A Review of One-Dimensional Finite-Volume Solvers for Mixed Free-Surface and Pressurized Flows

International Conference on Water Management Modeling

Toronto, Canada

March 6, 2025

Peter Klaver, PE

Senior Hydraulics Lead, Limnotech, Ann Arbor MI USA

LimnoTech

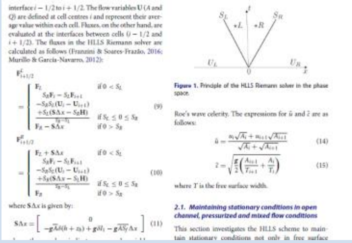
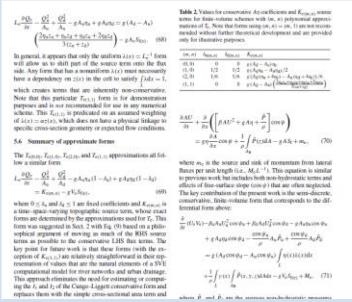
Why look at finite volume solvers?

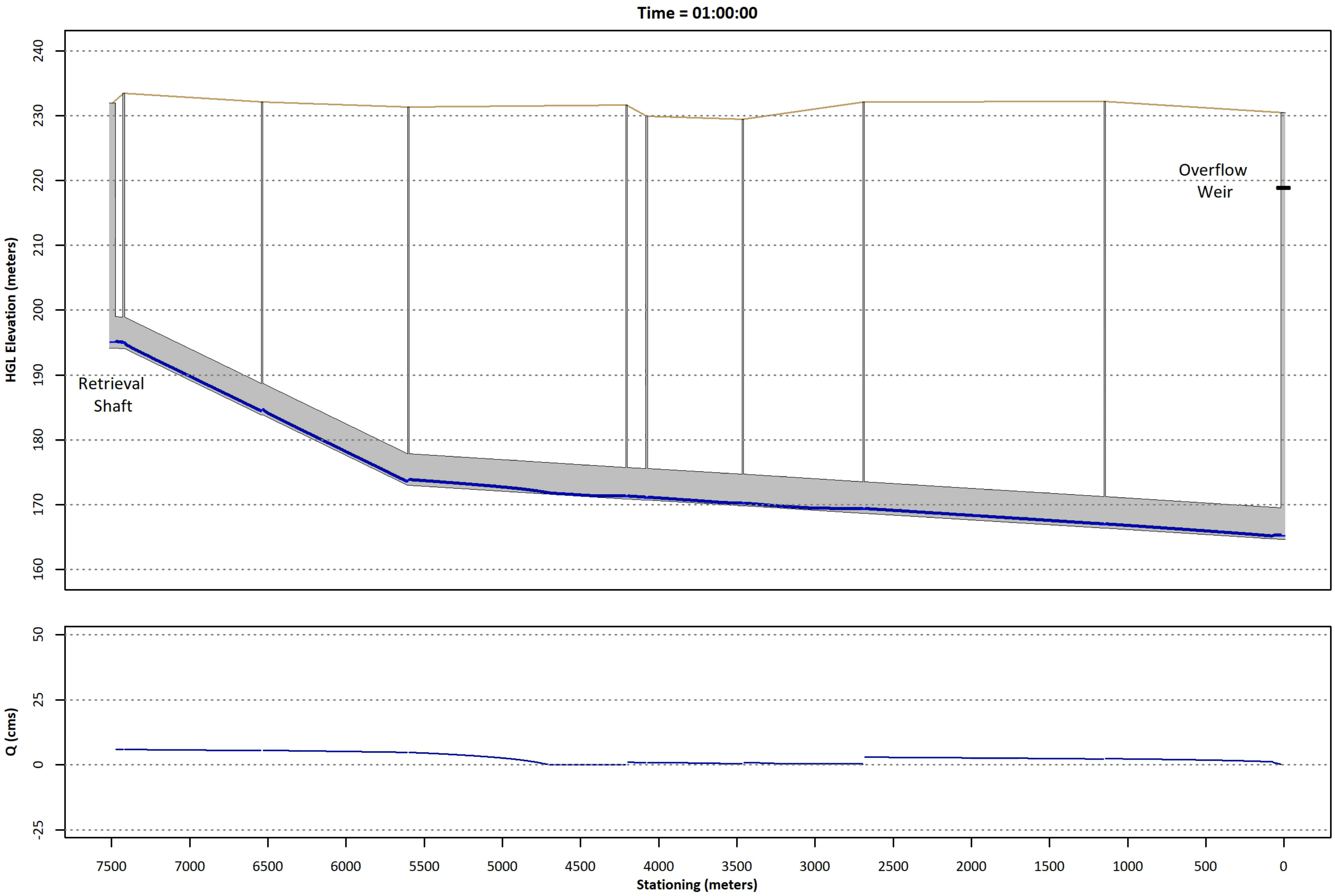
- “Finite volume” is a specific approach to the numerical solution of differential equations. The approach has desirable properties when applied to “conservation laws”.
- We use conservation laws, including a hyperbolic system that is notoriously tricky. The special case of closed conduits, where both free surface and pressurized flow regimes may be present at the same time, poses an additional challenge.
- It’s clear we should benefit from codes using this approach, but adoption of FVS by practitioners has been gradual.
- There is genuine value in getting FVS approaches into more general use:
  - Better information for designers;
  - Useful feedback from the so-called “real world”

A snapshot of FVS presentations at ICWMM

Title	Authors	Year
Surge Modeling in Sewers using the Transient Analysis Program (TAP)	Karen Ridgway and Gregory J. Kumpula	2007
An Efficient Finite-Volume Scheme for Modeling Water Hammer Flows	Arturo Leon, Mohamed S. Ghidaoui, Arthur R. Schmidt and Marcelo H. Garcia	2007
Surge Modeling in Sewers using Alternative Hydraulic Software Programs	Karen Ridgway and Gregory J. Kumpula	2008
Evaluating Surge Potential in CSO Tunnels	Karen Ridgway	2009
Surge Analysis for the Proposed OSIS Augmentation Relief Sewer Tunnel	M.P. Cherian, Ari Pandian, Karen Ridgway and Greg Barden	2010
Illinois Transient Model: Simulating the Flow Dynamics in Combined Storm Sewer Systems	Arturo Leon, Nils Oberg, Arthur R. Schmidt and Marcelo H. Garcia	2011
Kinematics of Entrapped Air Pockets Within Stormwater Storage Tunnels	Jose Vasconcelos and Carmen D. Chosie	2013
Modeling the Motion and Spread of Air Pockets within Stormwater Sewers	Thomas M. Hatcher, Carmen D. Chosie and Jose Vasconcelos	2014
Modeling of Transient Pneumatic Events in a Combined Sewer Overflow Storage Tunnel System	Peter Klaver, David Collins, Kurt Robinson and Scott Bell	2016
Application of a Hydraulic and Pneumatic Transient Model to Investigate Pavement Heaving near a Large Diameter Sewer	Peter Klaver, Joshua Hallsten and Jon Bergenthal	2019
Multiphase Rapid Filling Conditions of Tunnel System in Columbus, Ohio	Jose Vasconcelos, Hazem Gheith, Robson L. Pachaly, Mohamed Abdel-Latif and Robert Herr	2022

Three candidate FVS frameworks

Name	Mixed Flow Approach	Solution Scheme	Platform
Illinois Transient Model (ITM)	Two systems of equations, with interface tracking		Windows, operates through EPA SWMM GUI
OpenSHAFT	One system of equations, two-component pressure		Windows/Linux console
SWMM5-plus	One system of equations, dynamic Preissmann slot		Console prompt at present (Linux); integration with EPA SWMM coming

