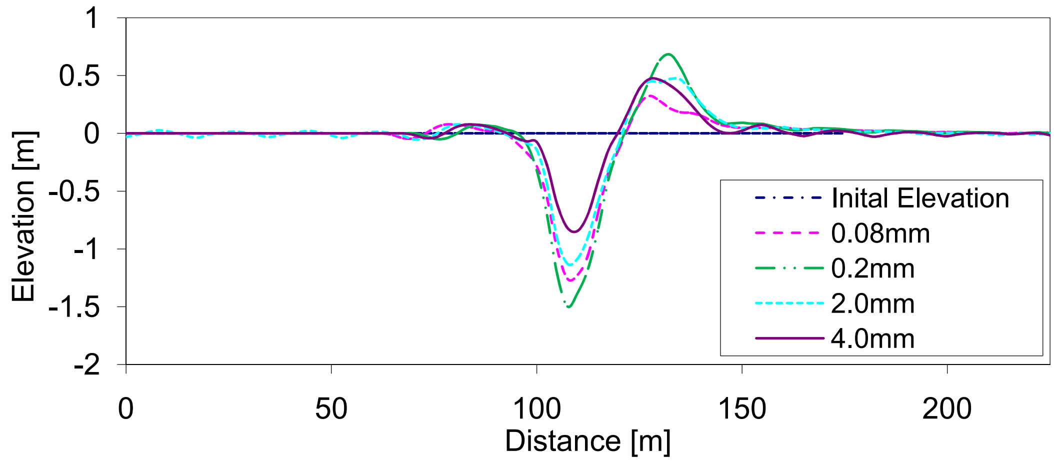

Figure C-46: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

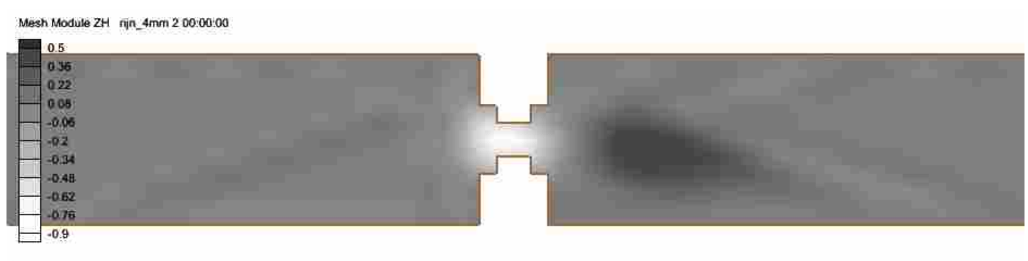

Figure C-47: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Van Rijn Method with the 4.0mm Particle Size

C.1.4 Wide Flume with a Abrupt Contraction

The steady state hydrodynamic results show subcritical flow throughout the entire model, are reasonable and are shown in Figures C-48 through C-51. As with the gradual contraction, the depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and slows down. The velocities upstream and downstream are quite small compared to the max velocity of 2.53 cfs in the contraction.

As with the gradual contraction test cases, the results show as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases. The general shape of the regions of scour and deposition appear to be valid. Most of the scouring happens along the center of the channel where the highest velocities are observed.

As with the gradual contraction test cases, the results for some of the contraction models show oscillations after a certain run time and if bed smoothing was implemented the results became unreasonable. Some of the results show odd bed formations in a diagonal pattern and needs to be investigated by the developers.

The results for all the test cases are shown in Figures C-52 through C-59. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the contraction and progressed downstream, depositing downstream of the contraction. Some of the test cases show deposition near the downstream boundary. The velocity slowed down at these locations causing the sediment to deposit.

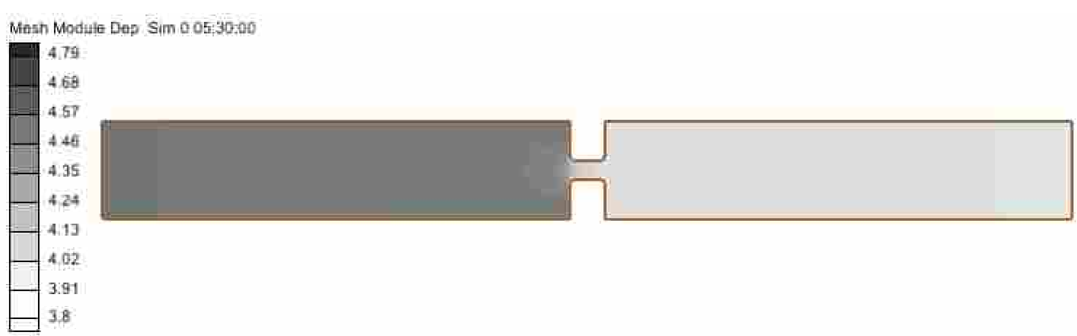

Figure C-48: Plan View of Steady-State Solution for Water Depth in the Wide Flume with an Abrupt Contraction

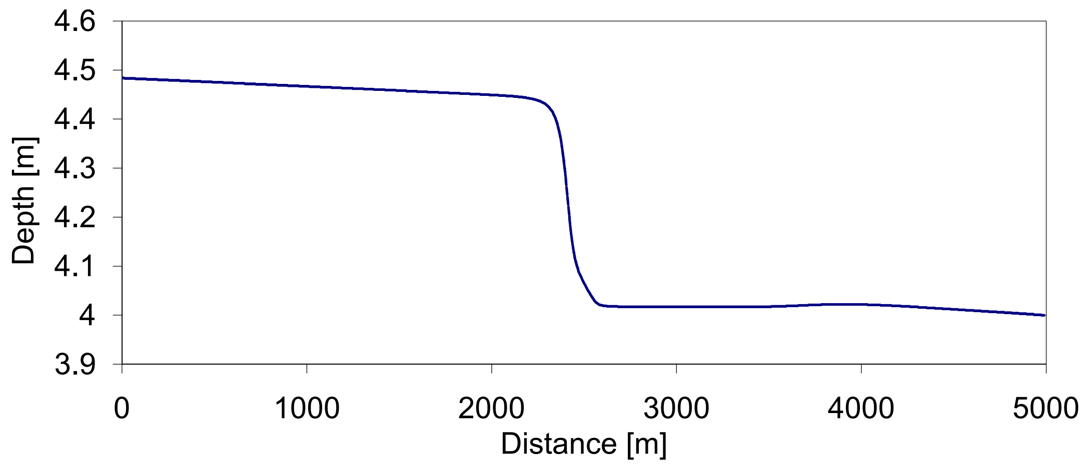

Figure C-49: Steady-State Solution for Water Depth in the Wide Flume with an Abrupt Contraction

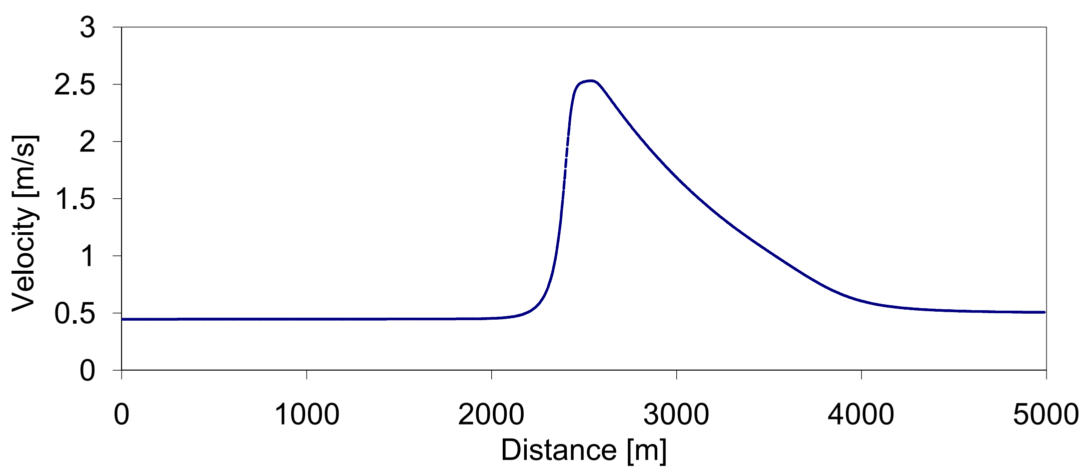

Figure C-50: Steady-State Solution for Velocity Magnitude for the Wide Flume with an Abrupt Contraction

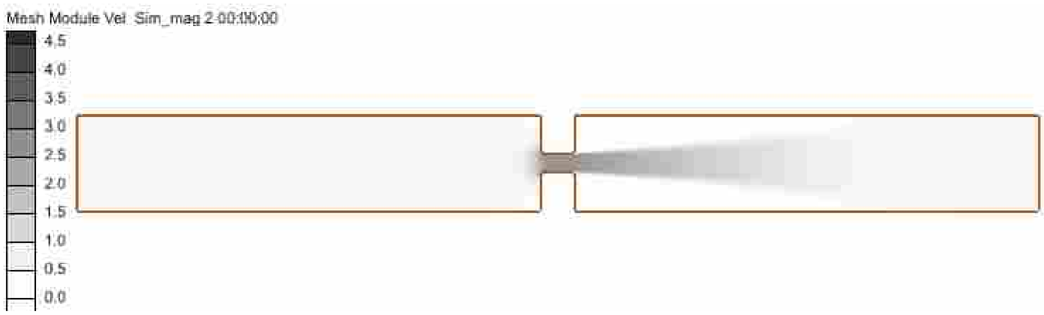

Figure C-51: Plan View of Steady-State Solution for Velocity Magnitude for the Wide Flume with an Abrupt Contraction

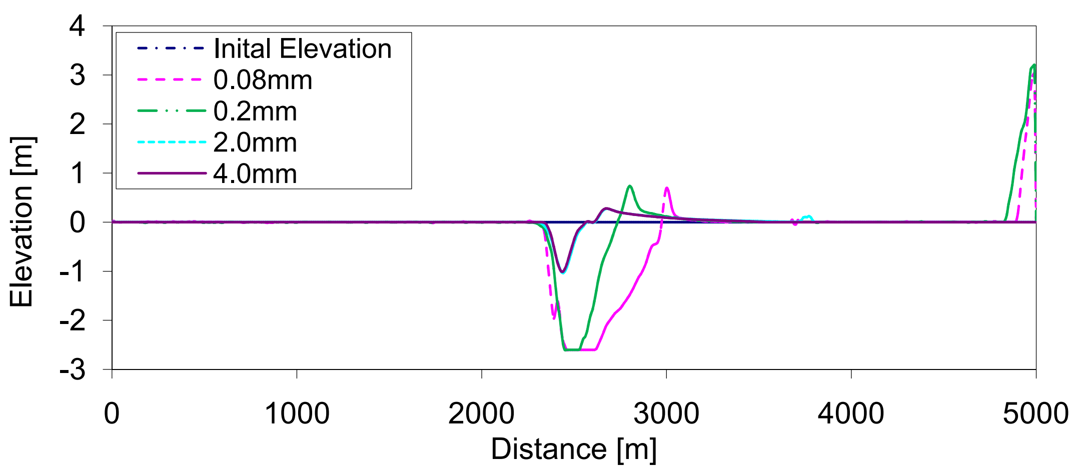

Figure C-52: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with a Abrupt Contraction Test Case using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

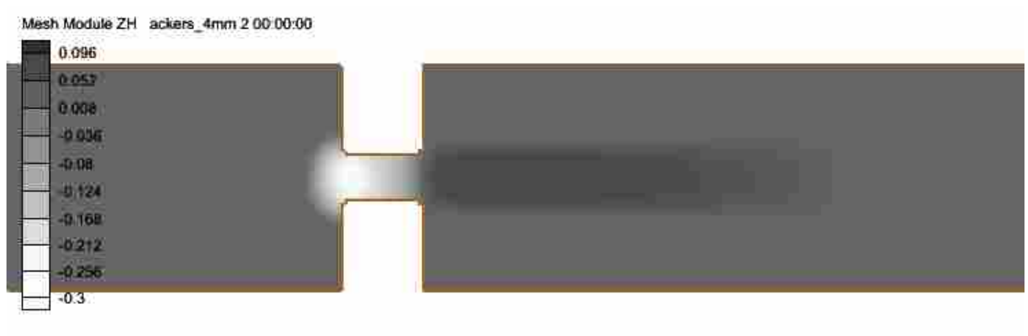

Figure C-53: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Ackers & White Method with the 4.0mm Particle Size

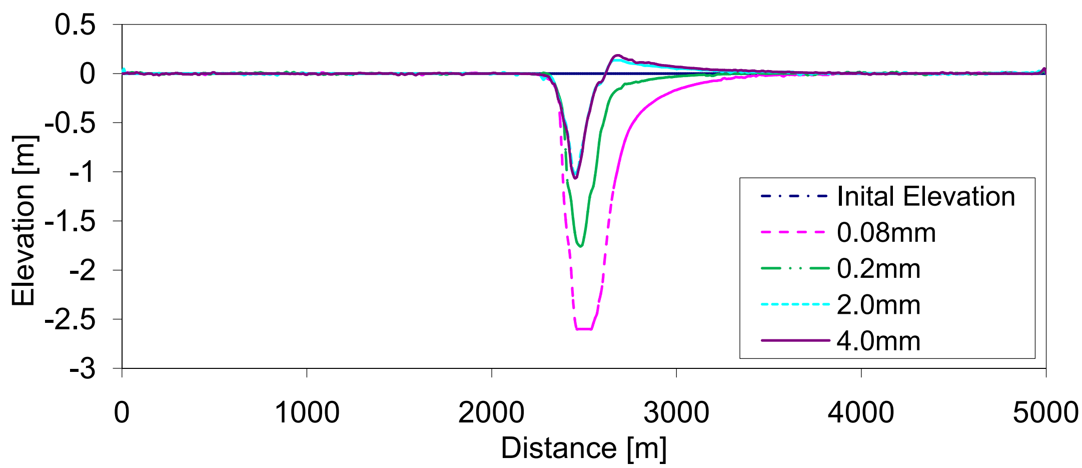

Figure C-54: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with a Abrupt Contraction Test Case using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

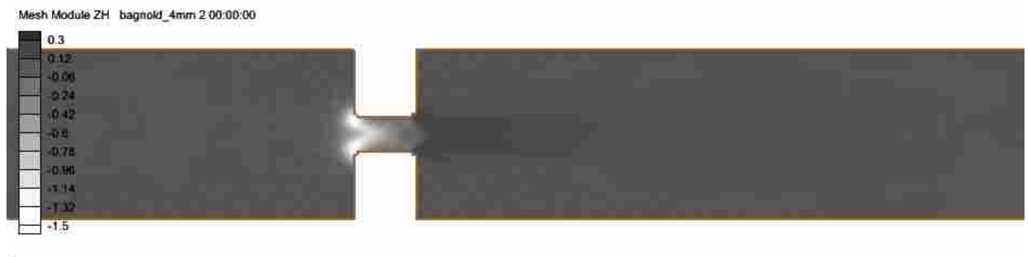

Figure C-55: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Bagnold Method with the 4.0mm Particle Size

