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Comparison of Numerical Model Results for Flow in a Constriction

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Abstract

The performance characteristics of the Diffusion Hydrodynamic Model (DHM) have been analyzed, with a focus upon its ability to predict the head loss for flow in a constriction. DHM has been in use since the late 1970s and was published by the USGS as a technical report in the mid-1980s The end DHM result is compared with the published data of three widely used hydraulic models (MIKE 21, TUFLOW and HEC-RAS 2D). For the purpose of verifying all the model outputs, the baseline data is obtained from the equation provided by the Federal Highways Administration (FHA). The comparison, along with the grid sensitivity test, underscores the reliability of the DHM.

Introduction

Numerical modeling of free surface flow requires the application of models that can be broadly placed under two categories – first and second-generation models. The first generation models, developed before the 1990s, focused on solving basic flow equations with few input parameters. These equations are based on the conservation of mass and energy principles. The rise in computational power and the need to capture phenomena at the microscale level brought the advent of second-generation numerical models that solve the higher dimensional shallow water or Navier Stokes equations (or its variants) since the 1990s. Characteristic features of these models include millions of cells or nodes in the computational domain, complex flow equations to predict various phenomena (i.e., turbulence, surface tracking, mixing length, air entrainment, simulation of eddys) across varying spatial and temporal scales, high-performance processors to reduce the computational time and colorful visualization tools. While some of the applications in hydraulics and hydrology require using these complex models, there are other applications where the results from first-generation models will suffice.

The Diffusion Hydrodynamic Model (DHM) is one of the first computational solutions of the Navier-Stokes equations written in the diffusion routing form and is formulated as an integrated control volume mass balance set of equations in matrix form [1]. Using an integrated finite difference numerical scheme, up to 250 nodes and cells were defined for use. The DHM soon served as a foundation for other finite-difference algorithms [2], resulting in computational programs for solving a variety of transport problems. As the first such computational program, the application of the DHM today serves the additional role as a baseline analysis that can be used to examine the performance of newer computational modeling algorithms in comparison to the computational results from the long-term tested DHM.

In this work, results from DHM are compared with the published results [3] of MIKE 21, TUFLOW, HEC-RAS 2D, and the baseline FHA equations for predicting the head loss from two-dimensional flow through a constriction in a rectangular channel. The close agreement in the results underscores the reliability of the freely available DHM.

Model Descriptions

> **" HEC-RAS 2D is one of the most widely used models in the hydraulics community. "**

DHM solves the two-dimensional overland flow coupled with one-dimensional open channel flow equations and includes an interface between these two flow regimes through using source and sink term approximations. It is one of the first general-purpose computational solutions to a 2D formulation of the Navier-Stokes equations. The model is capable of approximating such hydraulic effects as backwater, drawdown, channel overflow, storage, and ponding. DHM was upgraded to EDHM (Enhanced DHM), with the primary focus of the enhancement being to increase the array size of variables from 250 to 9999. The model's companion website (www.diffusionhydrodynamicmodel.com) has the source codes and documentation, along with various applications for which the model was applied.

MIKE 21 solves two-dimensional free surface flows where stratification can be neglected. It was originally developed for flow simulation in coastal areas, estuaries, and seas. The various modules of the system simulate hydrodynamics, advection-dispersion, short waves, sediment transport, water quality, eutrophication, and heavy metals. [4]

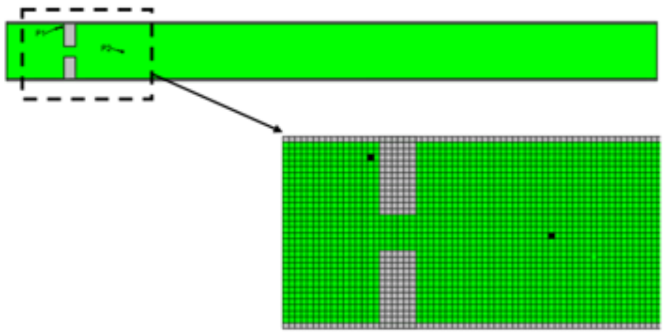
Two-dimensional unsteady flow (TUFLOW) solves the two-dimensional depth-averaged shallow water equations by using a structured grid system with an alternating direction implicit scheme (Stelling Finite Difference). The model incorporates the 1-D hydrodynamic network software ESTRY, or quasi-2D modeling system, based on the full one-dimensional free surface flow equations. [5]