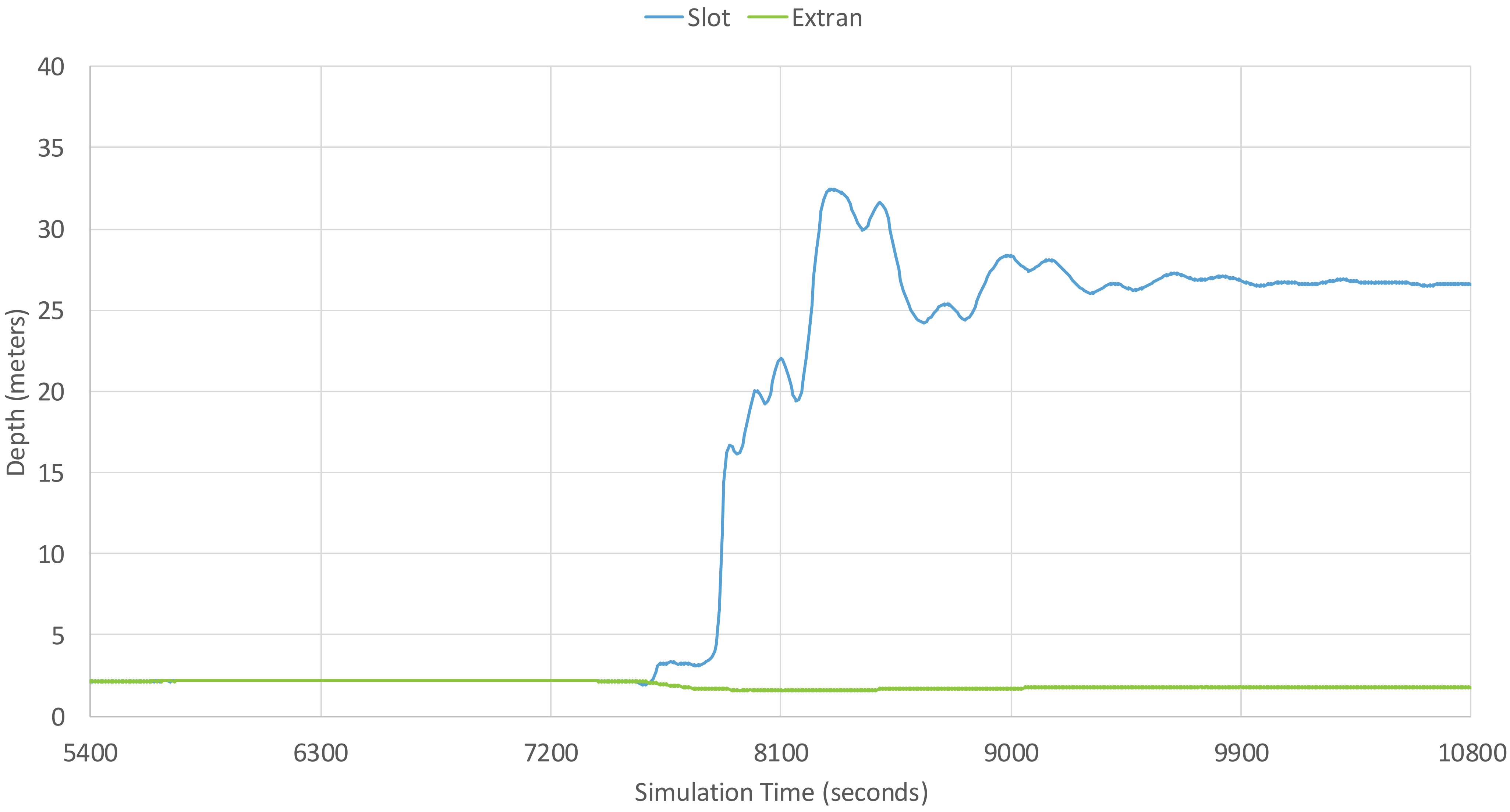

Time = 01:00:00
HGL Elevation (meters)
240
230
220
210
200
190
180
170
160
Overflow
Weir
Retrieval
Shaft
Q (cms)
50
25
0
-25
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Stationing (meters)

Evaluation of Modeling Results

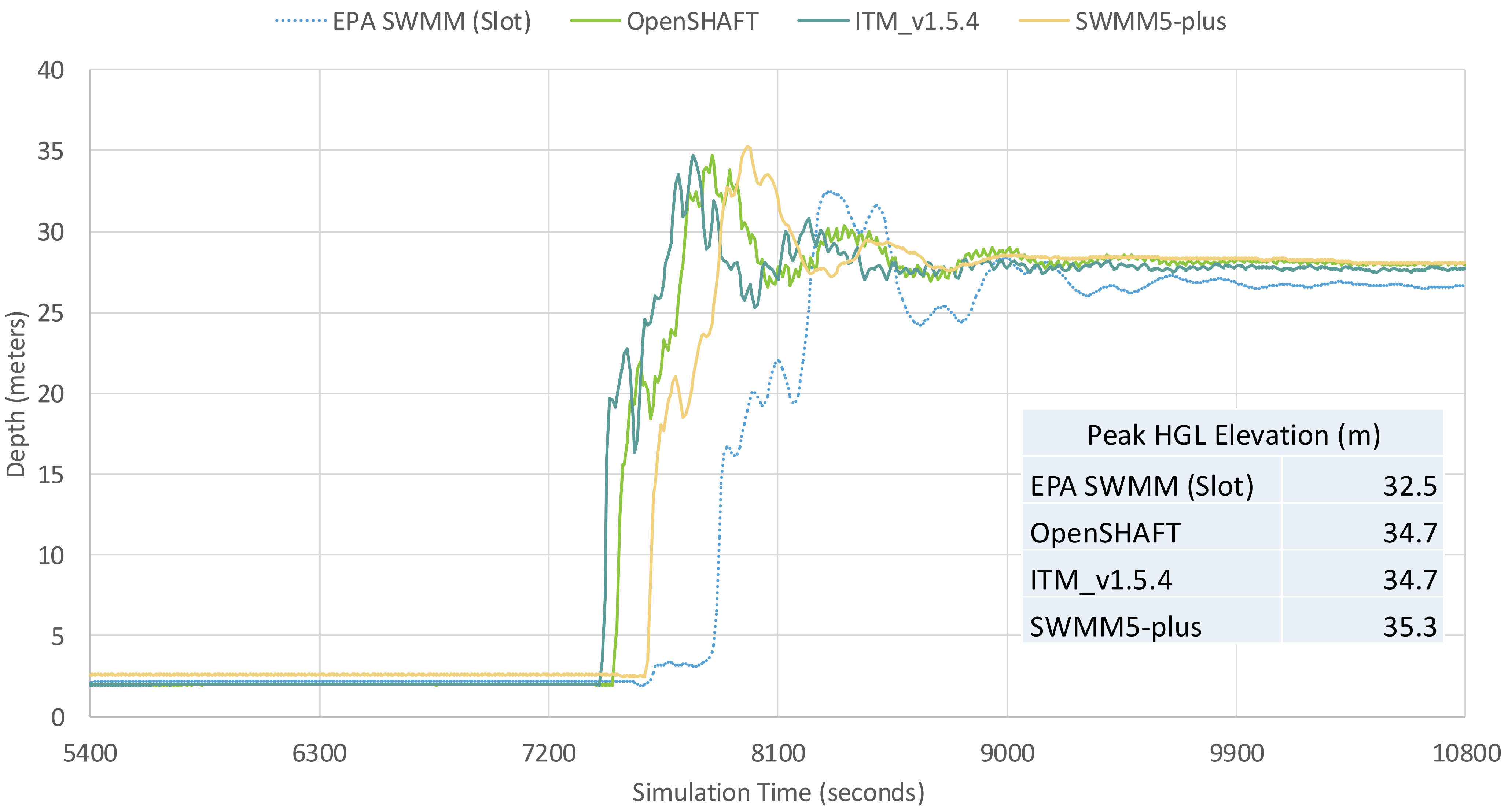
What happens when we model this system?