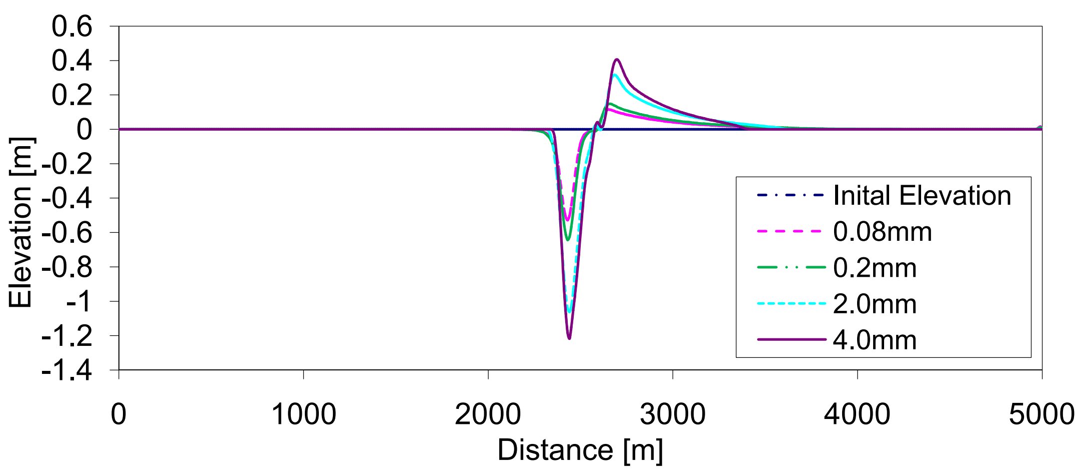

Figure C-56: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with a Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Figure C-57: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Meyer-Peter & Muller Method with the 4.0mm Particle Size

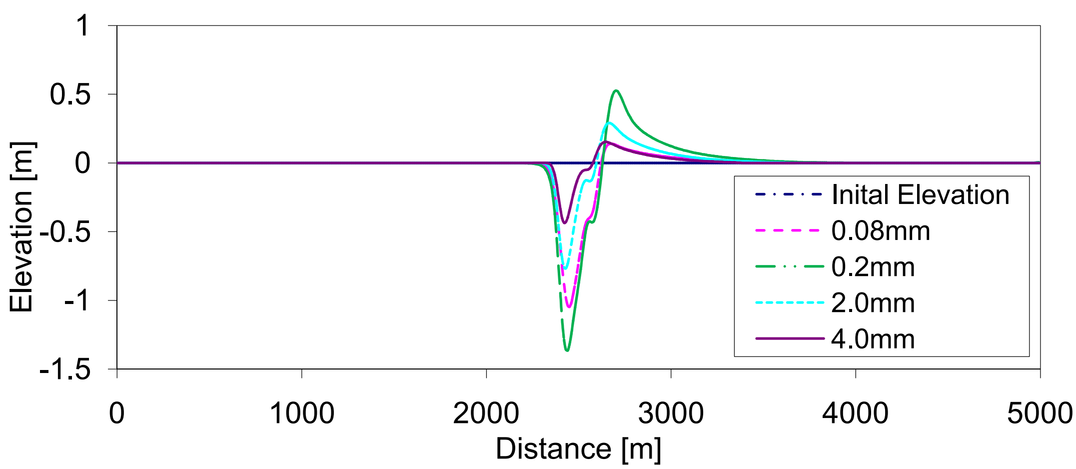

Figure C-58: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with a Abrupt Contraction Test Case using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

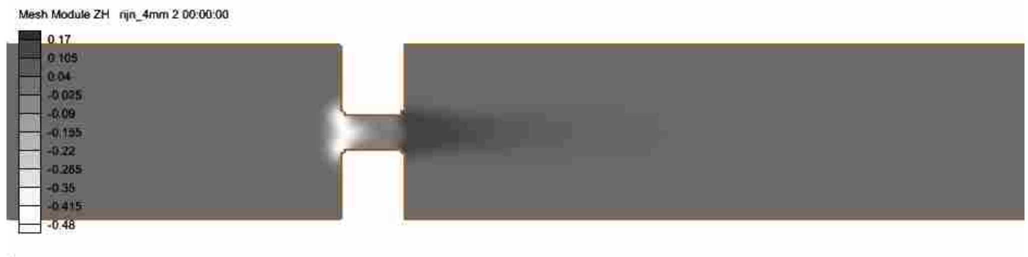

Figure C-59: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Van Rijn Method with the 4.0mm Particle Size

C.2 River with a Contraction

The steady state hydrodynamic results show subcritical flow throughout the entire model, are reasonable and shown in Figures C-60 through C-63. As with the contraction test cases, the depth of water drops due to the velocity increase near the contraction and rises once the flow has passed through the contraction and slows down. The velocities upstream and downstream are small compared to the max velocity of 1.6 cfs in the contraction.

As with the contraction test cases, the results show as the particle size increases, the location of scour remains constant, the location of deposition moves upstream, and the magnitude of deposition increases. The general shape of the regions of scour and deposition appear to be valid. Most of the scouring happens along the center of the channel where the highest velocities are observed.

As with the contraction test cases, the results for the river with a contraction test cases show oscillations after a certain run time and if bed smoothing was implemented the results became unreasonable.

The results for all the test cases are shown in Figures C-64 through C-71. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the contraction and progressed downstream, depositing downstream of the contraction. The results show large oscillations at the inflow and outflow boundaries during the simulation which could have a large effect on the results. The scouring and deposition near the contraction in the river are as expected.

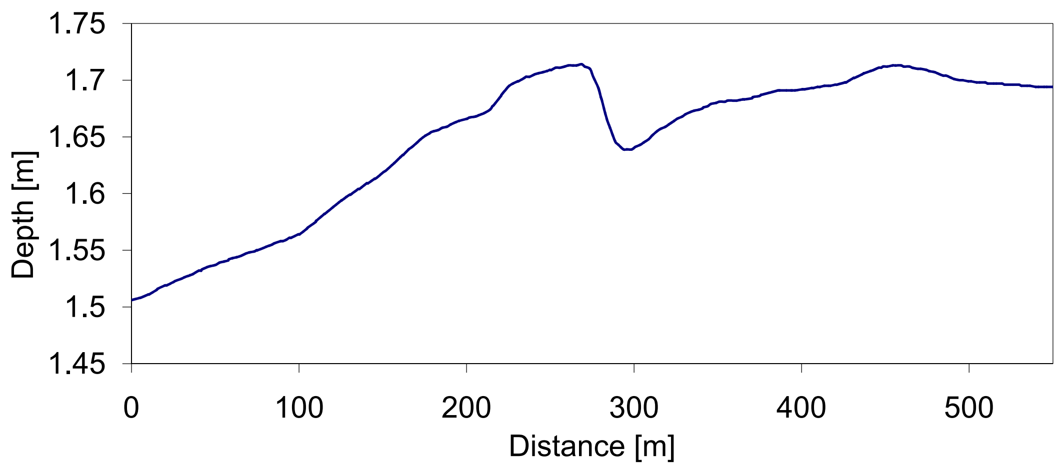

Figure C-60: Steady-State Solution for Water Depth of the River with a Contraction

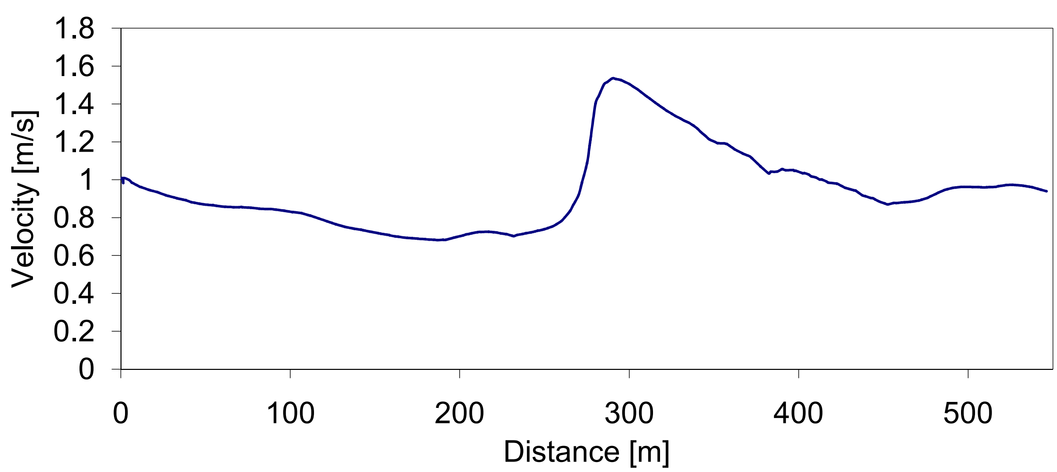

Figure C-61: Steady-State Solution for Velocity Magnitude of the River with a Contraction

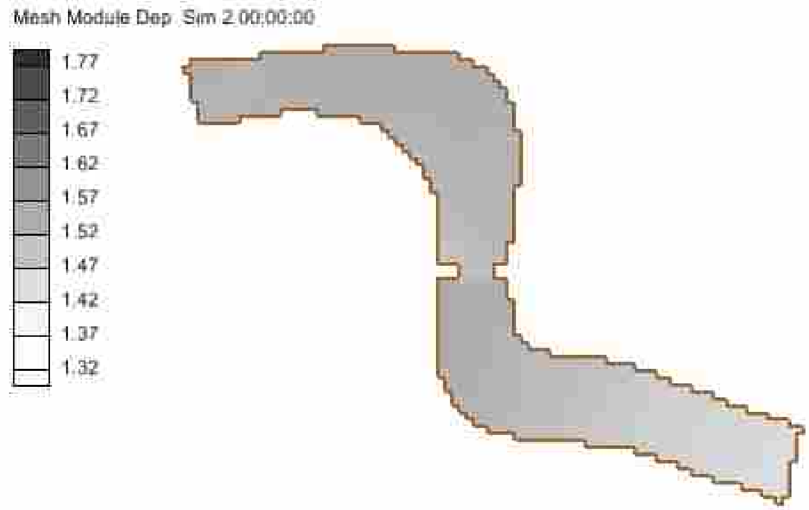

Figure C-62: Plan View of Steady-State Solution for Water Depth of the River with a Contraction

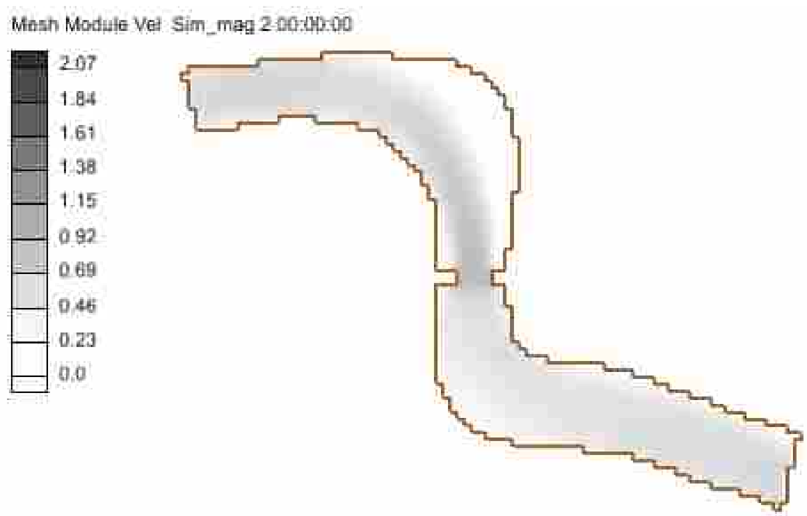

Figure C-63: Plan View of Steady-State Solution for Velocity Magnitude of the River with a Contraction

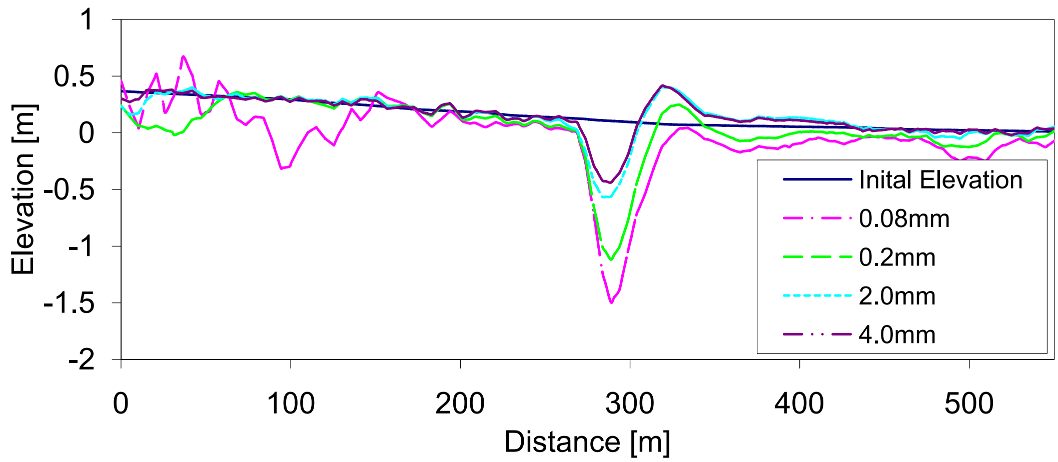

Figure C-64: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Ackers & White Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

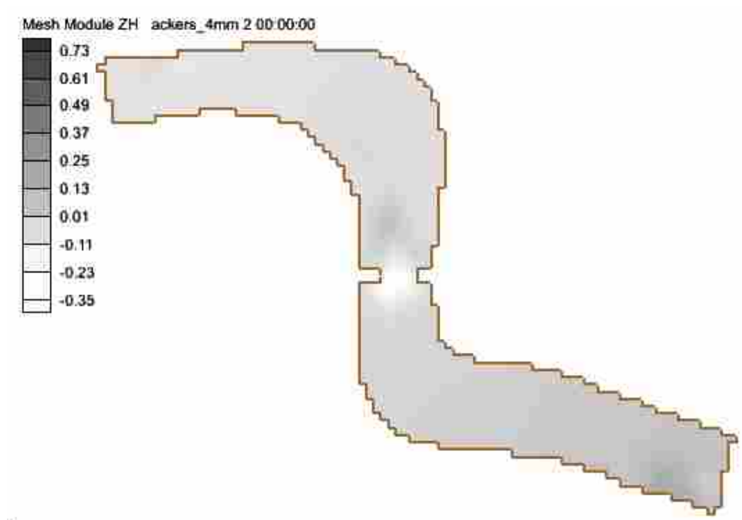

Figure C-65: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction Test Case using the Ackers & White Method with the 4.0mm Particle Size

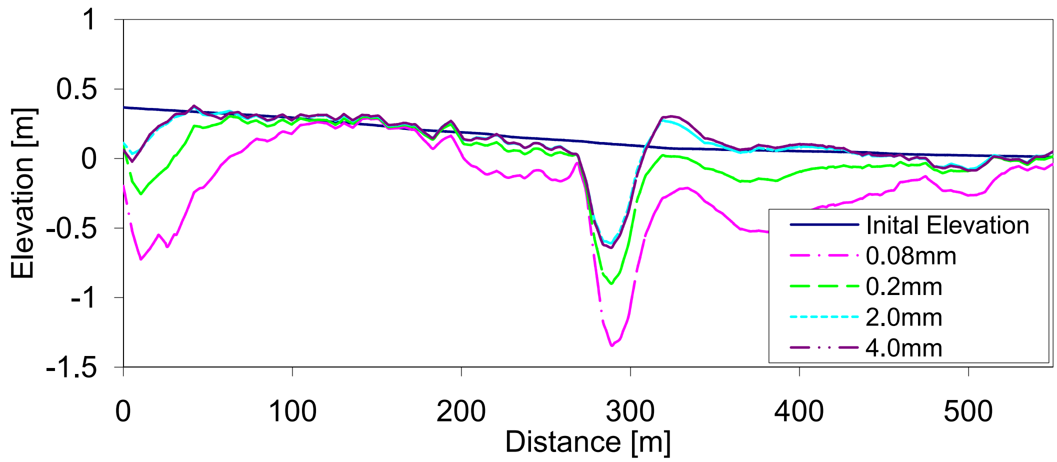

Figure C-66: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Bagnold Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