HEC-RAS 2D is one of the most widely used models in the hydraulics community. RAS 2D (5.0.1) solves the two-dimensional Saint-Venant equations [6] for shallow water flows using the full momentum computational method. The equations can model turbulence and Coriolis effects. For flow in sudden contraction, which is accompanied by high velocity, using the full momentum method in RAS 2D is recommended. The model uses an implicit finite volume solver.

DHM Development

Figure 1 is the definition sketch of the test problem. The rectangular channel was 3100 ft long and 320 ft wide. The constriction was 60ft x 60ft. The channel length before constriction was 310 ft and its length after constriction was 2730 ft. The computational domain in DHM had 10 ft square cells, and the total number of cells was 9920. The longitudinal slope was 1%, the transverse slope was zero, and the model ran for a total of 1 hour. The upstream inflow was 1000 cfs. Since there were 30 cells at the upstream end, a uniform steady inflow of 33.3 cfs was specified at each of the cells. At the downstream end, a free overall boundary was specified. Constricting the flow area resulted in loss of energy. This loss of energy was reflected in a rise in energy gradient line and energy upstream of the constriction. What was of interest was to estimate the head loss that occurs between points 1 and 2 (shown in Figure 1). The head loss (HL) was equal to WSE2 – WSE1, where WSE is the water surface elevation.

Figure 1. Definition sketch of the test problem along with the location of the two points (P1 and P2)



Results

Table 1 shows the comparison of the head loss value obtained from each of the models, along with the published data of other models. It is noted in this paper that the computational models are compared with respect to head loss (as given in [3]) through the constriction and this is the primary form of assessment. The DHM WSE change value is within the range of predictions from the other models, although all of them are above the FHA value. Sensitivity analyses on DHM cell size were performed to check the effect of varying cell size on water surface elevation change and energy loss (Table 2). Since the maximum number of cells in enhanced DHM is limited to 9999, the cell size was increased from 10ft to 20ft, which resulted in 2635 cells in the domain. The results showed that the DHM output is not sensitive to cell size. Figures 2 through 4 are plots of velocity flow vectors in the vicinity of the flow constriction. Figure 4, which is the normalized velocity vector plot, was generated using the quiver function available in matplotlib library of python.

" the DHM not only provides a computational approximation to the modeled flow equations, but it is also an approximation of the governing flow equations themselves. "

Table 1. Comparison of Change in Water Surface Elevation at Constriction between DHM and Published Modelling Results*

MODEL	WSE CHANGE (FT)
MIKE 21	1.28
TUFLOW	0.99
HEC-RAS 2D	1.27
DHM	1.16
FHA Equation	0.81

*Except for DHM, all other results were obtained from the literature [3]

Table 2. Effect of Cell Size on Change in Water Surface Elevation & Bernoulli's Energy Loss

DHM DOMAIN CHARACTERISTICS	CHANGE IN WATER SURFACE ELEVATION (FT)	BERNOULLI'S ENERGY LOSS (FT)
Number of cells = 9920 (10ft grid)	1.16	1.08
Number of cells = 2635 (20ft grid)	1.20	1.14