- We are very much interested in two major aspects of this system, both of which we can expect to affected by surge effects:
  - The peak HGL elevation at the upstream end
  - The overflow hydrograph at the downstream
- We'll start with an EPA SWMM model, and assess the potential for surge effects
  - SWMM model of the tunnel consists of 9 links and 10 storage junctions
  - There is an additional link and junction to represent the overflow weir
- Then, we'll make models of the same system in ITM, OpenSHAFT and SWMM5-plus, comparing the results
  - Cell length = 1 tunnel diameter (4.8 m)
  - Acoustic wave speed = 200 m/sec

EPA SWMM results for depth at Retrieval Shaft

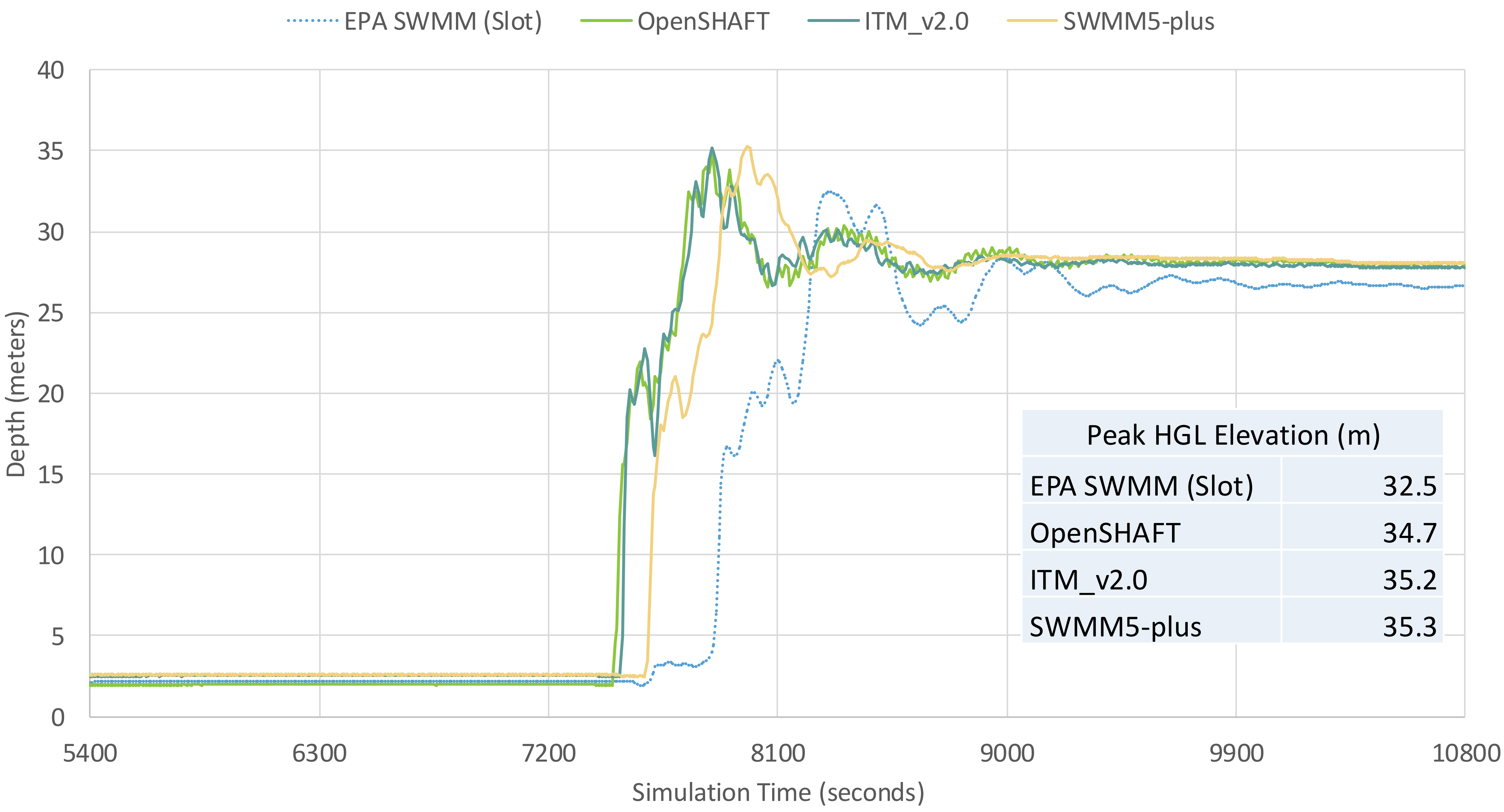


FVS results for depth at Retrieval Shaft



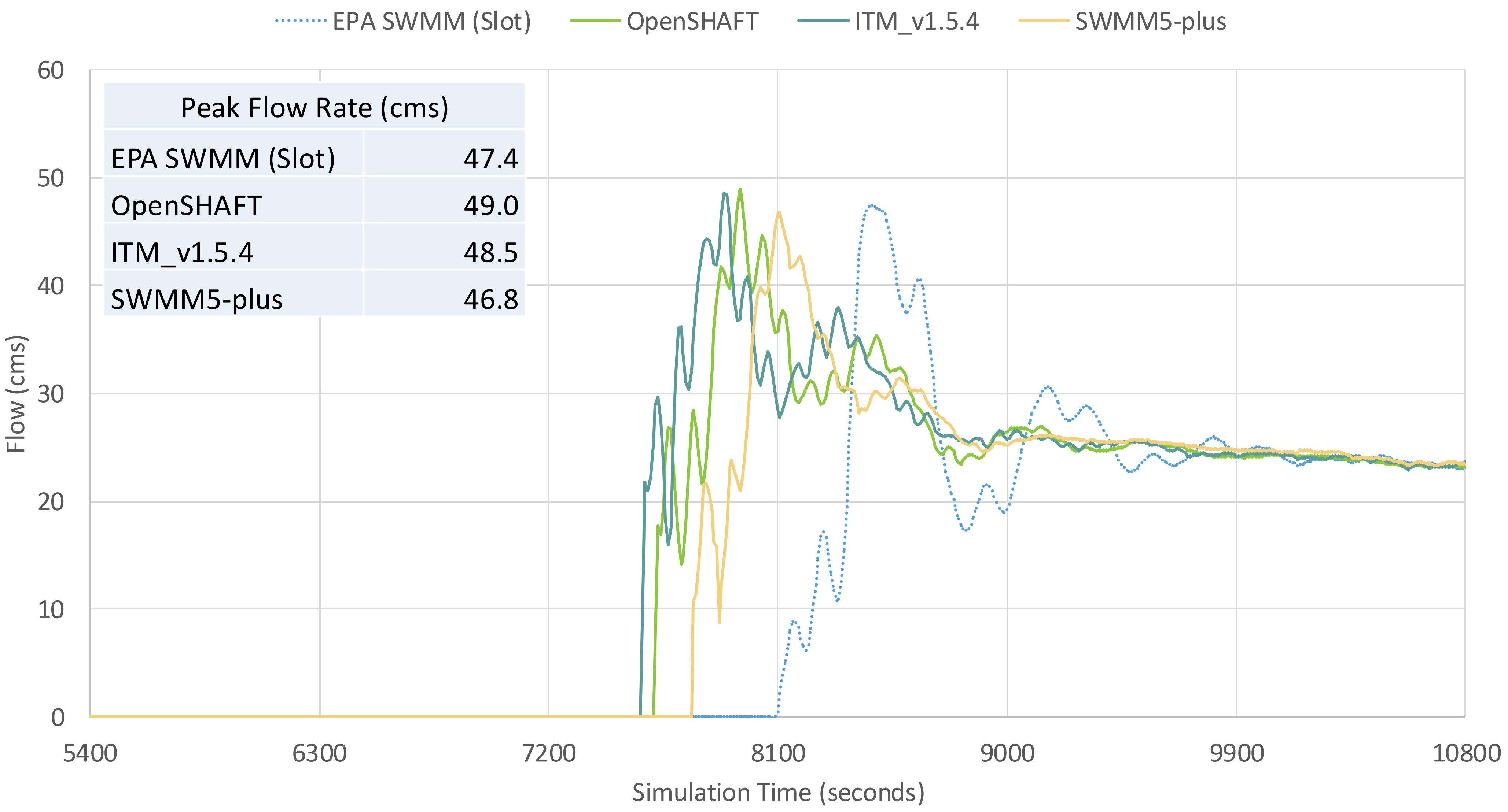
Peak HGL Elevation (m)	
EPA SWMM (Slot)	32.5
OpenSHAFT	34.7
ITM_v1.5.4	34.7
SWMM5-plus	35.3

FVS results for depth at Retrieval Shaft (part 2)