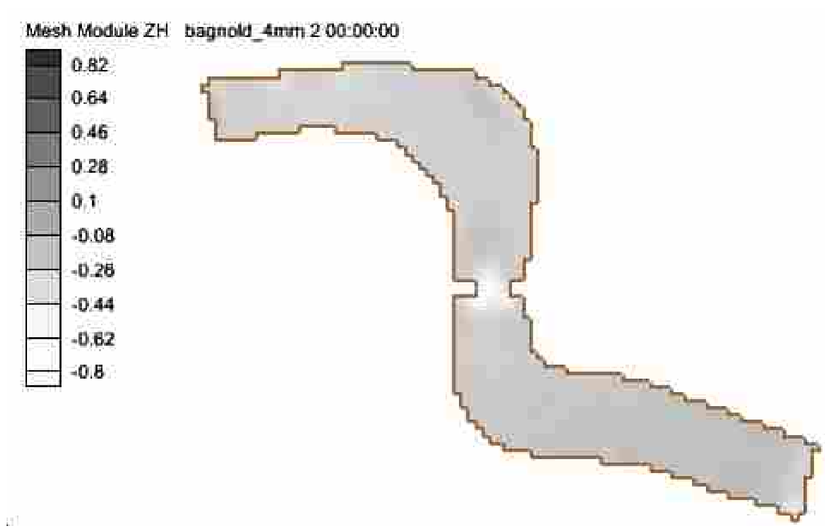

Figure C-67: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction Test Case using the Bagnold Method with the 4.0mm Particle Size

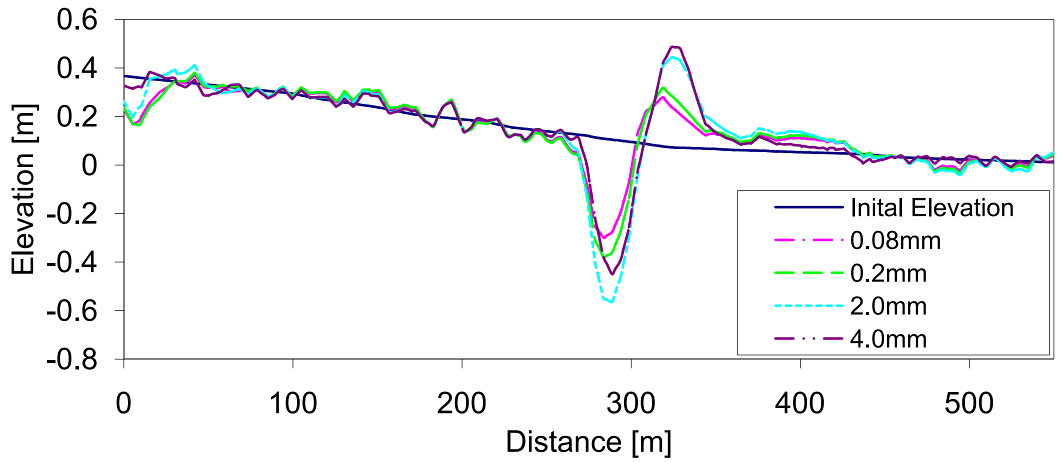

Figure C-68: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

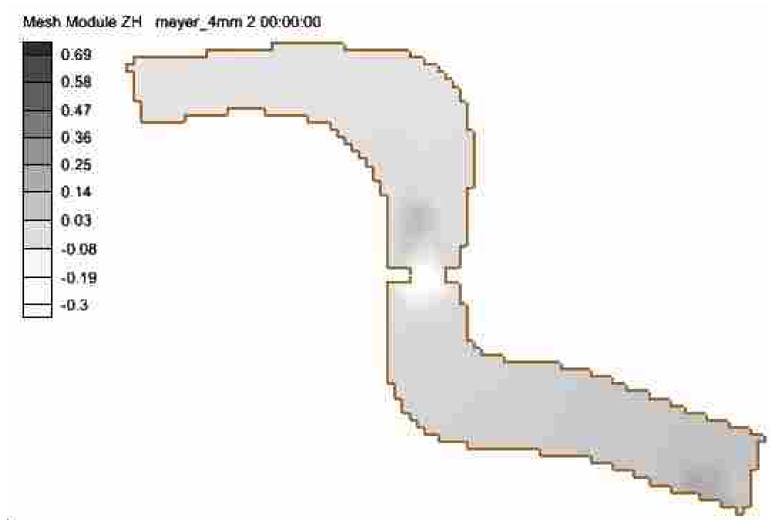

Figure C-69: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction Test Case using the Meyer-Peter & Muller Method with the 4.0mm Particle Size

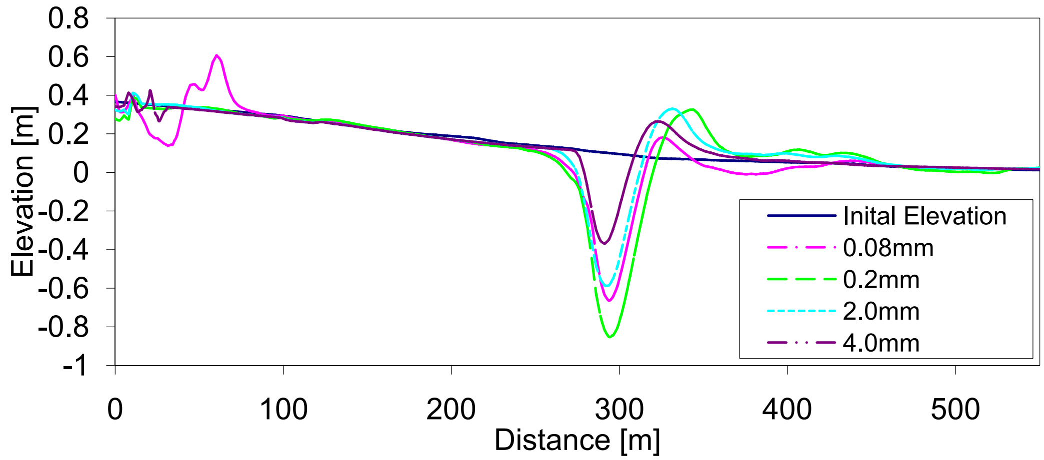

Figure C-70: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Van Rijn Method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

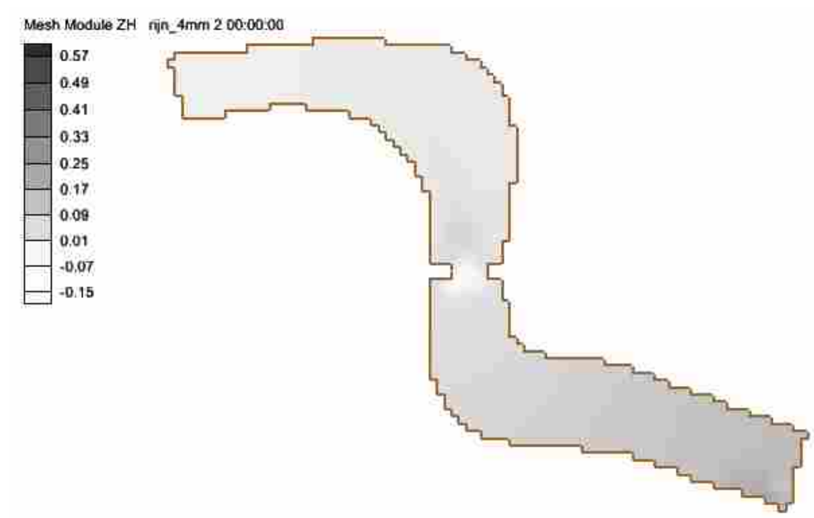

Figure C-71: Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction Test Case using the Van Rijn Method with the 4.0mm Particle Size

D MODEL RESULTS COMPARISON

The results given in Appendix C identified the specific sediment transport options that are currently functional in TUFLOW and also examined the degree to which the results obtained made sense intuitively. Appendix D provides comparisons between the results from TUFLOW and FESWMS.

D.1 FESWMS

D.1.1 Moderate Midsection Slope

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. In both cases, the peak happened downstream of the break in slope and decelerated when it reached the backwater. None of the test cases using the Ackers & White method for the moderate midsection sloped model were stable and no comparison could be made. All of the test cases for the Meyer-Peter and Muller ran to completion except the 4.0mm particle size.

The results for the Meyer-Peter & Muller method are shown in Figure D-1. Scouring for each of the test cases began at the break in slope and progressed upstream with deposition downstream of the break in slope. The results show scouring of the break in slope, as expected. The deposition is different than the TUFLOW models and will need to be considered.

Figures D-2, D-3, and D-4 show the comparison of each particle size, except the 4.0mm for both TUFLOW and FESWMS. The scour of the break point for both models look similar with scour stopping at the inflow boundary and reaching an equilibrium slope. FESWMS shows far more deposition than TUFLOW due to method of deposition.

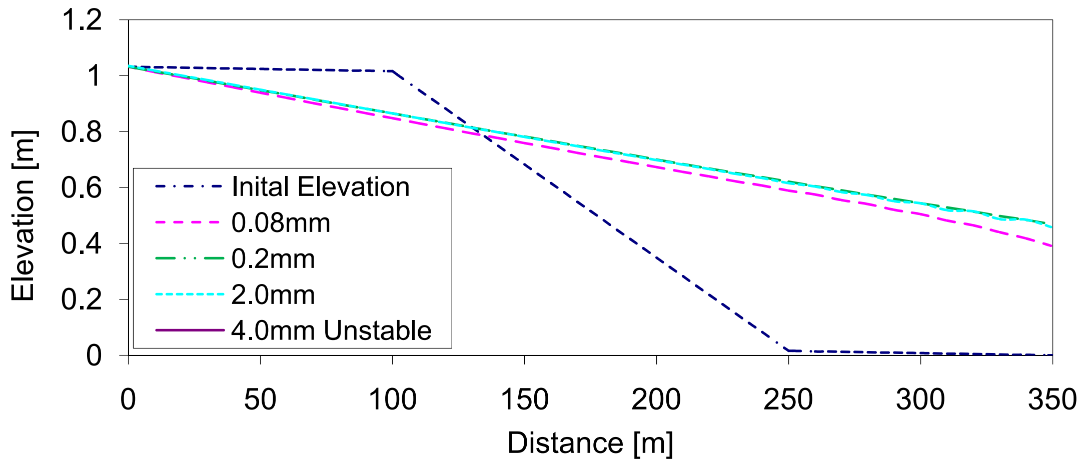

Figure D-1: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

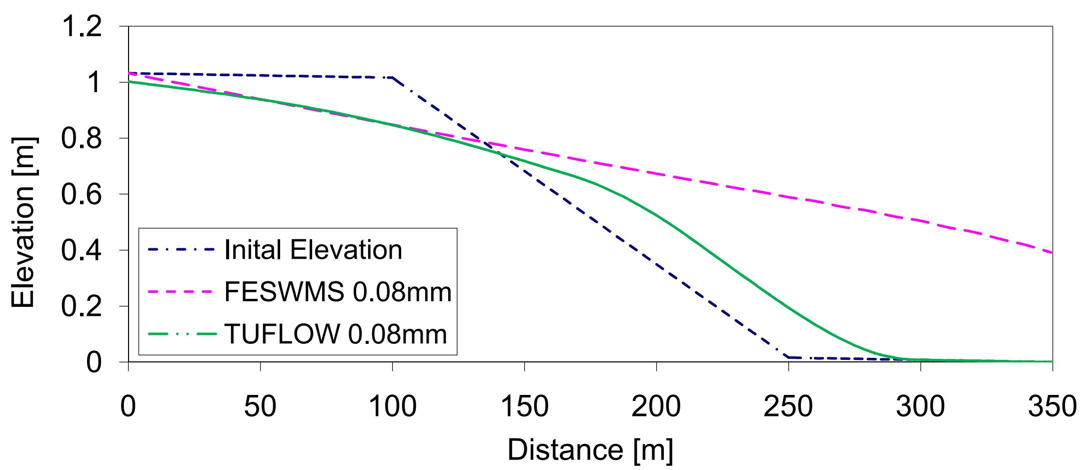

Figure D-2: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

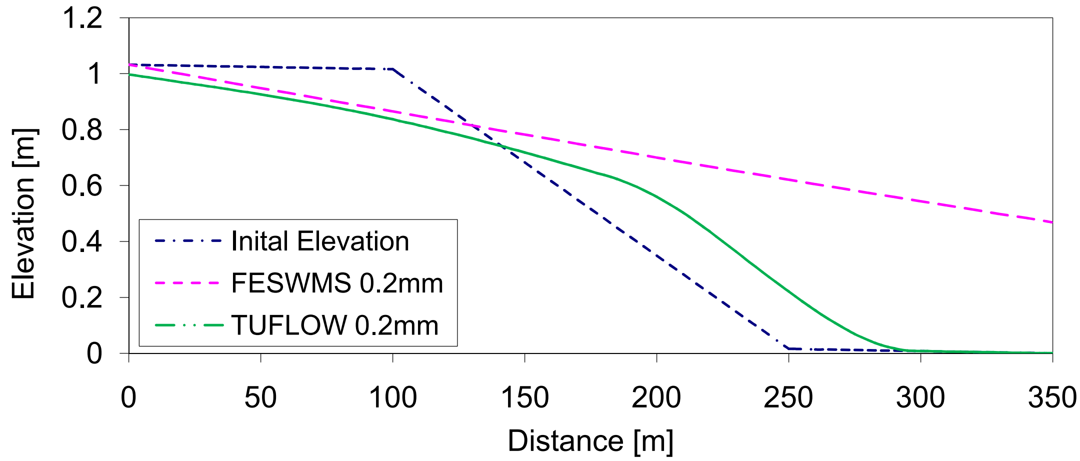

Figure D-3: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

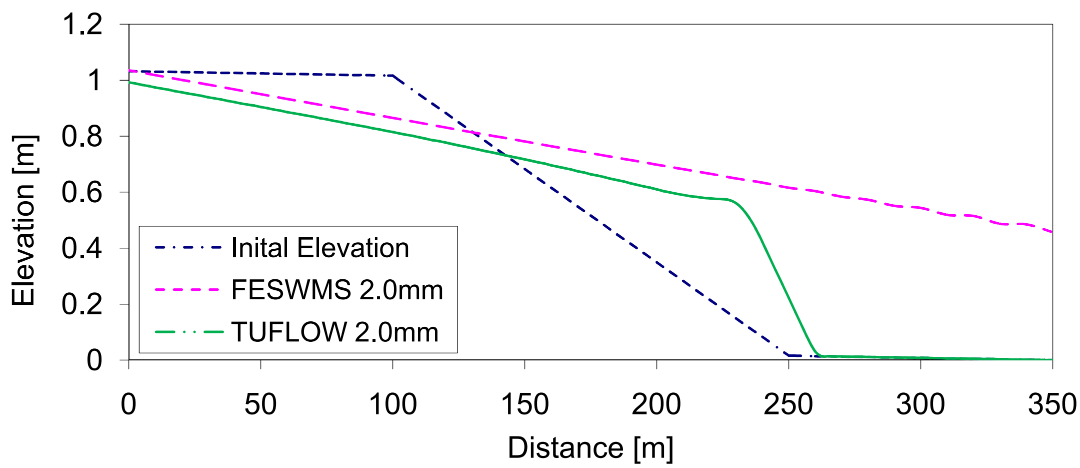

Figure D-4: Initial and Final Bed Elevations for a 48 Hour Simulation of the Moderate Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 2mm

D.1.2 Shallow Midsection Slope

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. In both cases, the peak happened downstream of the break in slope and decelerated when it reached the backwater. None of the test cases using the Ackers & White method for the shallow midsection sloped model were stable and no comparison could be made. All of the test cases for the Meyer-Peter and Muller ran to completion.

