U.S.ARMY

THE COASTAL MODELING SYSTEM (CMS) VALIDATION AND VERIFICATION

CMS TECH TRANSFER WORK UNIT

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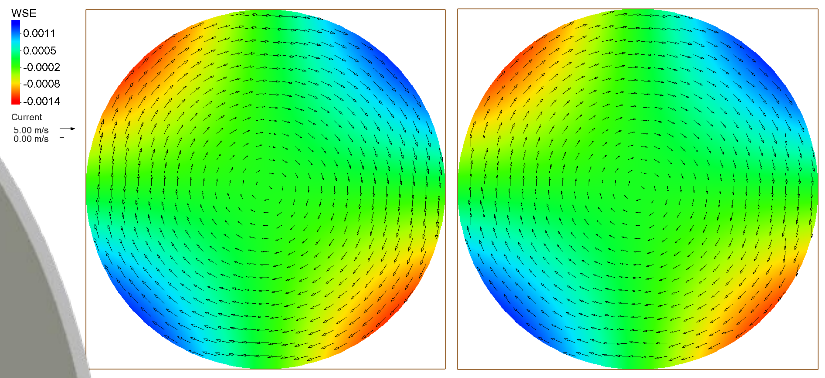
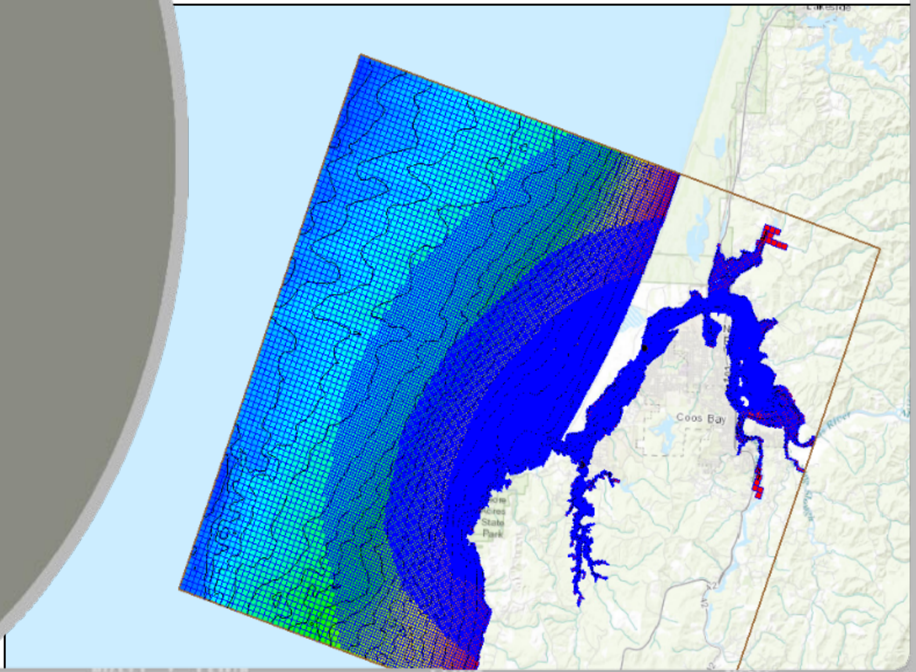




COASTAL INLETS RESEARCH PROGRAM

FY21 TECHNICAL DISCUSSION

CIRP
Mission Support
Technology Transfer
Research & Development

US Army Corps of Engineers

CHL COASTAL & HYDRAULICS LABORATORY

ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER

Background

- Validate and verify the CMS codebase for simulating hydrodynamics, wind waves, and sediment transport/morphological change
- Update and expand previous VVUQ completed in 2012
- Testing the CMS 5.x release
- Tripartite division to the VVUQ cases:
    - Analytical: Performance of simulating fundamental physics
    - Laboratory: Extensive observation coverage and detail
    - Field: Verification in real-world conditions
- Ongoing work