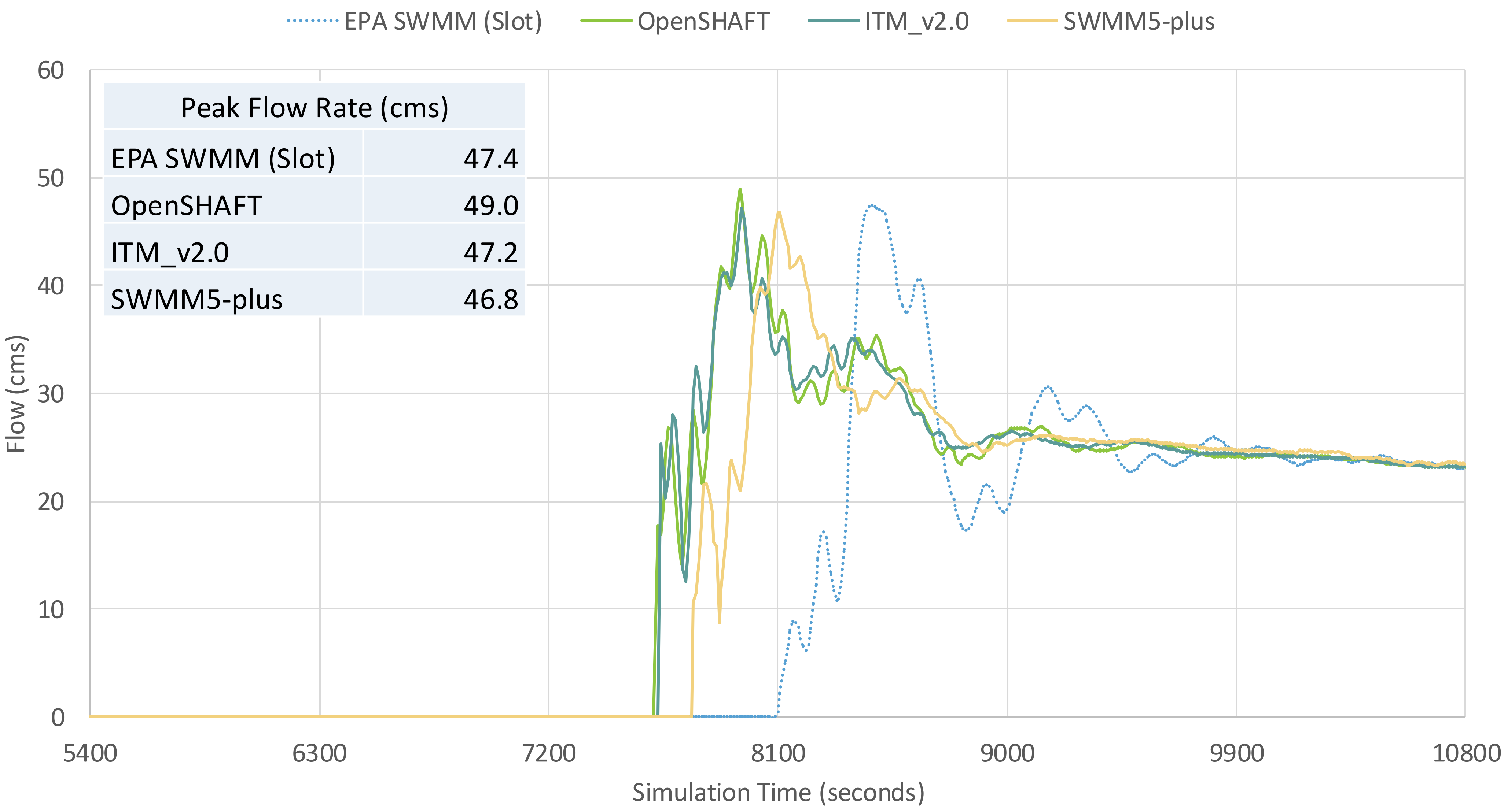
Peak HGL Elevation (m)	
EPA SWMM (Slot)	32.5
OpenSHAFT	34.7
ITM_v2.0	35.2
SWMM5-plus	35.3

FVS results for flow at downstream end



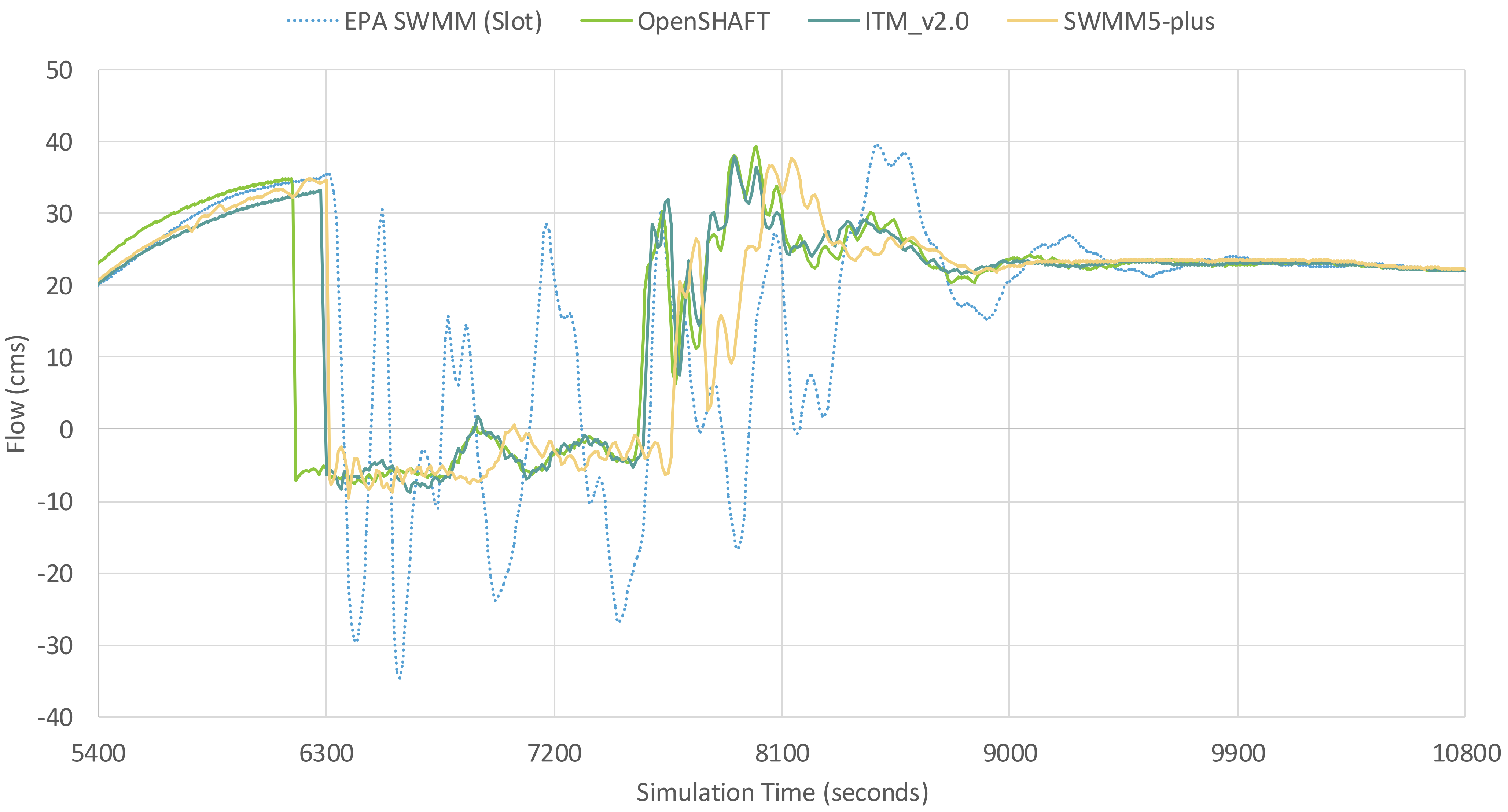
Peak Flow Rate (cms)	
EPA SWMM (Slot)	47.4
OpenSHAFT	49.0
ITM_v1.5.4	48.5
SWMM5-plus	46.8

FVS results for flow at downstream end (part 2)



Peak Flow Rate (cms)	
EPA SWMM (Slot)	47.4
OpenSHAFT	49.0
ITM_v2.0	47.2
SWMM5-plus	46.8