The results for the Meyer-Peter & Muller method in FESWMS are shown in Figure D-5. All test cases ran to completion with sediment transport. Scouring for each of the test cases began at the break in slope and progressed upstream with deposition downstream of the break in slope. The amount of scouring for all the test cases is reasonable. The amount of deposition for the 0.08mm test case is not what was expected when compared to the other particle sizes.

Figures D-6, D-7, D-8, and D-9 show the results for each particle size for both TUFLOW and FESWMS. The scour of the break point for both models look similar with scour stopping at the inflow boundary and reaching an equilibrium slope. FESWMS shows more scour than TUFLOW the larger the particle size. There are larger amounts of deposition for the FESWMS models than the TUFLOW models.

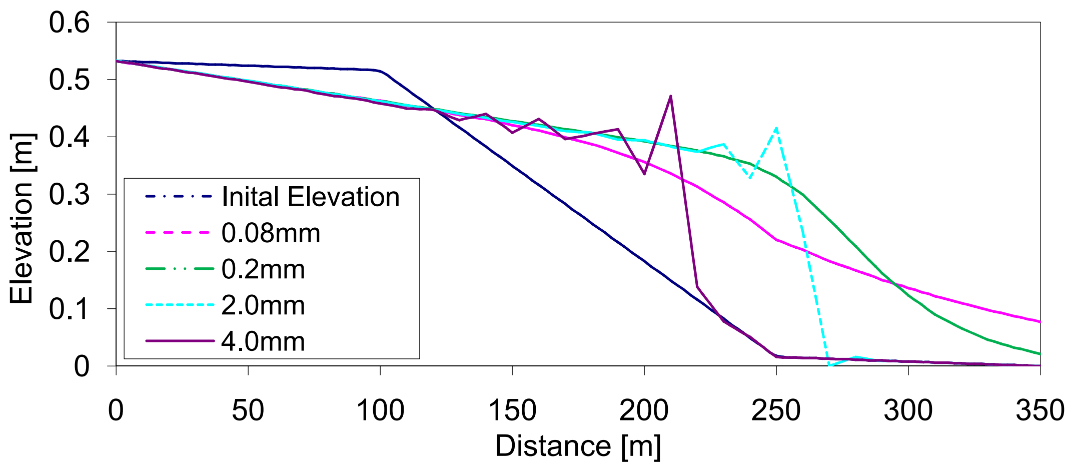

Figure D-5: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

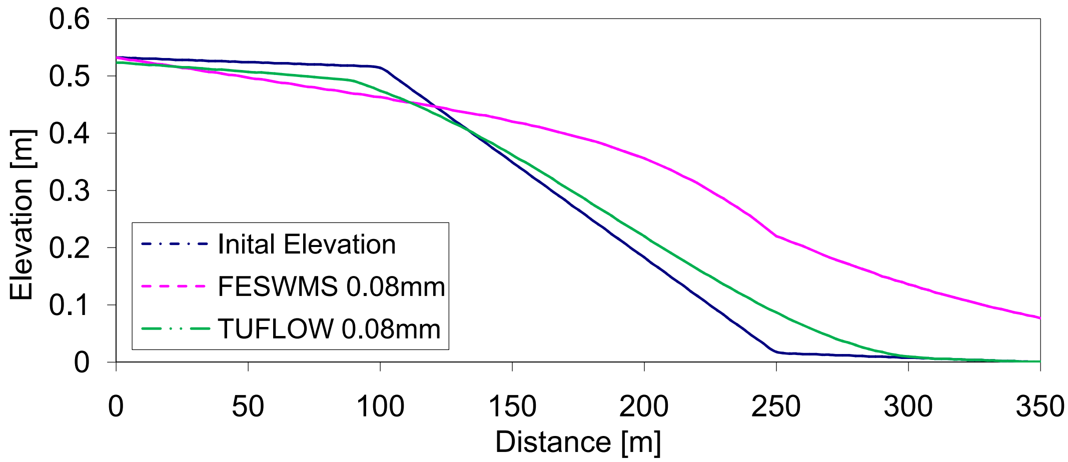

Figure D-6: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

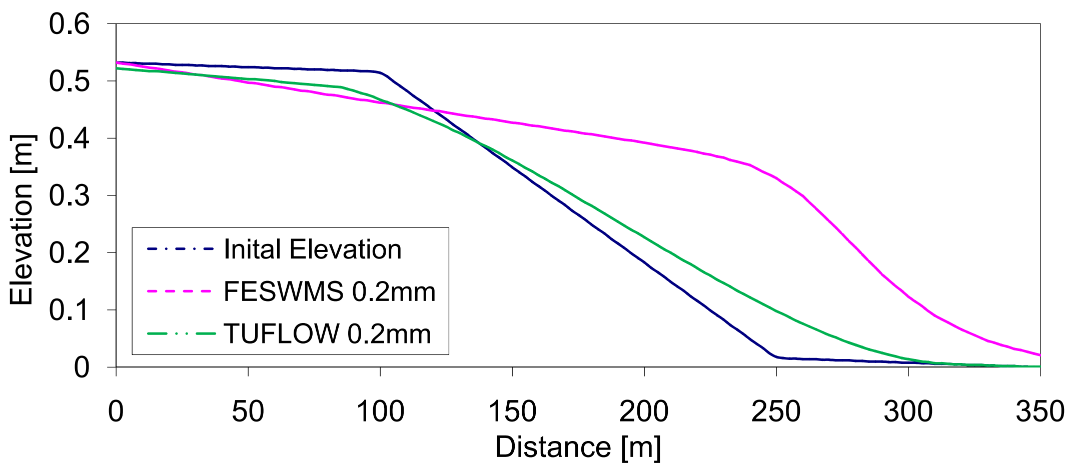

Figure D-7: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

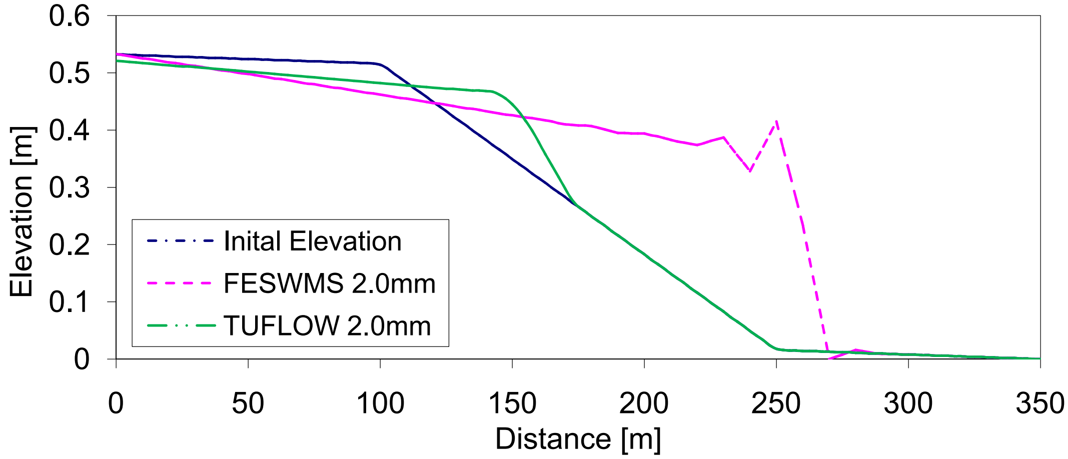

Figure D-8: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 2.0mm

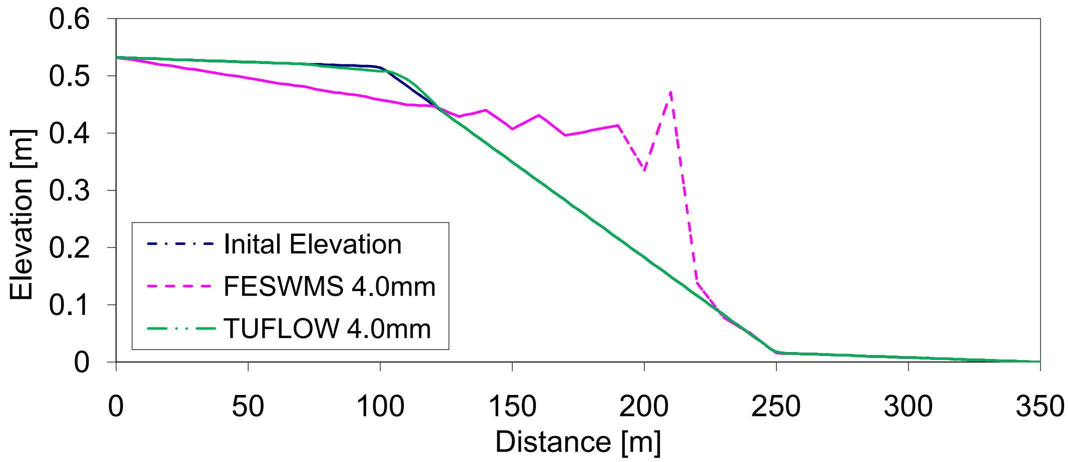

Figure D-9: Initial and Final Bed Elevations for a 48 Hour Simulation of the Shallow Midsection Slope Flume using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 4.0mm

D.1.3 Gradual Contraction

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. Scouring for each of the test cases began at the contraction and continued downstream. The particles were deposited downstream of the contraction where the velocity decelerated. Both models showed two scour holes for each test as was expected

None of the test cases using the Ackers & White method for the shallow midsection sloped model were stable and no comparison could be made. Only the two larger particle sizes were stable for the Meyer-Peter and Muller test cases and ran to completion. As with other FESWMS models; FESWMS had a tendency to deposit more sediment.

The results for the Meyer-Peter & Muller method in FESWMS are shown in Figure D-10. Scouring for each of the test cases began at the contraction and continued downstream. The particles were deposited downstream of the contraction where the velocity decelerated.

Figures D-11 and D-12 show the results for each particle size for both TUFLOW and FESWMS. The particles deposited downstream of the contraction where the velocity decelerated There are larger amounts of deposition for the FESWMS models than the TUFLOW models. Scouring for each of the test cases began at the contraction and continued downstream. The FESWMS results show more scouring and could be a reason why there is more deposition.

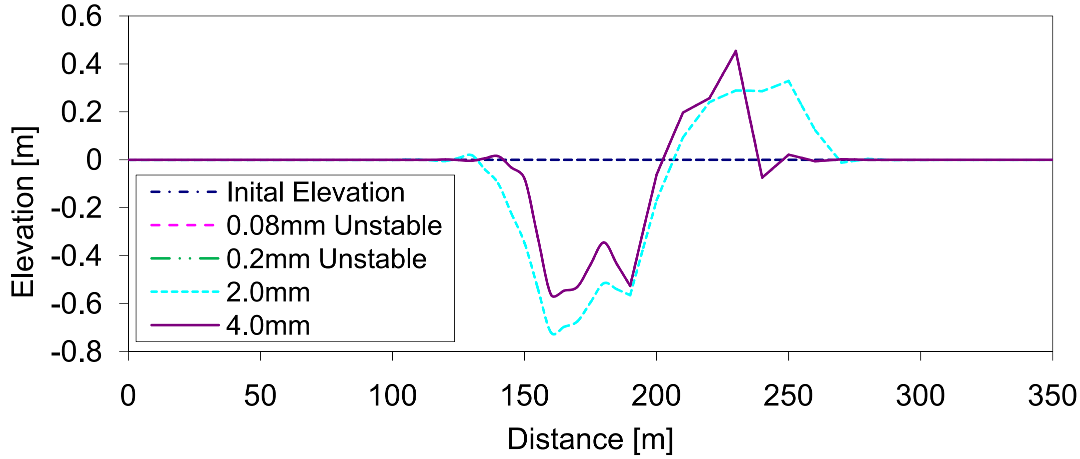

Figure D-10: Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Meyer-Peter and Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

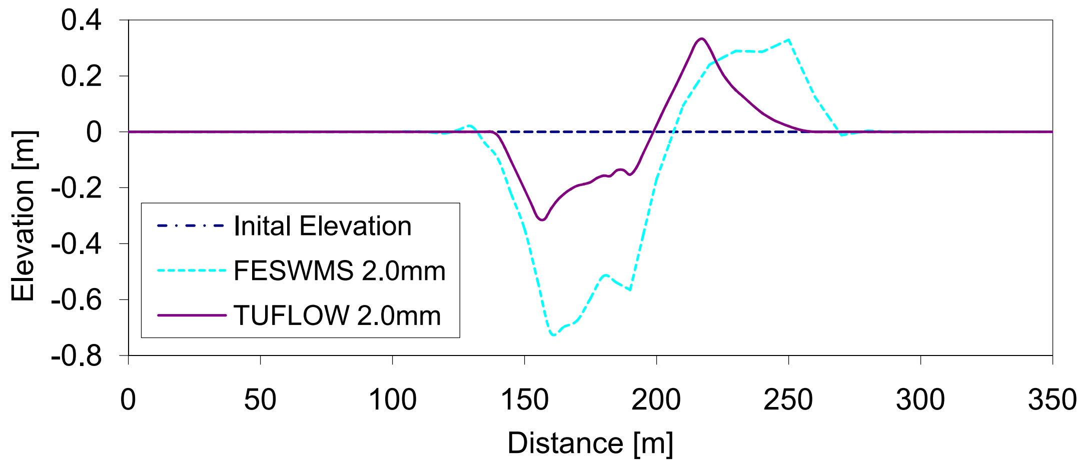

Figure D-11: Centerline Profile the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 2.0mm

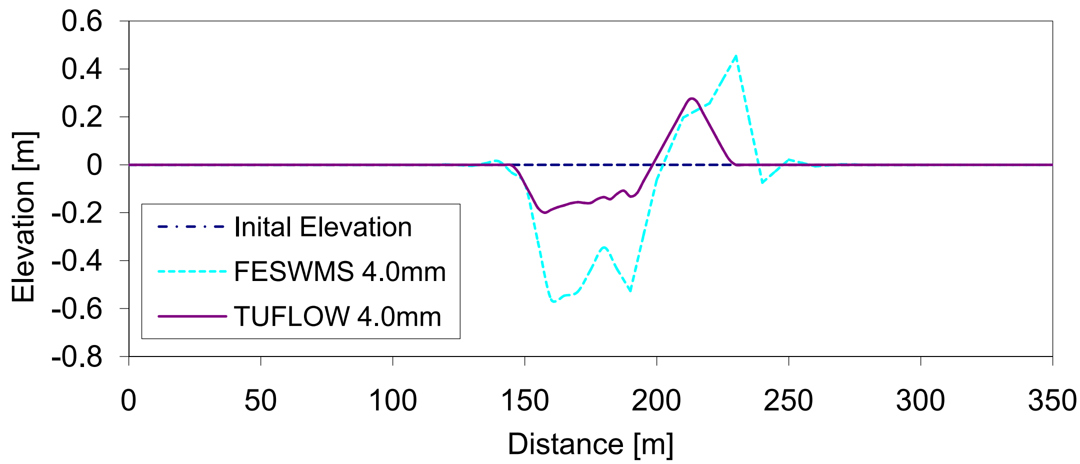

Figure D-12: Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Gradual Contraction Test Case using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 4.0mm

D.1.4 Long Abrupt Contraction

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. None of the test cases using the Ackers & White method for the shallow midsection sloped model were stable and no comparison could be made. Only the two smaller particle sizes were stable for the Meyer-Peter and Muller test cases and ran to completion.