Statistics

$$Bias\ (mean\ error) = \frac{1}{N}\sum^{N} x - x^*$$

$$R^2 = \left[\frac{\langle xx^*\rangle - \langle x\rangle\langle x^*\rangle}{\sqrt{\langle x^2\rangle - \langle x\rangle^2}\sqrt{\langle (x^*)^2\rangle - \langle x^*\rangle^2}}\right]^2$$

$$MAE = \frac{1}{N}\sum^{N} |x - x^*|$$

$$NMAE = \frac{MAE}{range(x^*)}$$

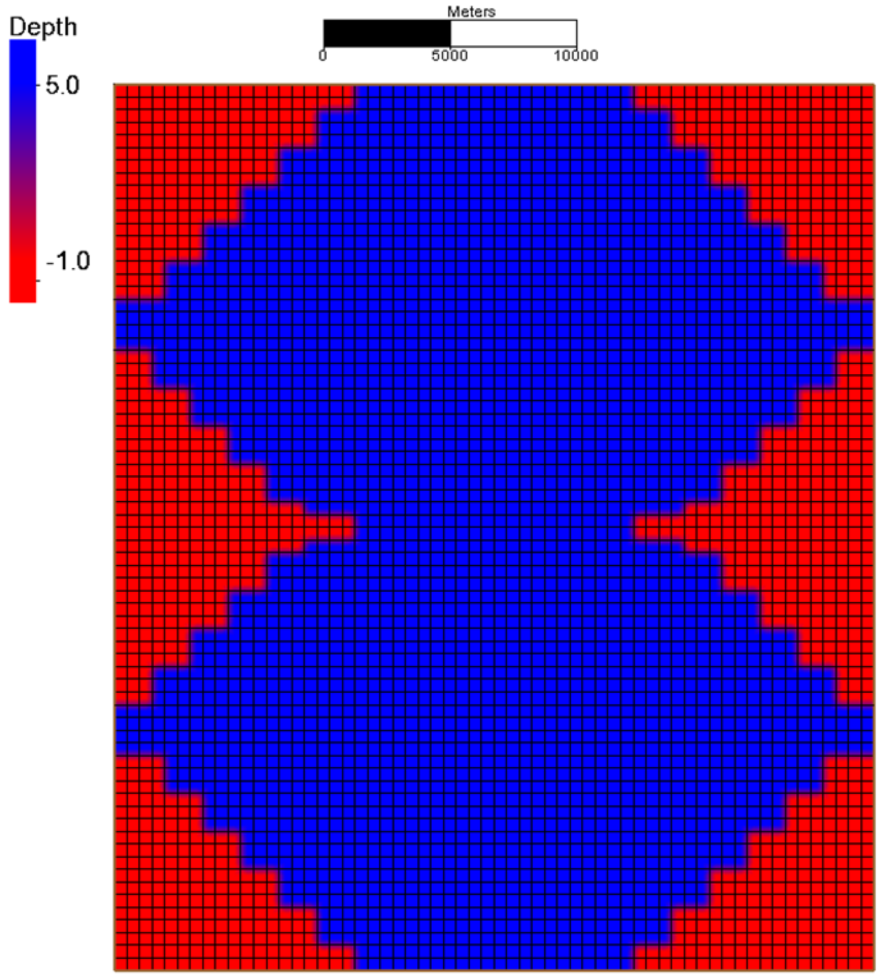
$$RMSE = \sqrt{\frac{1}{N}\sum^{N}(x - x^*)^2}$$

$$NRMSE = \frac{RMSE}{range(x^*)}$$

Analytical

Wind stress-induced Setup

Parameter	Value
Numerical Scheme	Implicit
Time step	600 s
Simulation Duration	48 hr
Wind Speed	10 m/s
Drag coefficient	0.00161
Advection Terms	Off
Mixing terms	Off
Bottom friction	Off
Wall friction	Off
Coriolis effect	Off



$$\rho g h \frac{\partial \eta}{\partial y} = \tau_{si} = \rho_a C_d |W| W$$

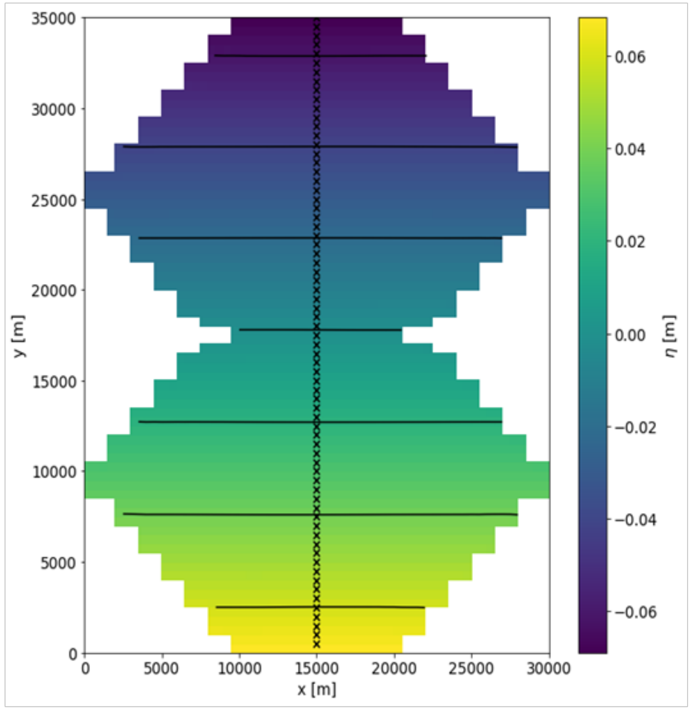
$$C_d = \left(\frac{\kappa}{14.56 - 2 \ln W}\right)^2$$