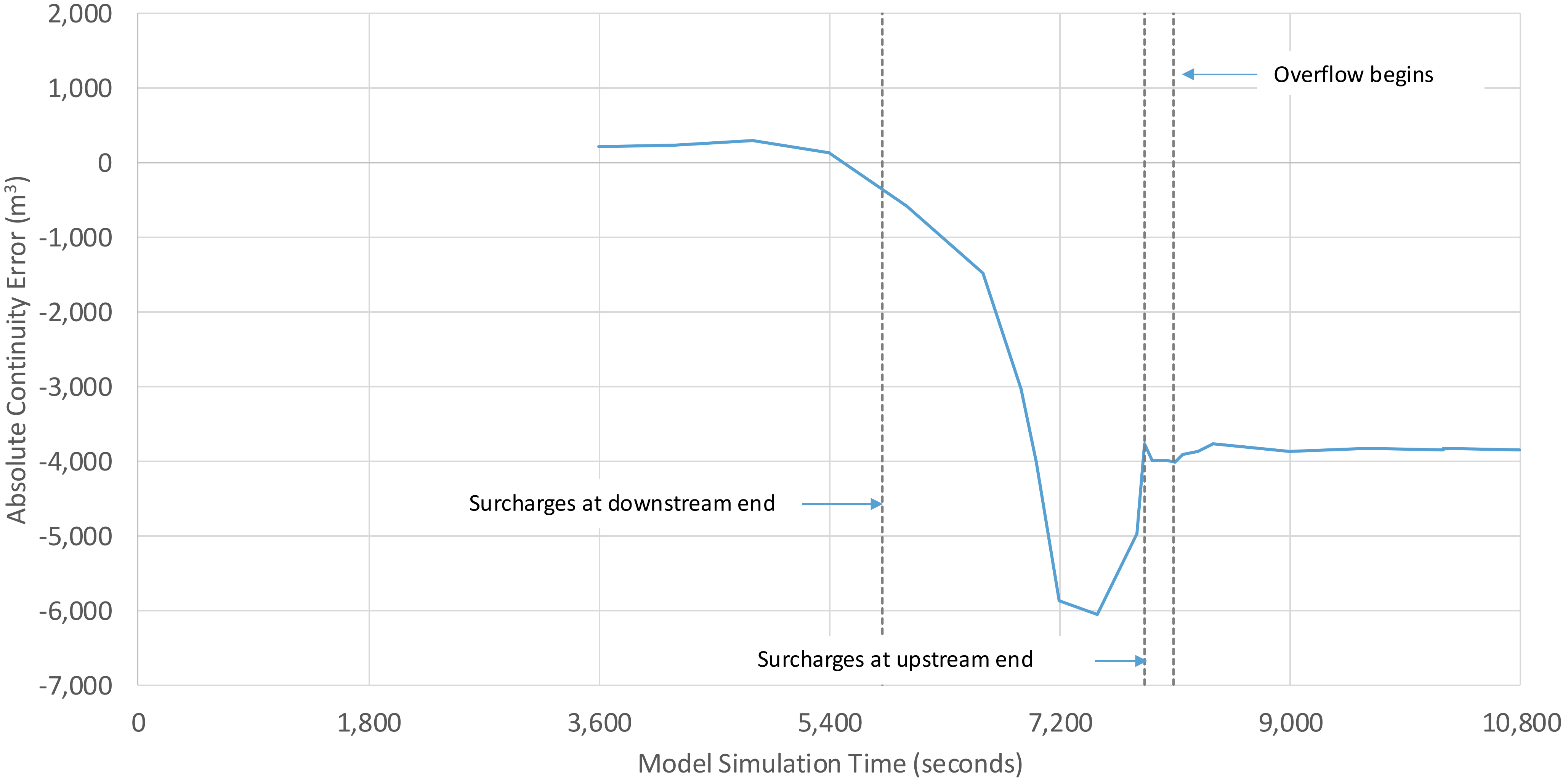
FVS results for flow at 31+00 (mild slope)



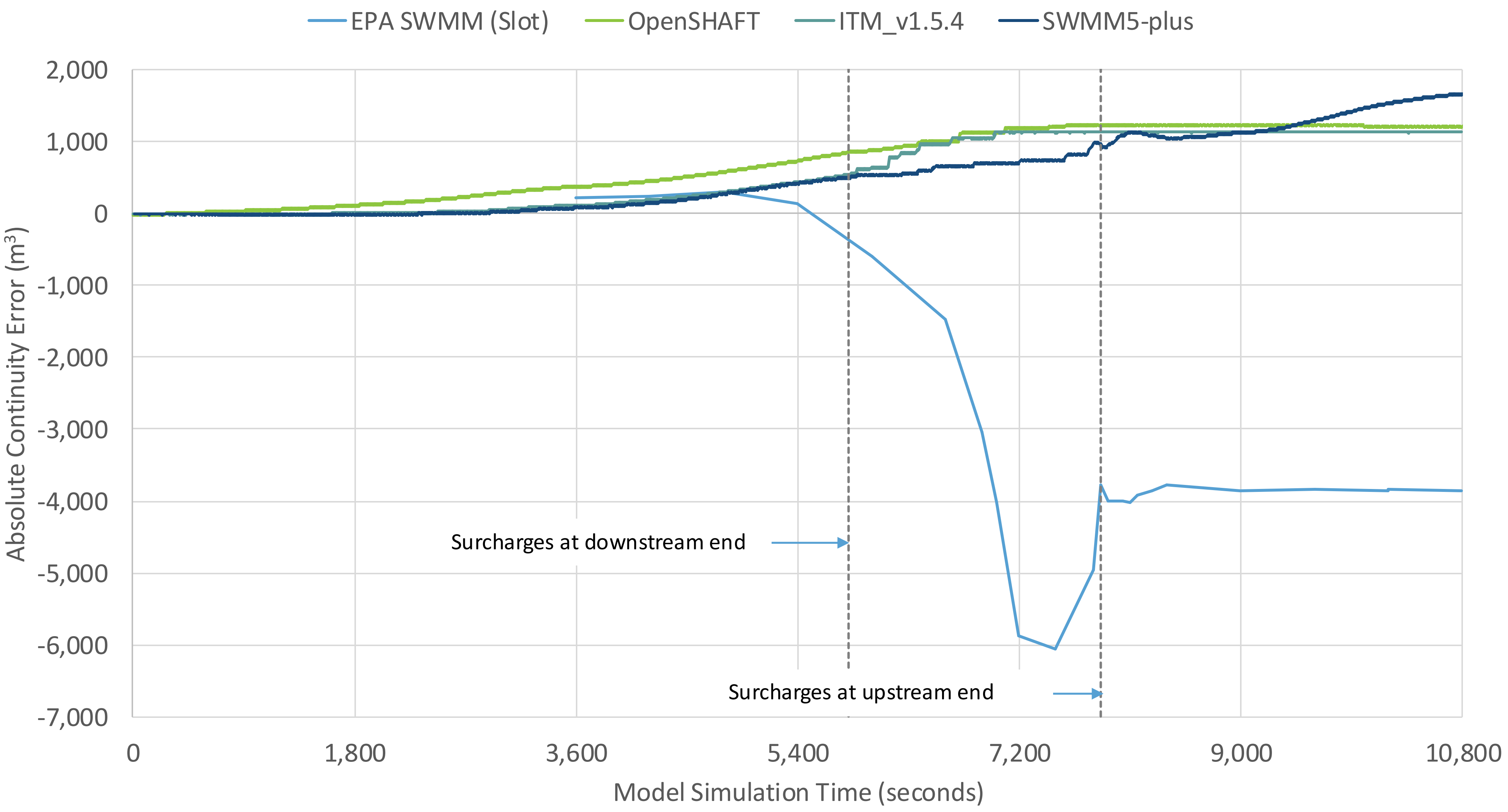
Why do the FVS results differ from each other?