Figure D-13 shows scouring that began at the contraction and continued downstream. The particles were deposited downstream of the contraction where the velocity decelerated. The amount of scour for the 0.08mm is less than the 0.2mm test case which is not reasonable.

Figures D-14 and D-15 show the comparison of TUFLOW and FESWMS. Both models have two scour holes for each test, as expected. The FESWMS model has a larger second scour hole than TUFLOW. The scour holes for the TUFLOW models start further upstream than the FESWMS model. The TUFLOW models have more deposition, differing from the other FESWMS models.

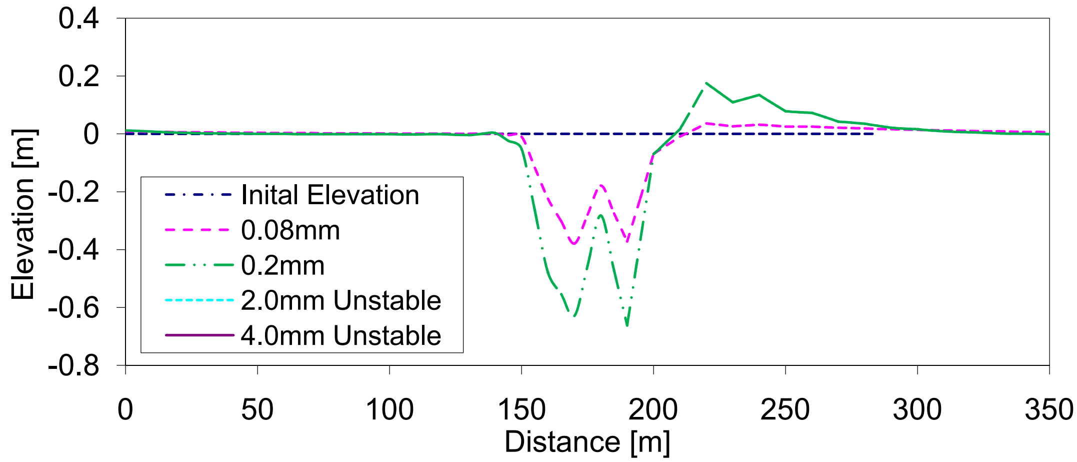

Figure D-13:Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Meyer-Peter and Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

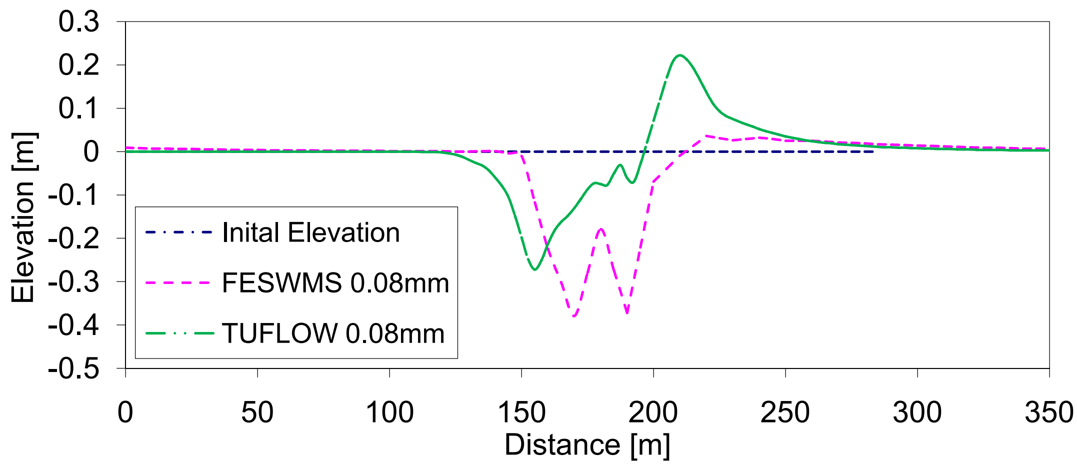

Figure D-14: Centerline Profile of the Final Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

D.1.1 Short Abrupt Contraction

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. The test cases using the Ackers & White method for the short abrupt contraction model were unstable and a comparison could not be made. The 4.0mm particle size Meyer-Peter & Muller test case was unstable and a comparison could not be made.

The results for the Meyer-Peter & Muller method in FESWMS are shown in Figure D-16. Scouring for each of the test cases began at the contraction and continued downstream. The particles were deposited downstream of the contraction where the velocity decelerated.

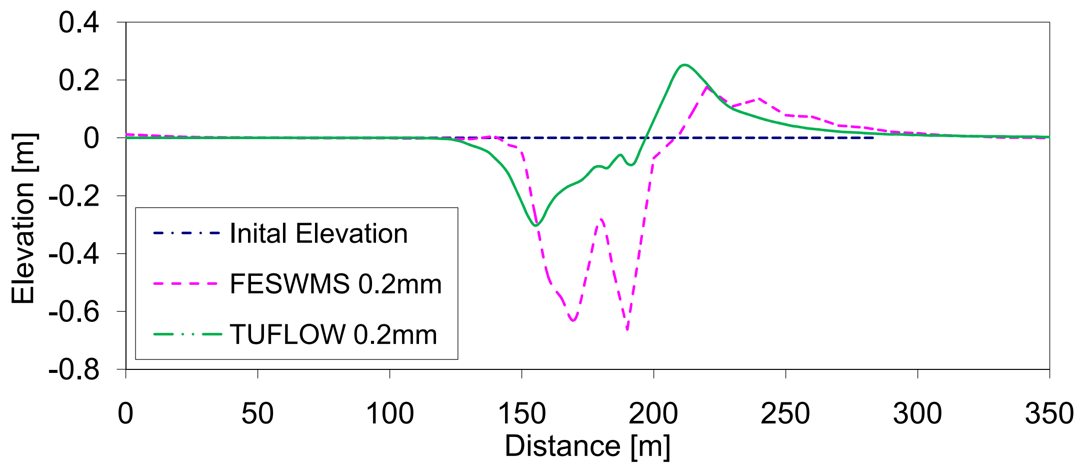

Figure D-15: Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Long Abrupt Contraction Test Case with using the Meyer-Peter and Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

Figures D-17, D-18, and D-19 show the TUFLOW and FESWMS comparisons for each particle size. The scour holes for the TUFLOW models start approximately in the same location as the FESWMS model. The scour holes for the FESWMS models are not reasonable. The larger particles should scour less but FESWMS shows more scour for the larger particles. The TUFLOW models have more deposition which is different from the other FESWMS models.

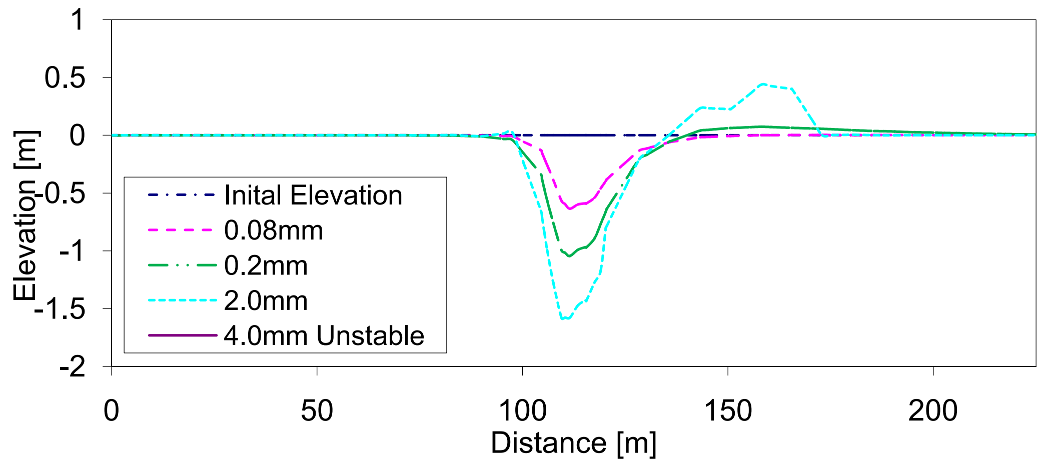

Figure D-16:Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

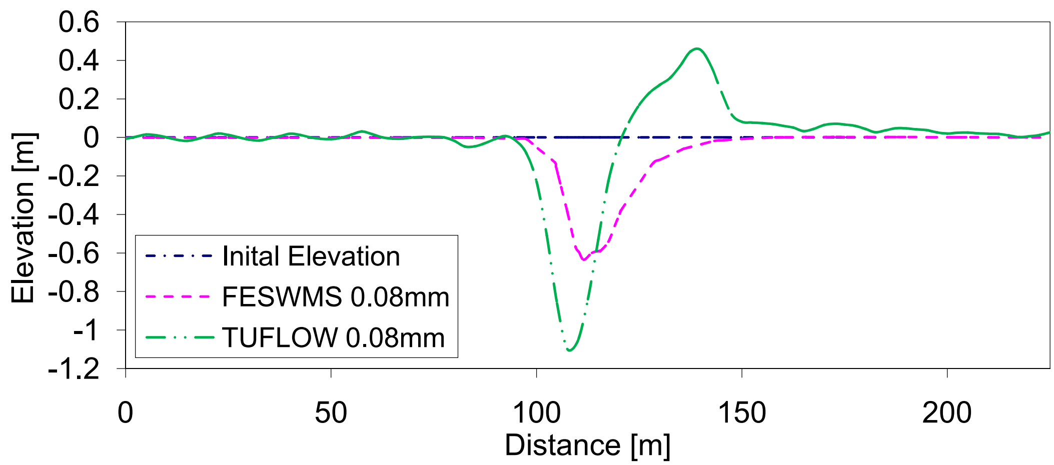

Figure D-17: Centerline Profile of the Final Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

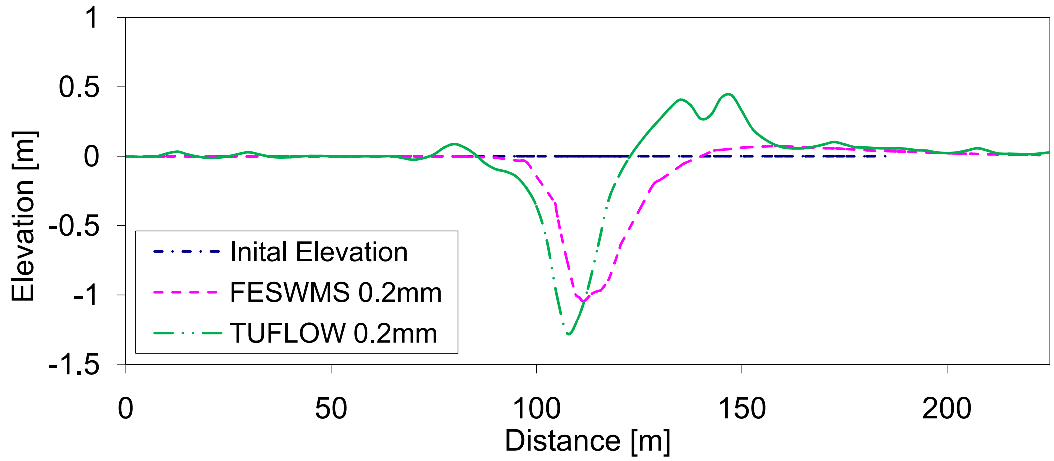

Figure D-18: Centerline Profile of the Final Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

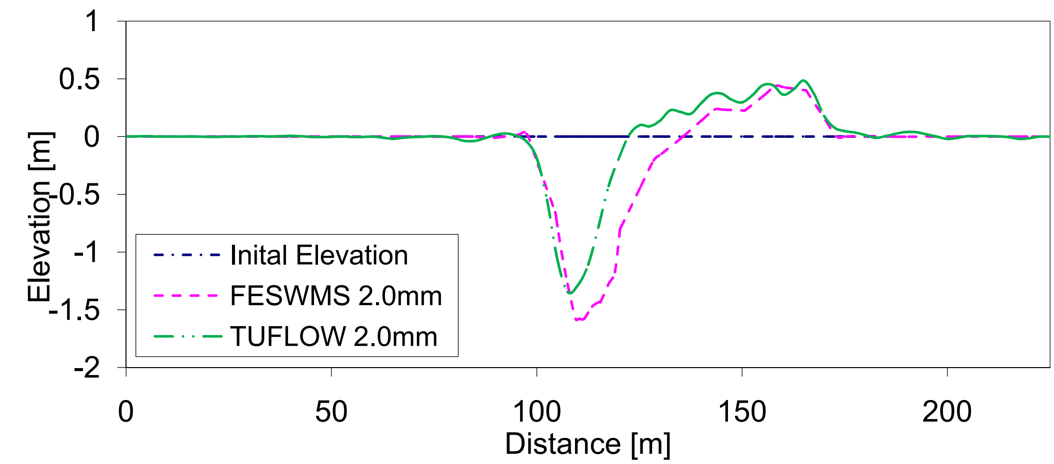

Figure D-19: Centerline Profile of the Final Elevations for a 48 Hour Simulation of the Short Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 2.0mm

D.1.2 Wide Flume with an Abrupt Contraction

The hydrodynamic solutions for TUFLOW and FESWMS provided similar profiles for the velocity magnitude and water surface elevation. The test cases using the Ackers & White method for the wide abrupt contraction model were unstable and a comparison could not be made. All of the test cases using the Meyer-Peter & Muller method ran to completion.

The results for the Meyer-Peter & Muller method in FESWMS are shown in Figure D-20. Scouring for each of the test cases began at the contraction and continued downstream. The results show that the larger the particle the more scour, which is not reasonable. The particles were deposited downstream of the contraction where the velocity decelerated.