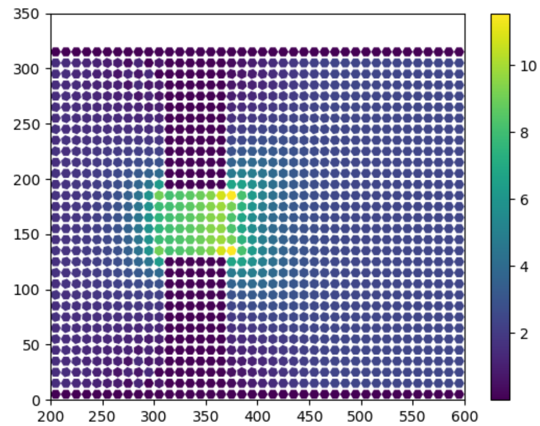


Figure 2. DHM predicted flow velocities at the center of the cells in the vicinity of the flow constriction

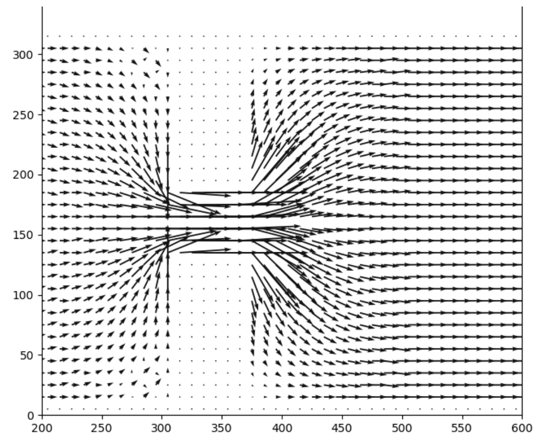


Figure 3. DHM predicted velocity vector plot

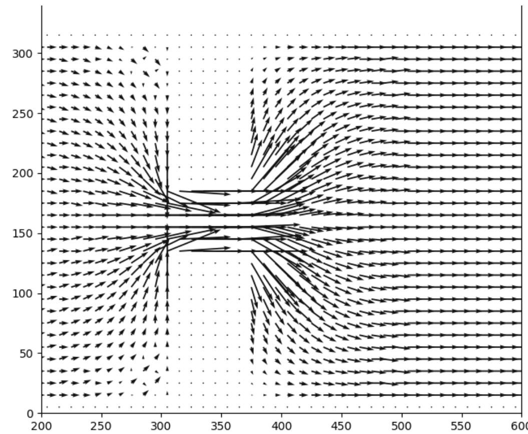


Figure 4. DHM predicted normalized color-coded velocity vector plot

Conclusions

The primary goal of this paper was to evaluate the performance of DHM against more popular hydraulic models and to compare their predicted head loss value for flow in a constriction at a constant mesh size. Our intent was not to determine if one model is better than the others or to recommend any particular model. Instead, it was to demonstrate the ability of DHM, which solves simplified flow equations and, as such, is an approximate solution to the governing boundary value problem under study. Consequently, the DHM not only provides a computational approximation to the modeled flow equations, but it is also an approximation of the governing flow equations themselves.

Having a baseline modeling outcome, such as one produced by the DHM, provides a link that spans across the modeling technology evolution that depicts computational outcome variation with modeling technology growth. Currently, some of the most computationally intense outcomes are developed by application of CFD type technology, which entails tens of thousands to millions of computational cells being involved in the computational solution. Such intensity is beyond practical quality control without the use of still more computational software applications which, in turn, are subject to their own quality control issues. Having the early computational capability available provides another path towards quality control and validation of the computations. Continued work is still needed in connecting computational solutions to actual flow regime characteristics for even some of the more fundamental hydraulic situations. For example, the fundamental junction structure in storm drain systems involves multiple inflow pipe or channel inlets into a junction structure that contains properties of elevation drops and angle points, among other features. Although there are several computer programs that purport to solve the energy and pressure-plus-momentum equations for that situation, there still is yet to be a general solution that provides a high-precision computation. Other complicated hydraulic situations exist, as well. Currently, there appears to be more attention and investment being given to computational detail and visualization techniques, while the need to develop closed-form mathematical solutions continues to be a challenge. Consequently, having other computational options for solving complicated situations, such as the example use that was given for the DHM technology, provides another venue for examining quality control of computational modeling.

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