- Differences among the FVS results appear to be largely the result of differing continuity error
  - Continuity error comes in part from the numerical method, but also may be sensitive to discretization
  - Wave speed will affect surge propagation to some extent, but is (probably) less likely to affect continuity error
- We'll examine what happens when changing discretization holding wave speed fixed, and vice versa
- It will be useful and instructive to look at how the error evolves through the simulation

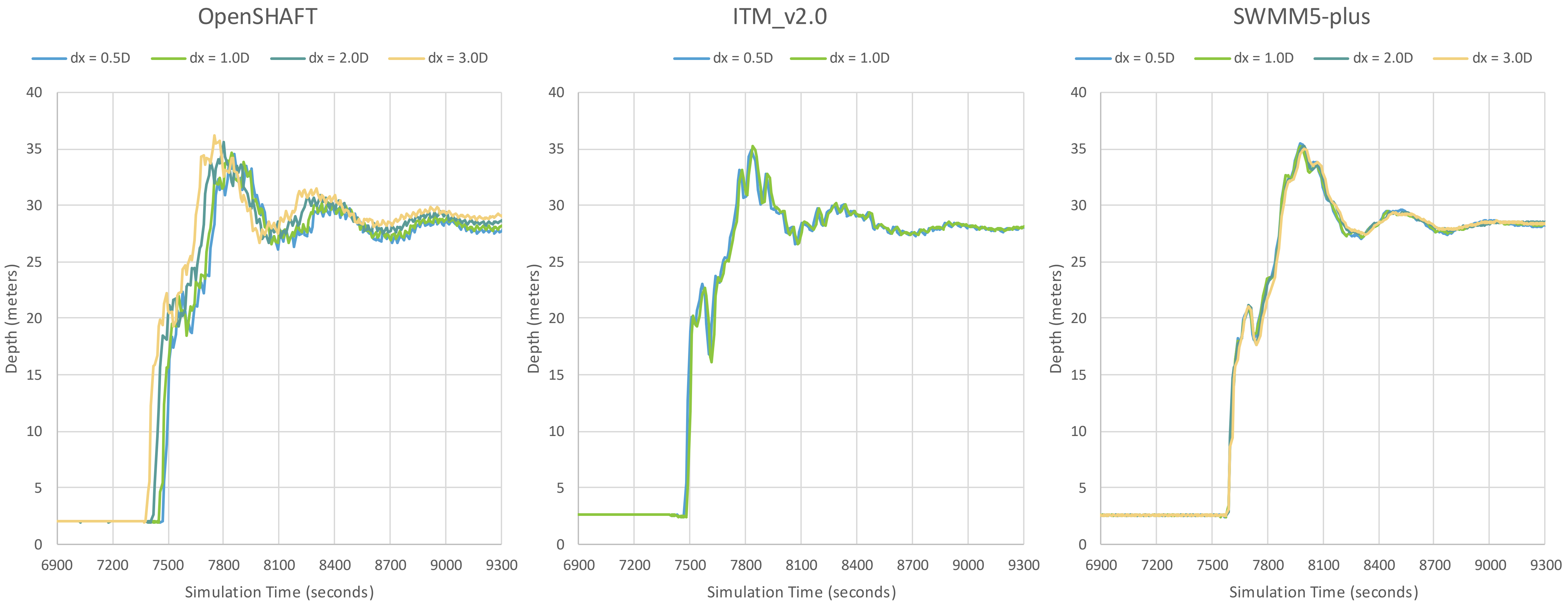
Evolution of continuity error in EPA SWMM