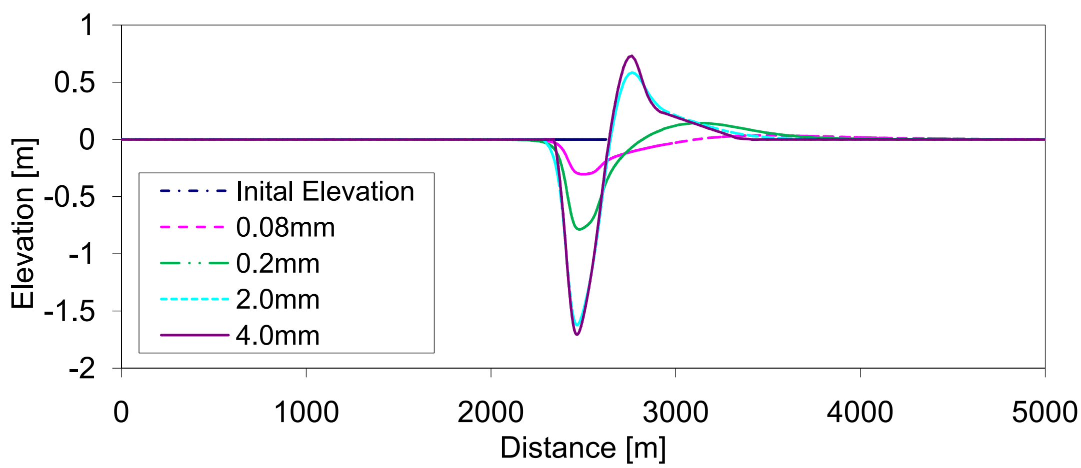

Figure D-20: Centerline Profile of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction using the Meyer-Peter & Muller method with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Figures D-21, D-22, and D-23, and D-24 show the TUFLOW and FESWMS comparisons for each particle size. The scour holes for the TUFLOW models start approximately in the same location as the FESWMS model. As with the other comparisons, FESWMS has more deposition than TUFLOW. The deposition for both models start roughly in the same location for the two larger particle sizes.

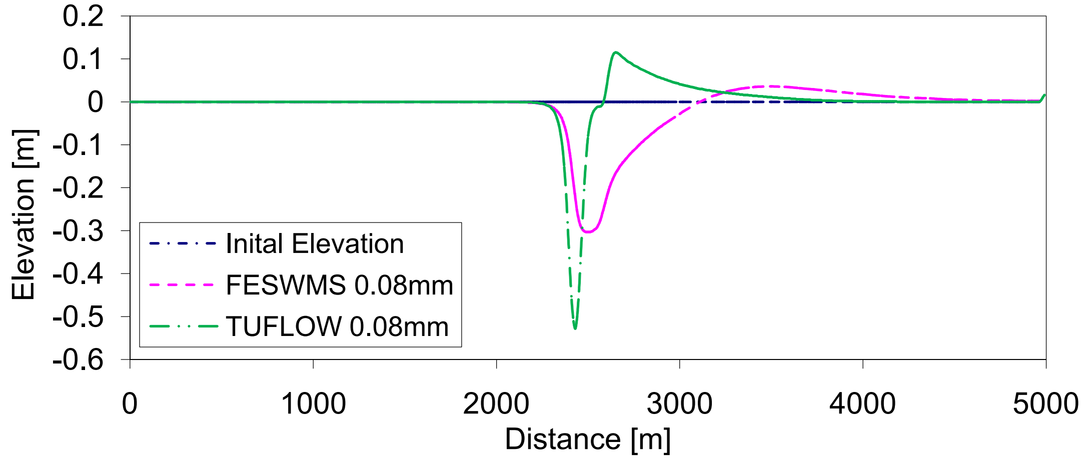

Figure D-21: Centerline Profile and Plan View of the Final Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.08 mm

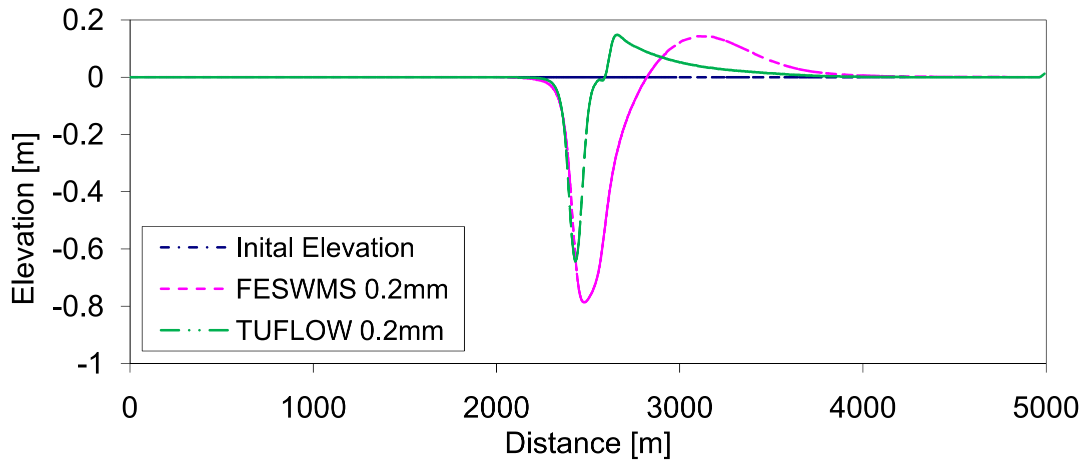

Figure D-22: Centerline Profile and Plan View of the Final Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

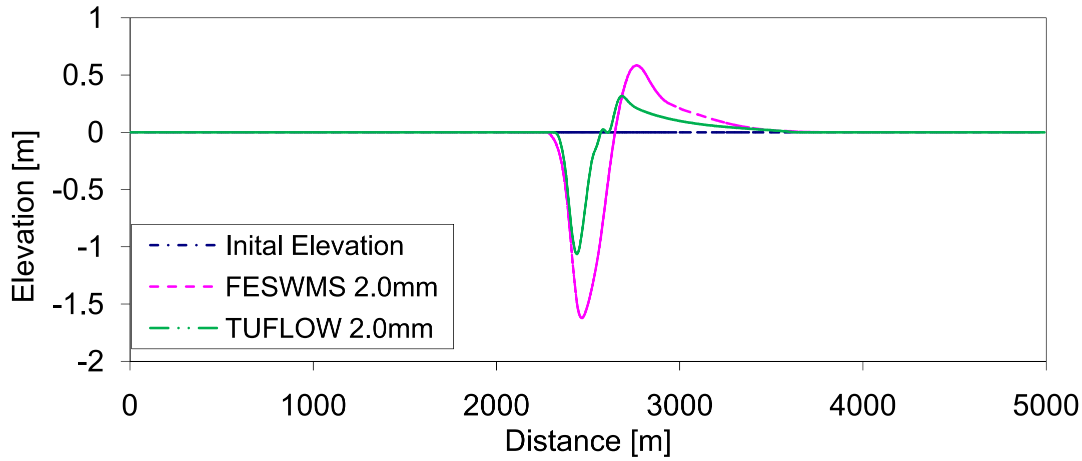

Figure D-23: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 2.0mm

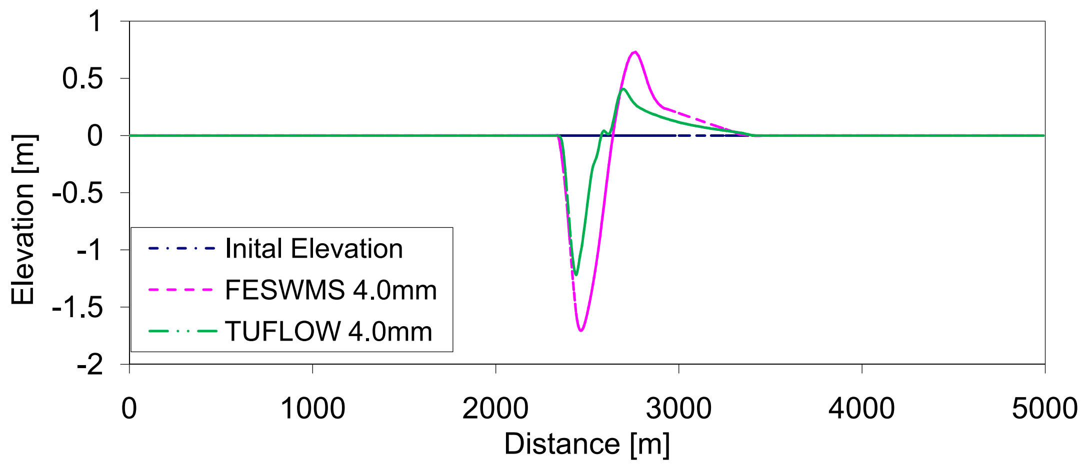

Figure D-24: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the Wide Flume with an Abrupt Contraction Test Case using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 4.0mm

D.1.3 River with a Contraction

The hydrodynamic solutions for TUFLOW and FESWMS provide similar profiles for the velocity magnitude and water surface elevation. The test cases using the Ackers

& White method for the river with a contraction model were unstable and a comparison could not be made.

All the test cases ran with the Meyer-Peter & Muller method in FESWMS and are shown in Figure D-24. Scouring for each of the test cases began at the contraction and continued downstream. The particles were deposited downstream of the contraction where the velocity decelerated. The 0.08mm test case had less scour than the larger particle sizes which is not reasonable.

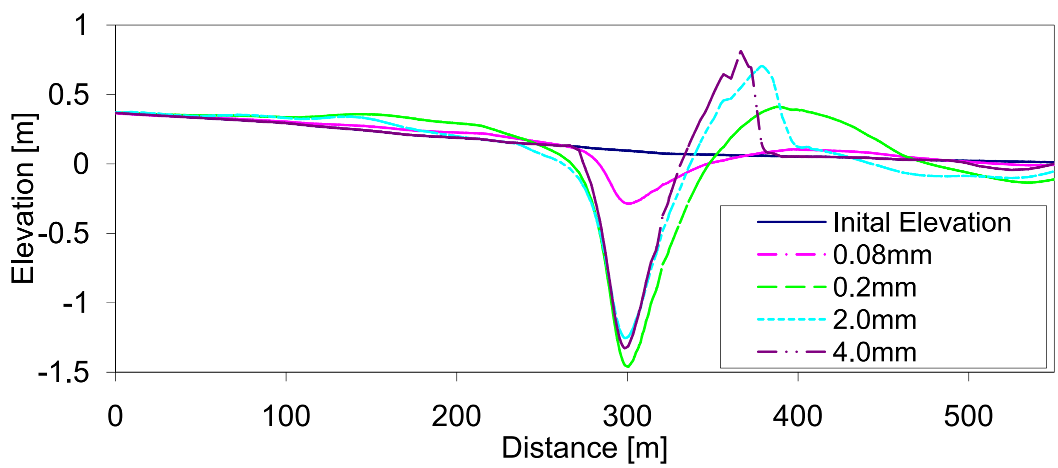

Figure D-25: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller method in FESWMS with Particle Sizes of 0.08mm, 0.2mm, 2.0mm, and 4.0mm

Figures D-26, D-27, and D-28, and D-29 show the TUFLOW and FESWMS comparisons for each particle size. The TUFLOW models have less deposition and scouring in most of the test cases. The scour holes for the TUFLOW models start approximately in the same location as the FESWMS model. The 0.08mm particle shows little scour for both models which was not expected and is either a deficiency in the code or limitation of the method.

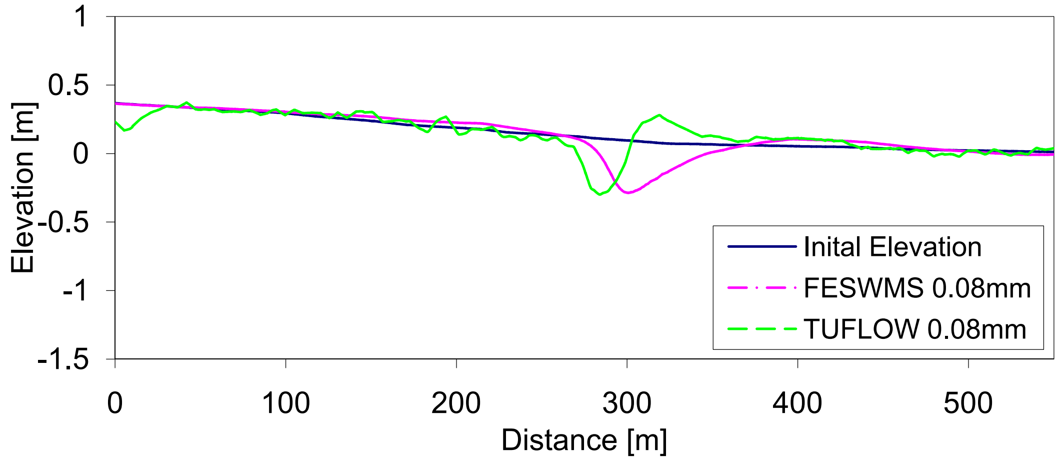

Figure D-26: Centerline Profile and Plan View of the Final Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.08mm

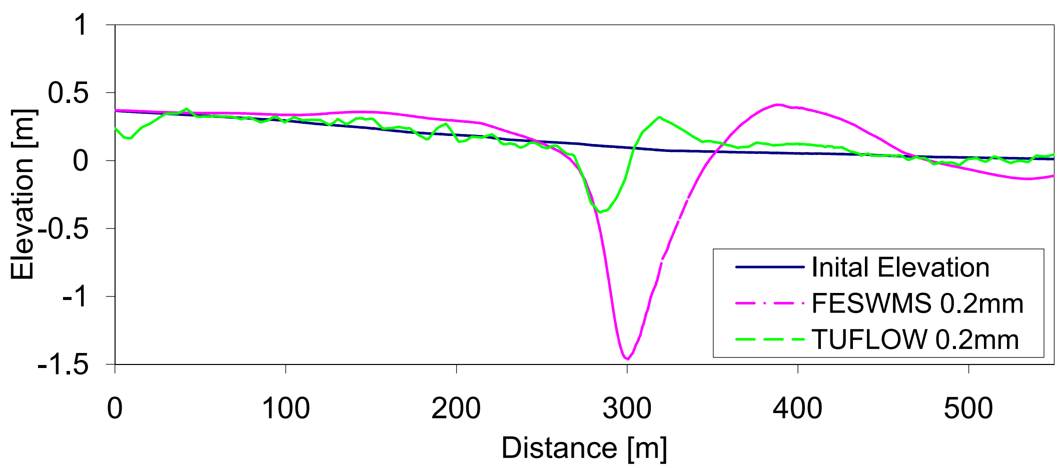

Figure D-27: Centerline Profile and Plan View of the Final Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 0.2mm

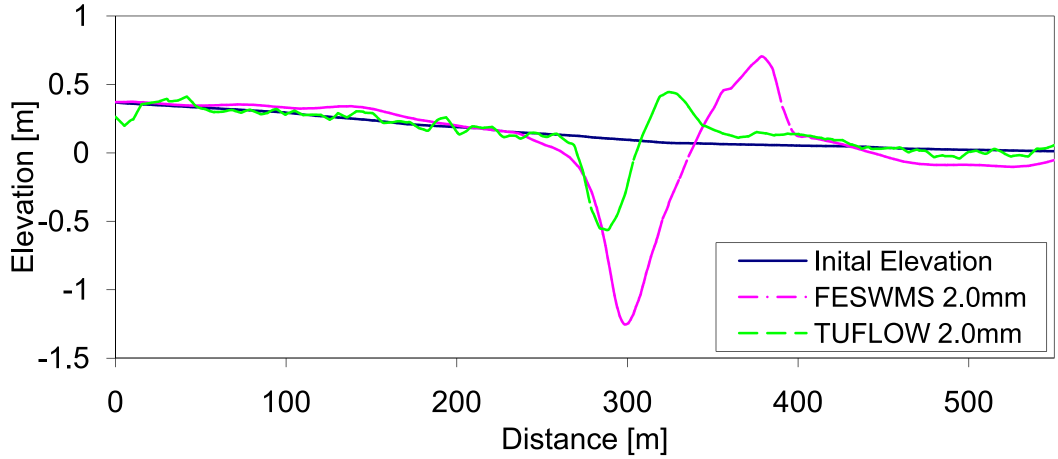

Figure D-28: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 2.0mm

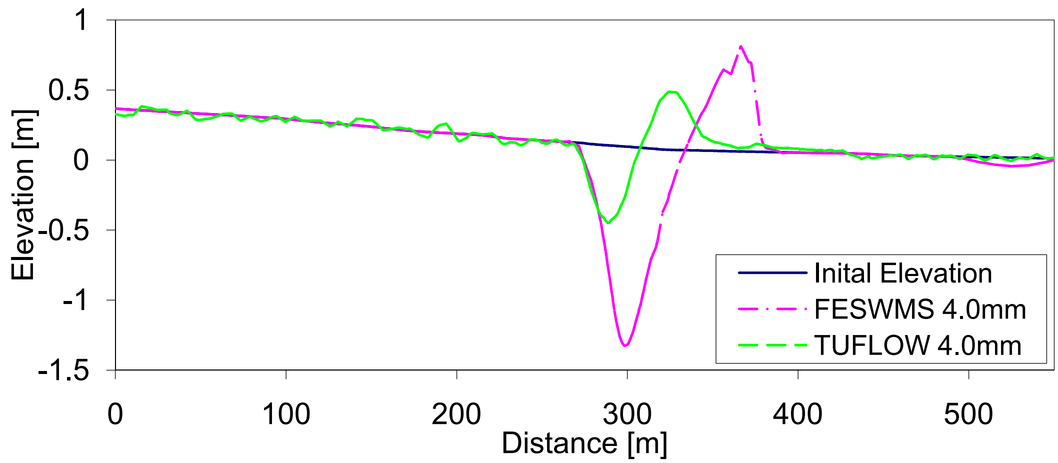

Figure D-29: Centerline Profile and Plan View of the Final Bed Elevations for a 48 Hour Simulation of the River with a Contraction using the Meyer-Peter & Muller method in FESWMS and TUFLOW with Particle Size of 4.0mm

E QUANTITATIVE

Appendix E gives the results from the TUFLOW test cases built with data from previous research with laboratory flumes and comments on those results. The last section in this chapter reviews the results from a TUFLOW simulation modeling the deposition of sediment at a river's entrance into a reservoir

E.1 Laboratory Models

The two test cases of different laboratory flumes provided additional information about the modeling of sediment transport in TUFLOW. Research included the setup of two different laboratory flumes in the St. Anthony Falls flume. Each of the test cases illustrated that TUFLOW will provide logical and intuitive results for hypothetical sediment transport test cases, some difficulties arise when modeling specific laboratory models.

As with Ipson (2006), one of the main difficulties when modeling the small laboratory flumes was the size of the model. The small size of the grid cells caused the hydrodynamic runs to give unrealistic results with wide fluctuations in velocity and water surface elevation. Another issue with the small grid cell sizes was run time. The first setup for the models created run times of two weeks, which caused difficulties in correcting errors found in the model. Others have experienced difficulties in modeling small channels with small grid cell sizes (Barton 2001). An attempt was made to scale the flume to a larger size to determine if the results would be realistic with no oscillations. The larger model did give reasonable results and had a smaller run time. While scaling the flumes could be done, it would not represent the actual conditions and would not give comparable results.

Another difficulty was the current functionality limitation of the sediment capabilities in TUFLOW. The two laboratory flumes used sediment concentration as inflow rates of sediment. TUFLOW currently only allows equilibrium inflow of sediment. A solution to this was to replicate an inflow transport rate by applying an equilibrium flowrate to an extended, sloped upstream addition to the flume as in Ipson (2006). Because of the limitations of TUFLOW, the exact laboratory conditions could not be replicated. The test cases did illustrate pattern and deposition as expected.

The following sections give a general overview and results of the two models. Because of the difficulties expressed above the narrow flume with downstream fining did not give valid results due to invalid hydrodynamic results. The wide flume with downstream fining only gave valid results for the Bagnold and Meyer-Peter & Muller sediment transport methods.

E.1.1 Narrow Flume with Downstream Fining

Seal et al. modeled downstream fining in a rectangular flume with a width of 0.3m and smooth walls (Seal et al. 1997). The flume had a flowrate of 0.049 cms which carried sediment fed to the flume at its upstream end down the flume. Because there is no option for specifying inflow sediment concentration or flowrate into TUFLOW, a steeper sloped segment was added at the upstream end of the flume. This was done to simulate a sediment concentration being dropped at the beginning of the actual flume.

Hydrodynamic models were set up for this model using a variety of grid cell sizes ranging from 0.06m to 0.3m. The hydrodynamic results for all of the models showed oscillations and inconsistent results. Others who have used small grid cell sizes have had similar problems (Barton 2001). Because there were no valid hydrodynamic results, no sediment transport models were set up.

E.1.2 Wide Flume with Downstream Fining

Toro-Escobar et al. completed several flume experiments on downstream fining in flumes with a width of 0.3 and 2.7 meters (Toro-Escobar et al. 2000). These experiments were an extension of seal et al. (1997) with three additional experiments called run 4, 5, and 6. Only run 5 was setup and tested in TUFLOW. Run 5 had a flume with a width of 2.7 meters and examined downstream fining of sandy sediment along the length of the flume. As with Seal's experiments, run 5 included an inflow sediment rate, but TUFLOW does not currently have that capability. Therefore, the model was modified by adding a steeper sloped extension to the upstream boundary. The same model setup used in Ipson (2006) with a slope that gave approximately 20 kg/min (roughly two-thirds used in actual experiment) entered the grid. This was chosen to test if the results were as expected and not the same issues found in Ipson (2006). The results show a lot more deposition than expected. To minimize deposition on the added extension, sediment transport for this section was turned off by changing the bed code to 0. Doing this caused a different amount of sediment to deposit which did not match the laboratory flume, but gave insight on deposition downstream.

Figure E-1 shows the hydrodynamic water surface and elevation solution for the wide flume with downstream fining. The flow is subcritical throughout the entire model with little backwater up the extended section of the flume. Figure E-2 shows the steady state solution for the flume. The results show a high velocity on the steep section which then drops off when it reaches the actual section of the flume. The velocity decelerated before it reaches the actual flume.

Figure E-3 through E-6 show the change in bed elevation over time for the modified Toro-Escobar test case using the Bagnold and Meyer-Peter & Muller method respectively for sediment transport. The pattern of deposition begins at the break in slope due to the velocity decelerating. The amount of deposition increases over time and extends downstream as expected. Because the velocity drops upstream of the actual flume, deposition happened upstream of actual flume, which causes the results to not match the observed final bed elevation. The observed results show that more sediment was being added to the flume than the water could transport. Figure E-4 and E-6 show a different deposition pattern at the downstream end of the flume than the laboratory flume.

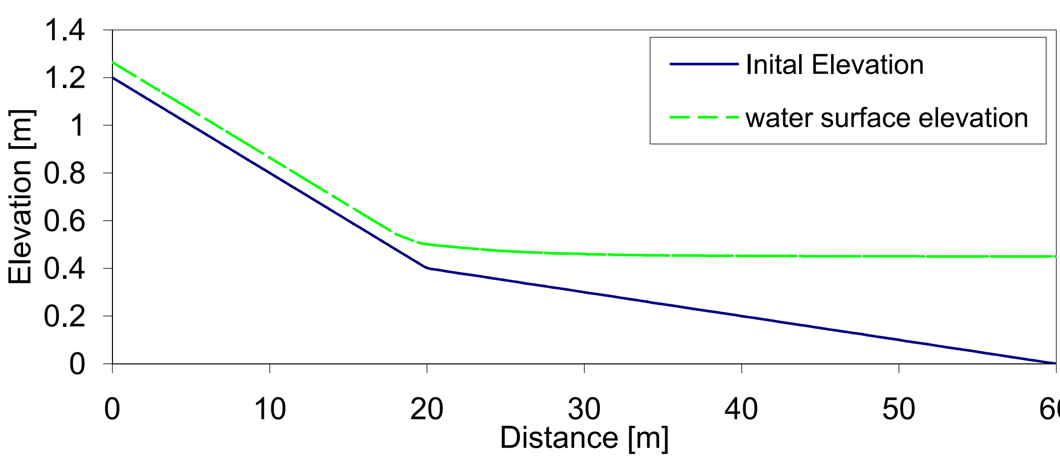

Figure E-1: Steady State Solution of Water Surface Elevation for a 48 Hour Simulation of the Wide Flume with Downstream Fining

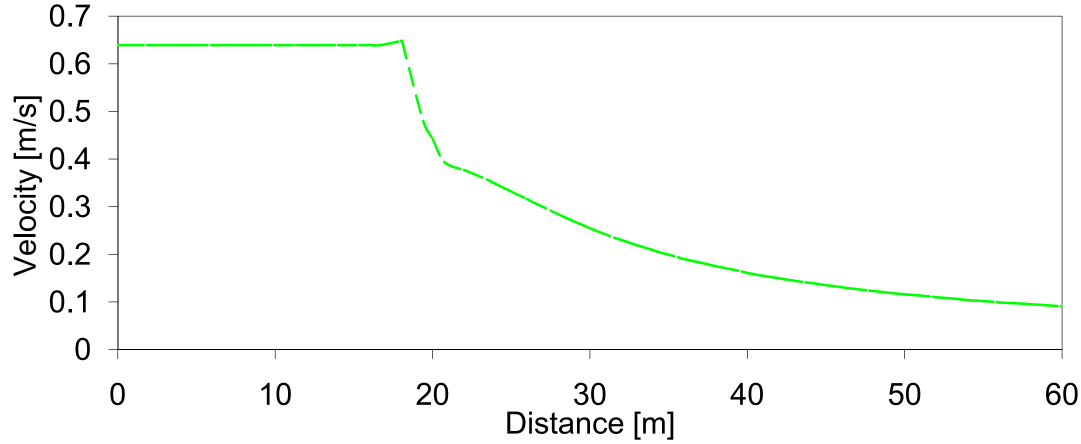

Figure E-2: Steady State Solution of Velocity for a 48 Hour Simulation of the Wide Flume with Downstream Fining

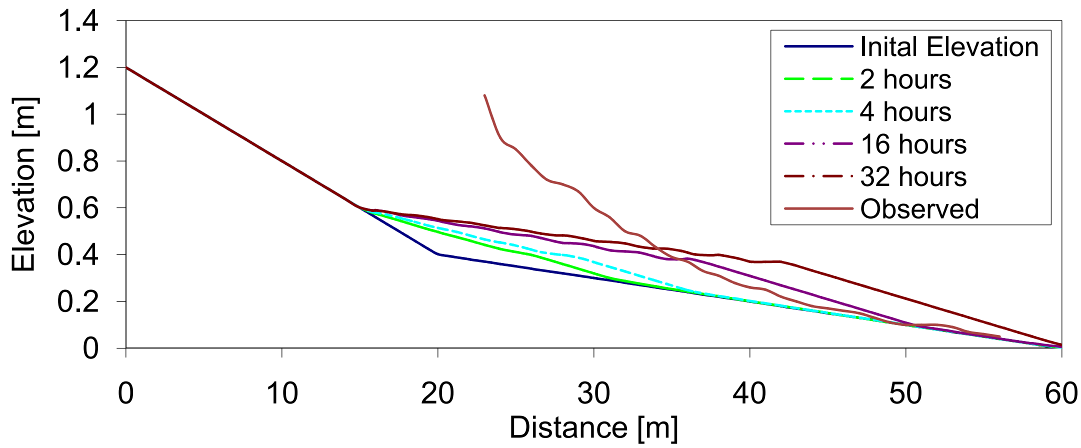

Figure E-3: Centerline Profile and Plan View of the Final Elevations over a 48 Hour Simulation of the Wide Flume using the Bagnold Method with Bed Smoothing

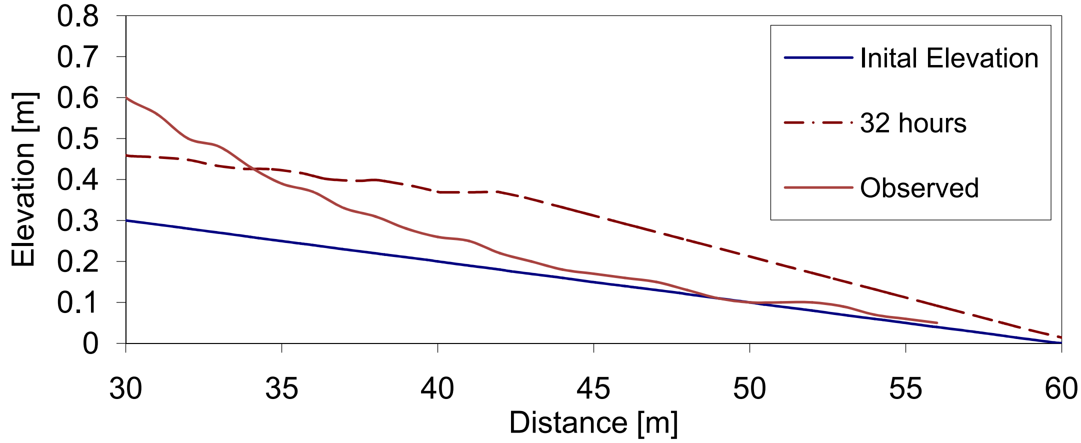

Figure E-4: Zoomed in Centerline Profile and Plan View of the Final Elevations over a 48 Hour Simulation of the Wide Flume using the Bagnold Method with Bed Smoothing

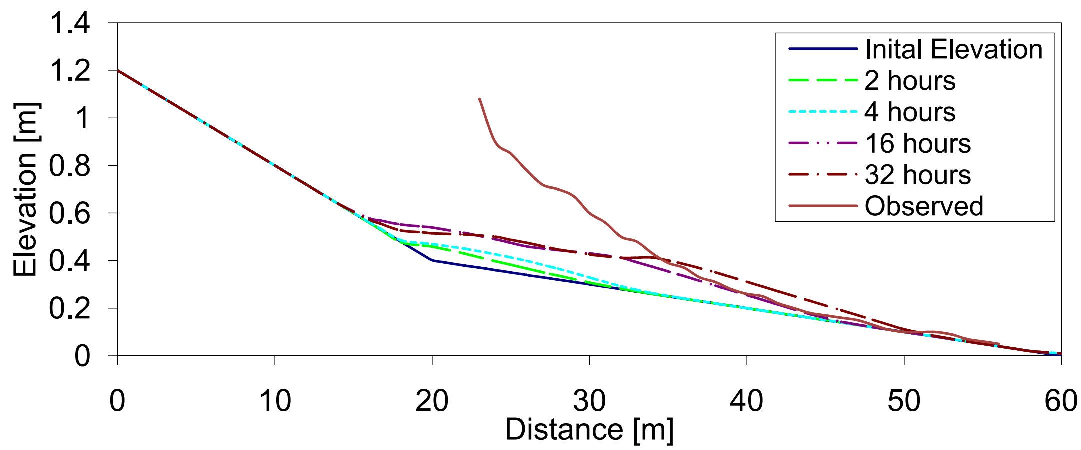

Figure E-5: Centerline Profile and Plan View of the Final Elevations over a 48 Hour Simulation of the Wide Flume using the Meyer-Peter & Muller Method

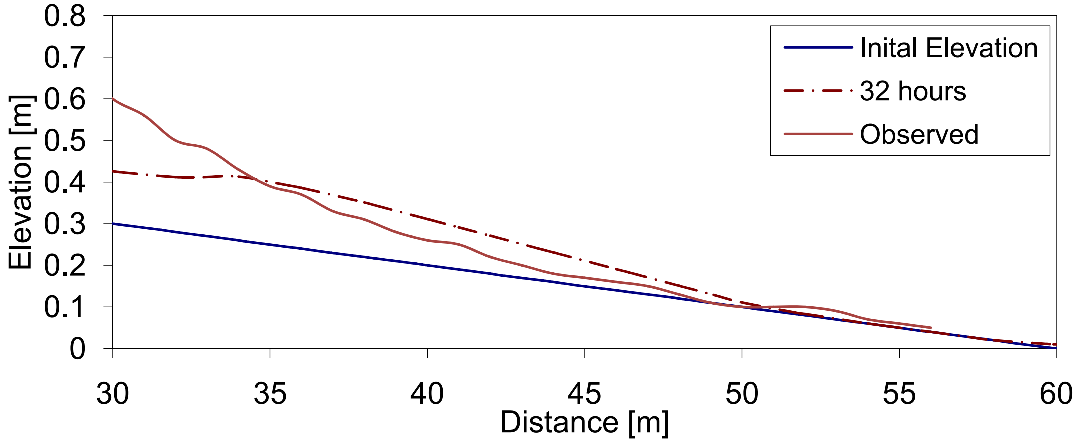

Figure E-6: Zoomed in Centerline Profile and Plan View of the Final Elevations over a 48 Hour Simulation of the Wide Flume using the Bagnold Method with Bed Smoothing

E.2 Deposition in a Reservoir

The test case for the flume entering the reservoir completed all 180 days for the hydrodynamic run and each method of sediment transport. The steady state water surface elevations at the downstream end of the flume are shown in Figure E-7. The results show subcritical flow throughout the entire model with a large amount of backwater.