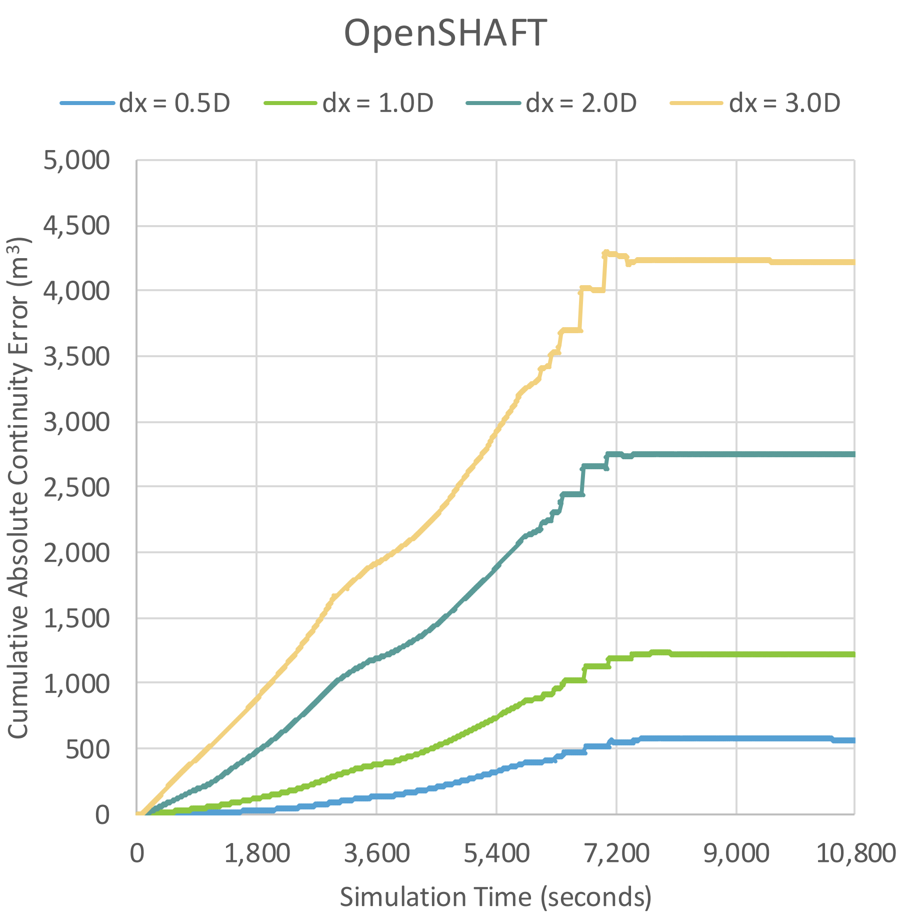
Evolution of continuity error in FVS

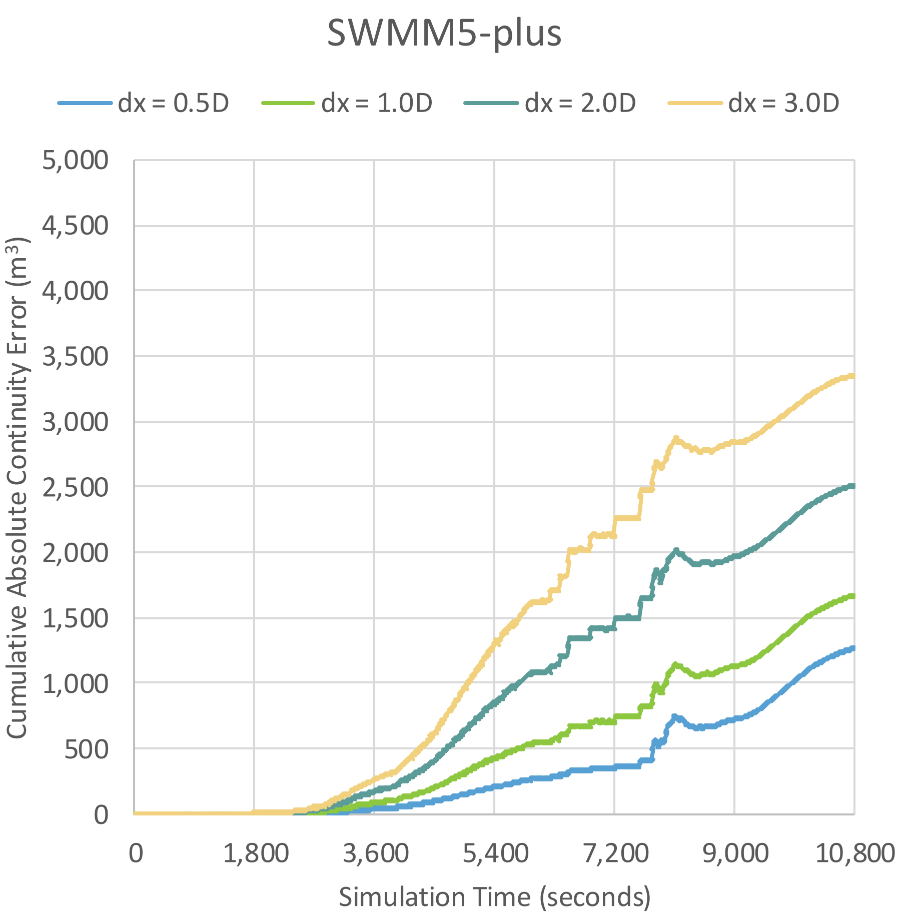


Effect of cell sizes on depth at Retrieval Shaft

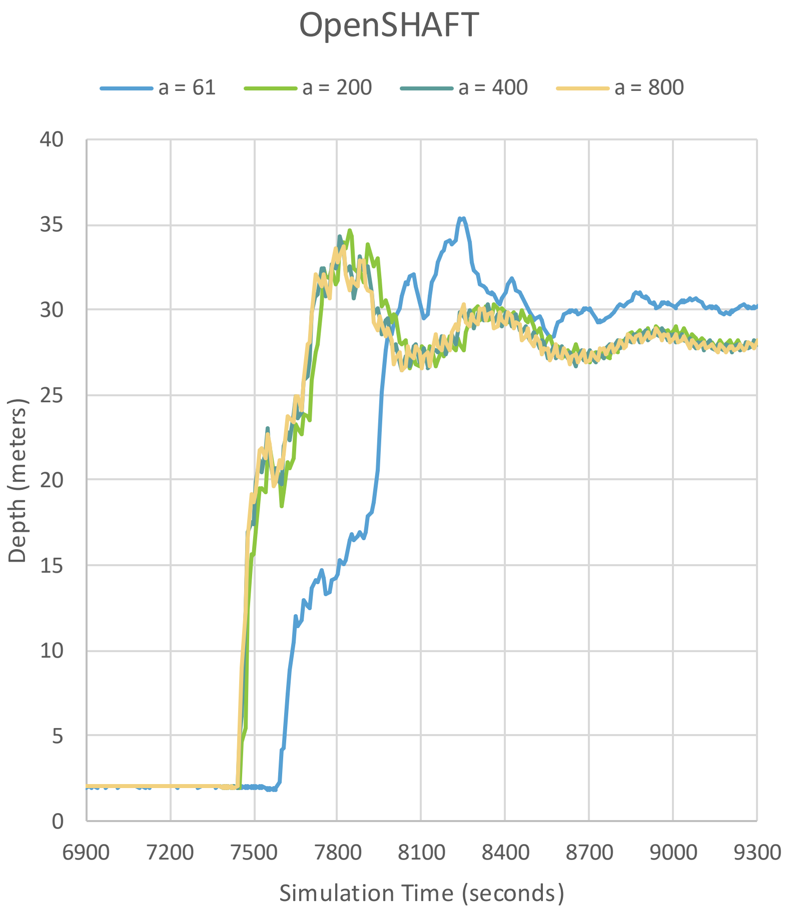


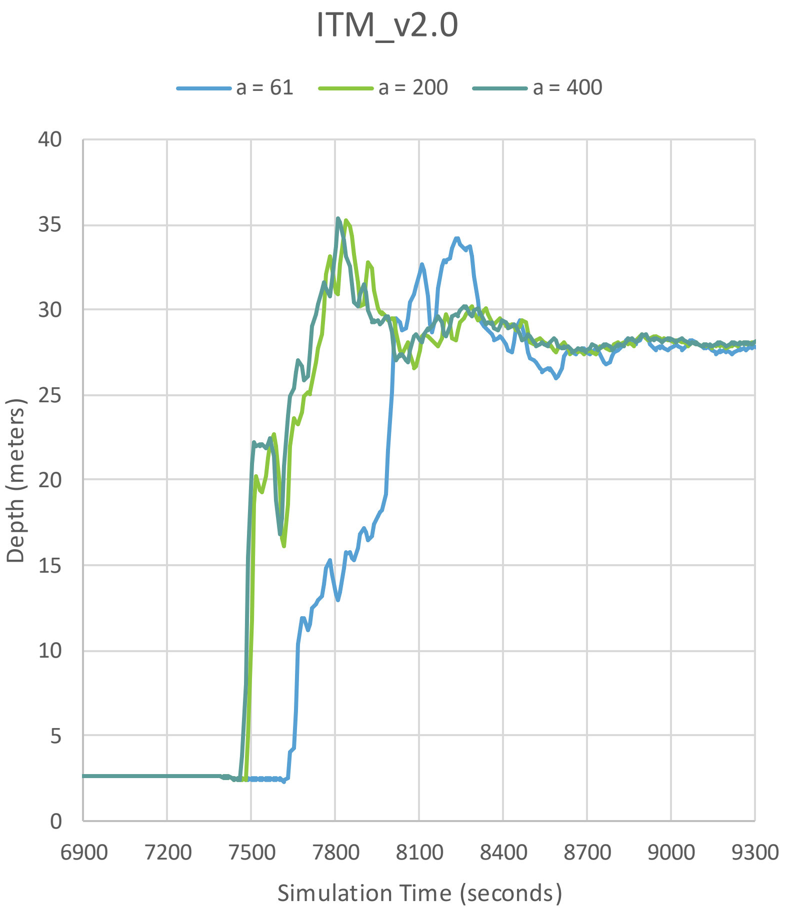
Effect of cell size on continuity error

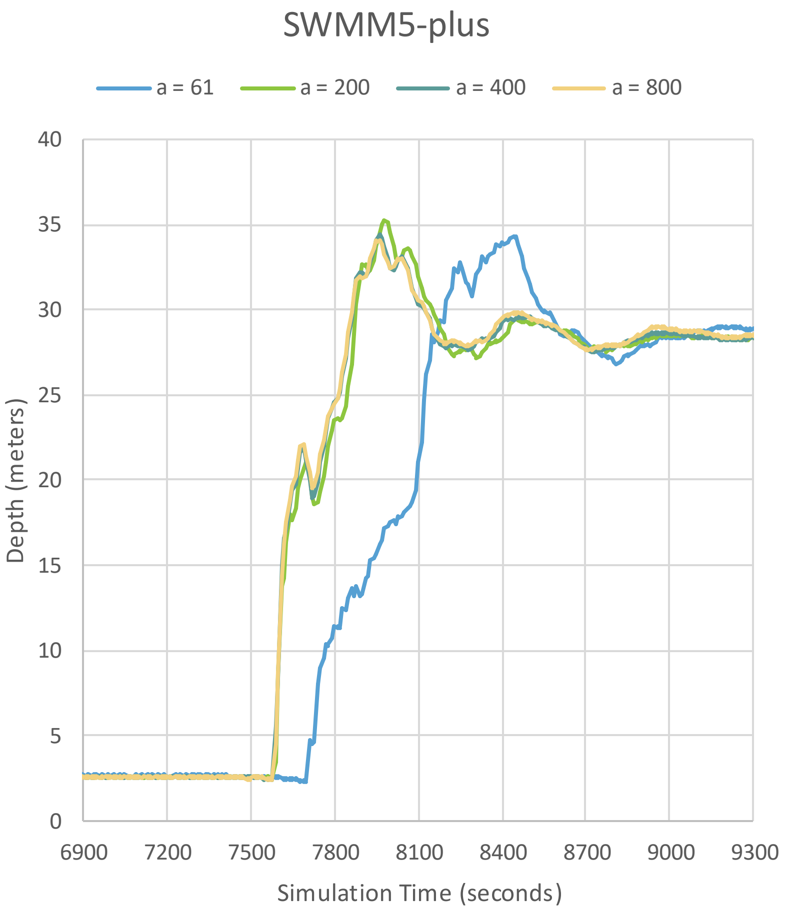




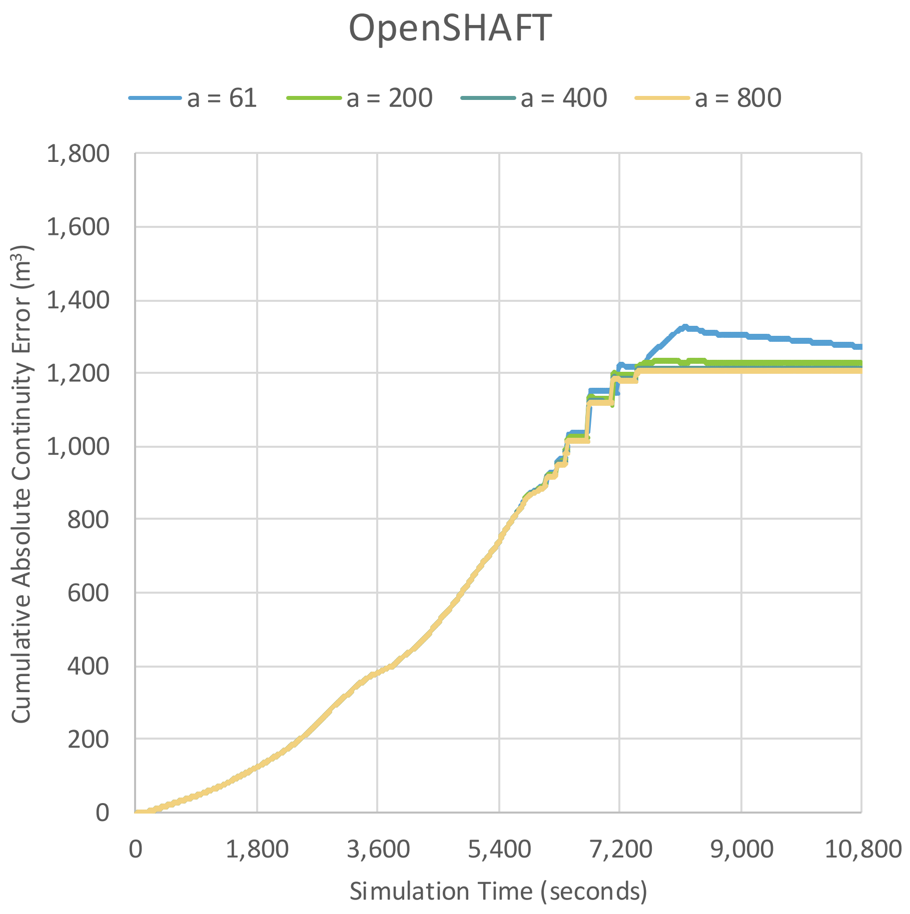
Effect of wave speed on depth at Retrieval Shaft