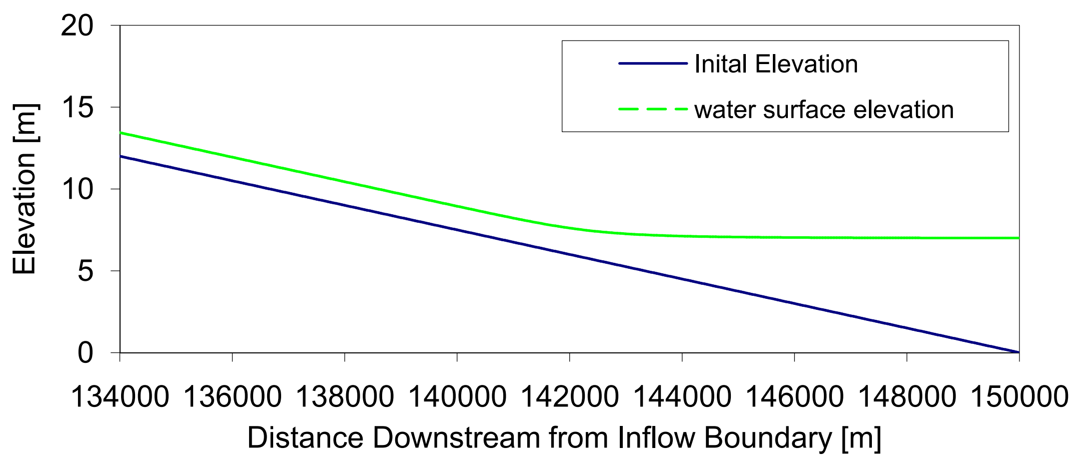

Figure E-7: Profiles for Water Surface Elevation and Original Bed Elevation

Figure E-8 shows the steady state solution for the velocity at the downstream end of the flume. The velocity peaks at 1.4 cms than slows down to 0.2 cms when the flow reaches the backwater.

Figures E-9 through E-12 show the change in bed elevation over time for the deposition in a river test cases. The pattern of deposition begins where the velocity begins to decelerate due to the backwater. The amount of deposition increases over time and extends downstream. The Ackers & White method shows the formation of a delta and looks comparable to the results found in Hotchkiss and Parker (2001). The other methods do not form deltas and deposition is spread out farther than expected.

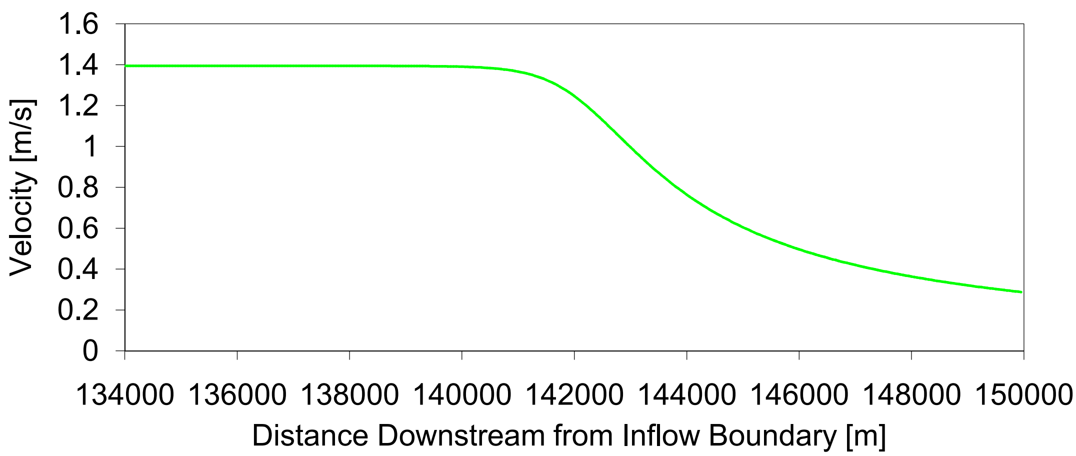

Figure E-8: Steady State Solution of Velocity for a 180 Day Simulation at Downstream End of Flume Emptying into a Reservoir

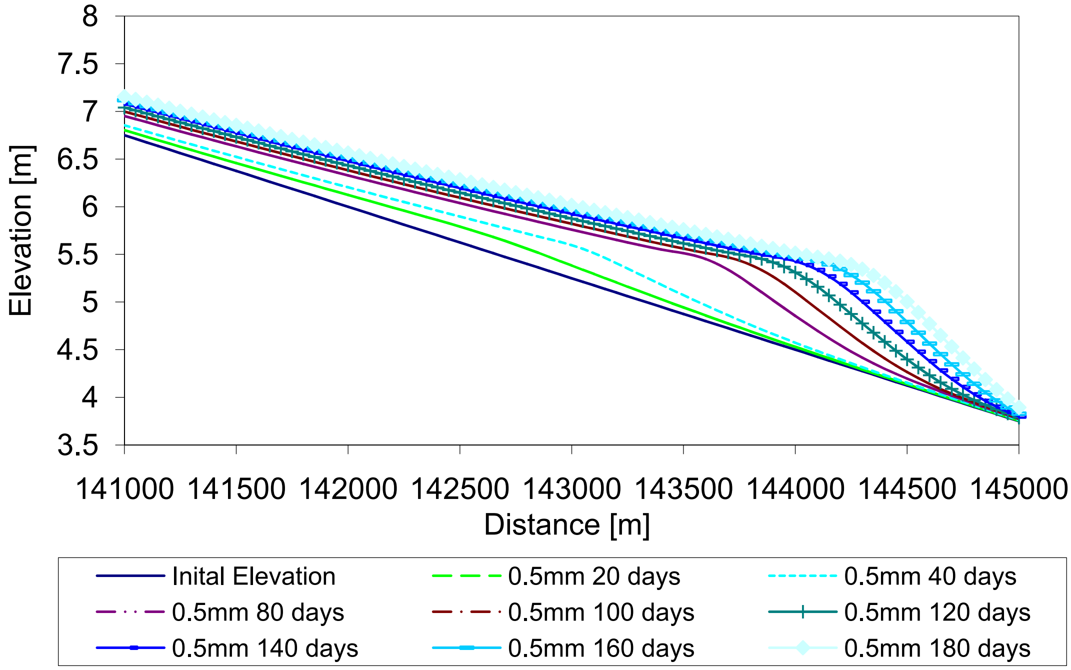

Figure E-9: Profiles for Original Elevation, and Bed Elevations over 180 Days using the Ackers & White Method

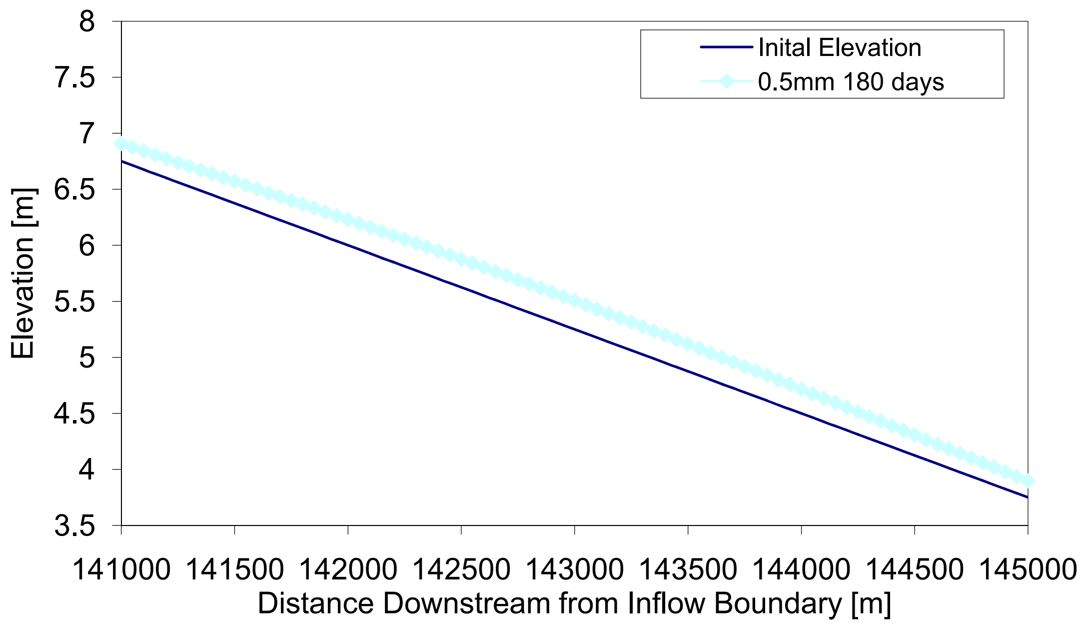

Figure E-10: Profiles for Original Elevation, and Bed Elevations over 180 Days using the Bagnold Method

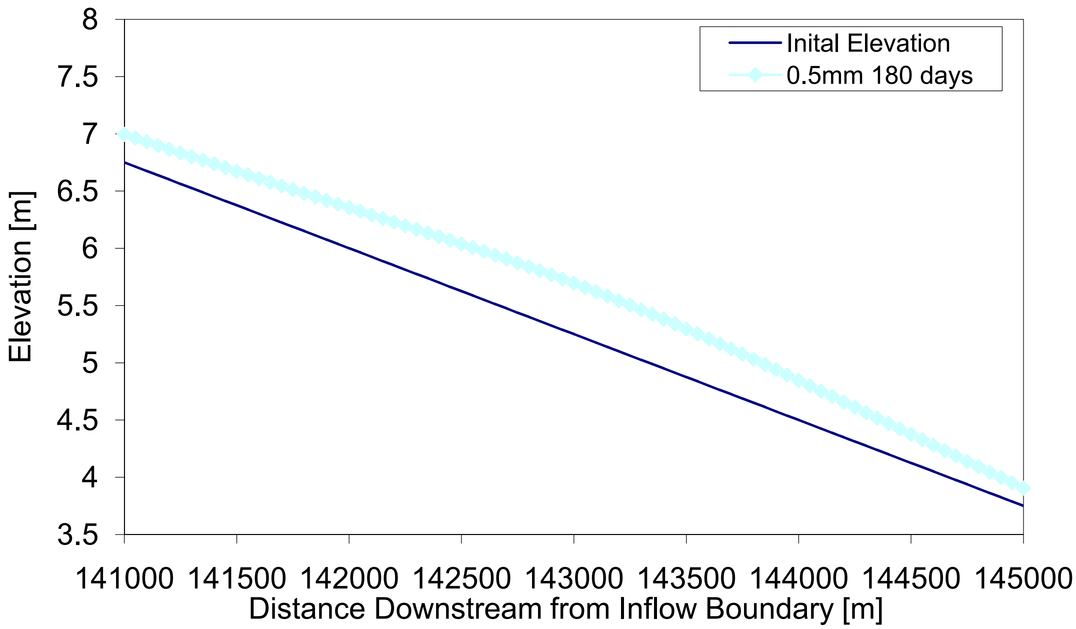

Figure E-11: Profiles for Original Elevation, and Bed Elevations over 180 Days using the Meyer-Peter & Muller Method

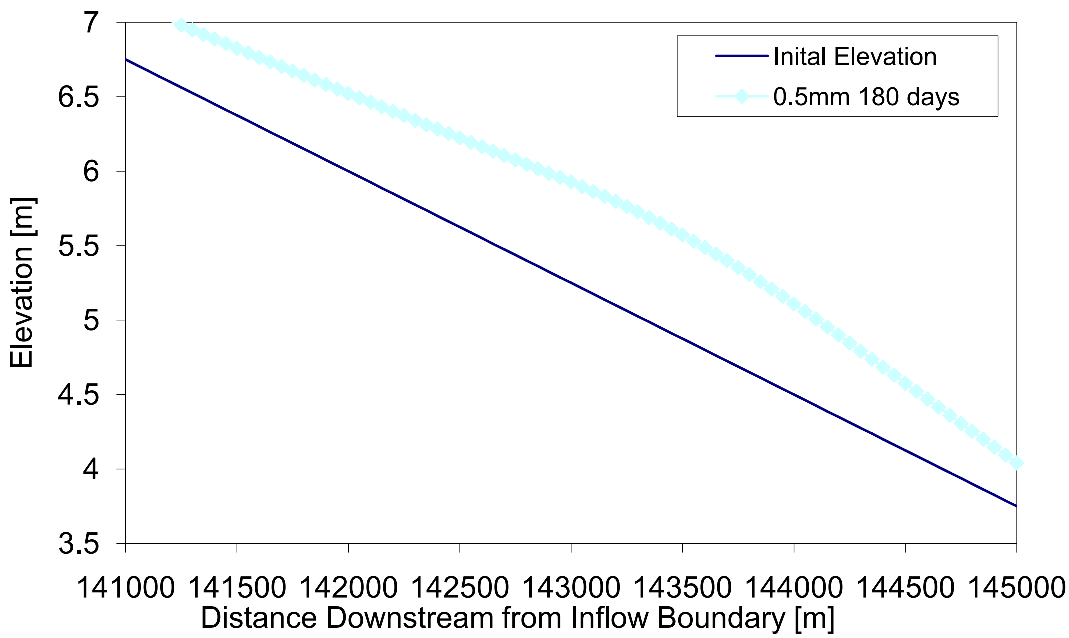

Figure E-12: Profiles for Original Elevation, and Bed Elevations over 180 Days using the Van Rijn Method