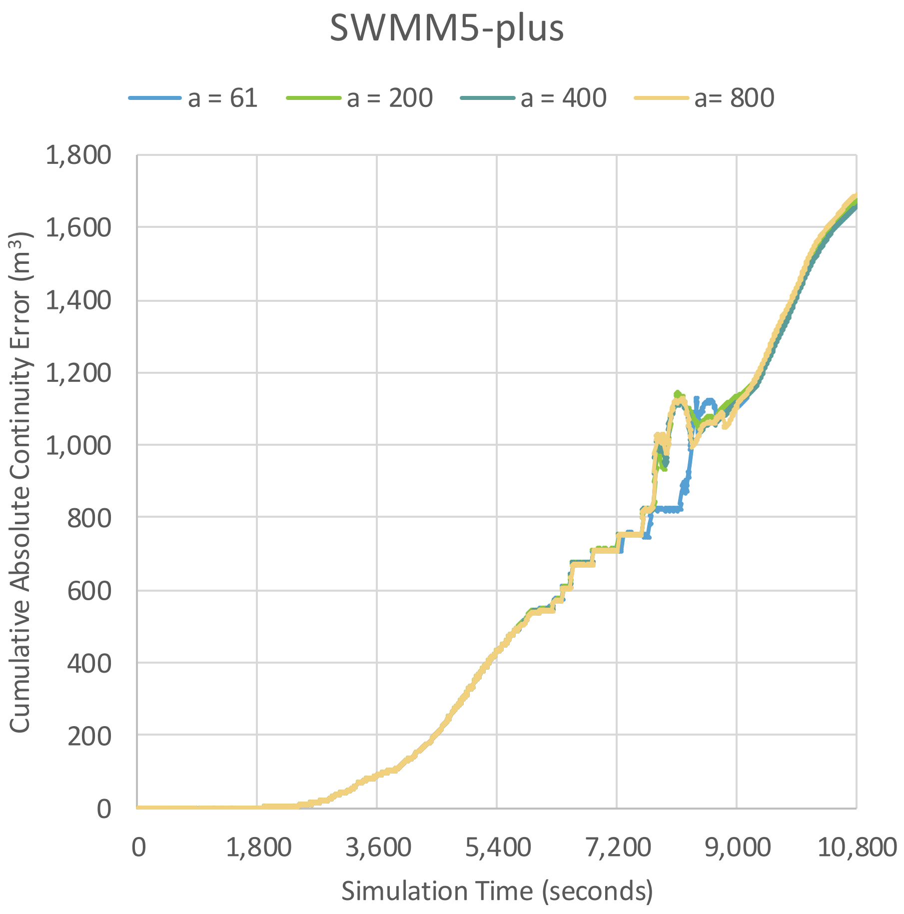




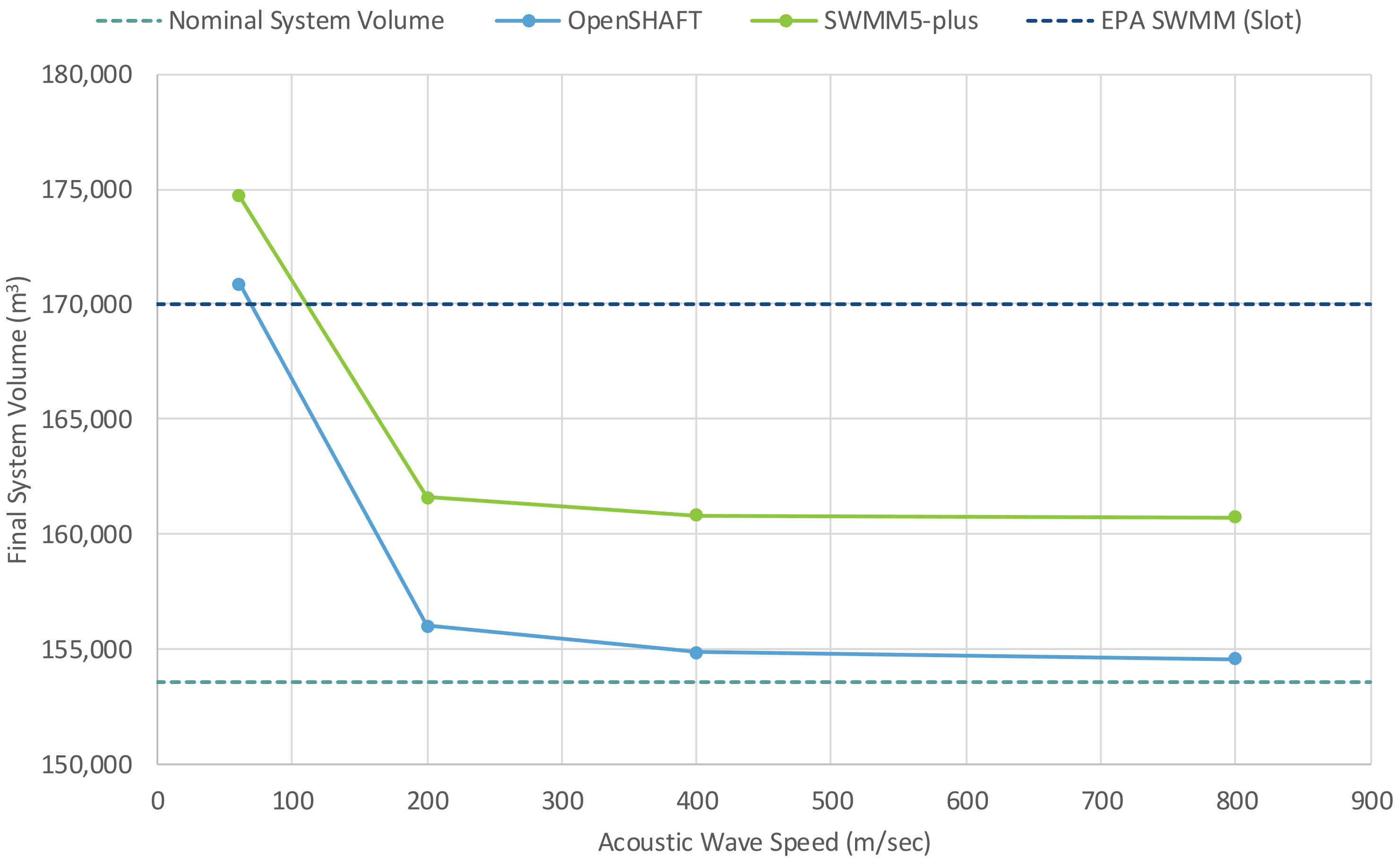


Effect of wave speed on continuity error





Effect of wave speed on final system volume



Takeaways for practitioners

- Be certain you actually need a finite volume approach to get the answers you're looking for
- Have a clear idea of how the model will provide those answers, and how you'll use them
- Consider using more than one modeling framework as a way of understanding the uncertainty in the results
- Examine model sensitivity to parameter choices

Acknowledgments

- Dr. Jose Vasconselos (for SHAFT)
- Dr. Arturo Leon & Sam Glovick (for ITM)
- Dr. Ben Hodges (for SWMM5-plus)

Peter Klaver

Senior Hydraulics Lead

limno.com

pklaver@limno.com