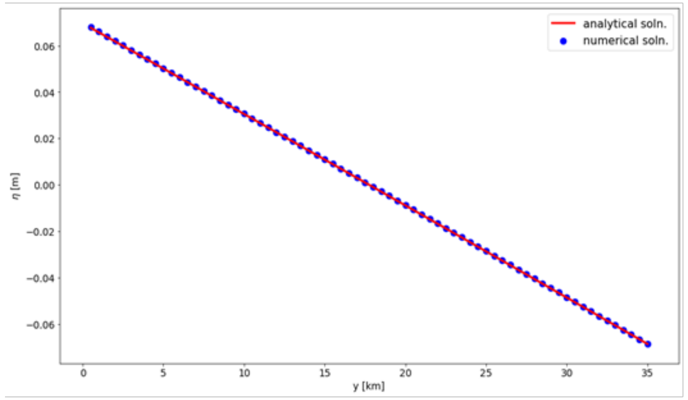
$$\eta = \sqrt{\frac{2\rho_a C_d |W| W}{\rho g}(y + C) + \zeta^2} - \zeta$$

(Dean and Dalrymple, 1984)

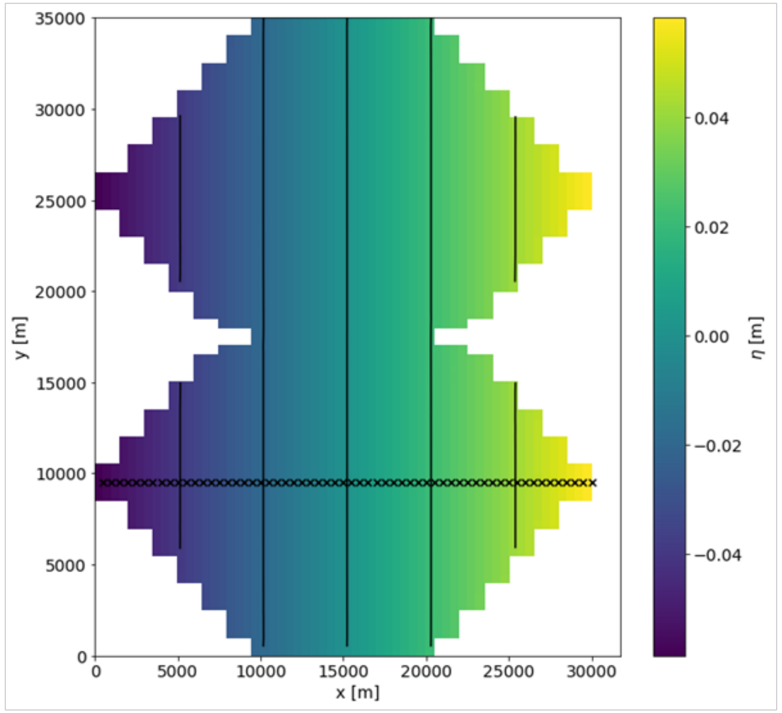
(Hsu, 1988)

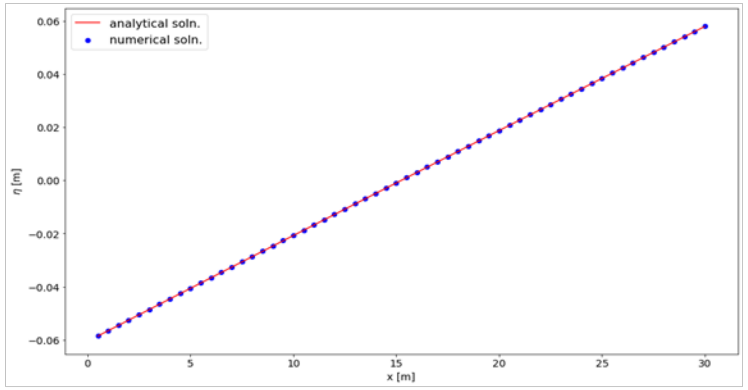
North Wind





West Wind

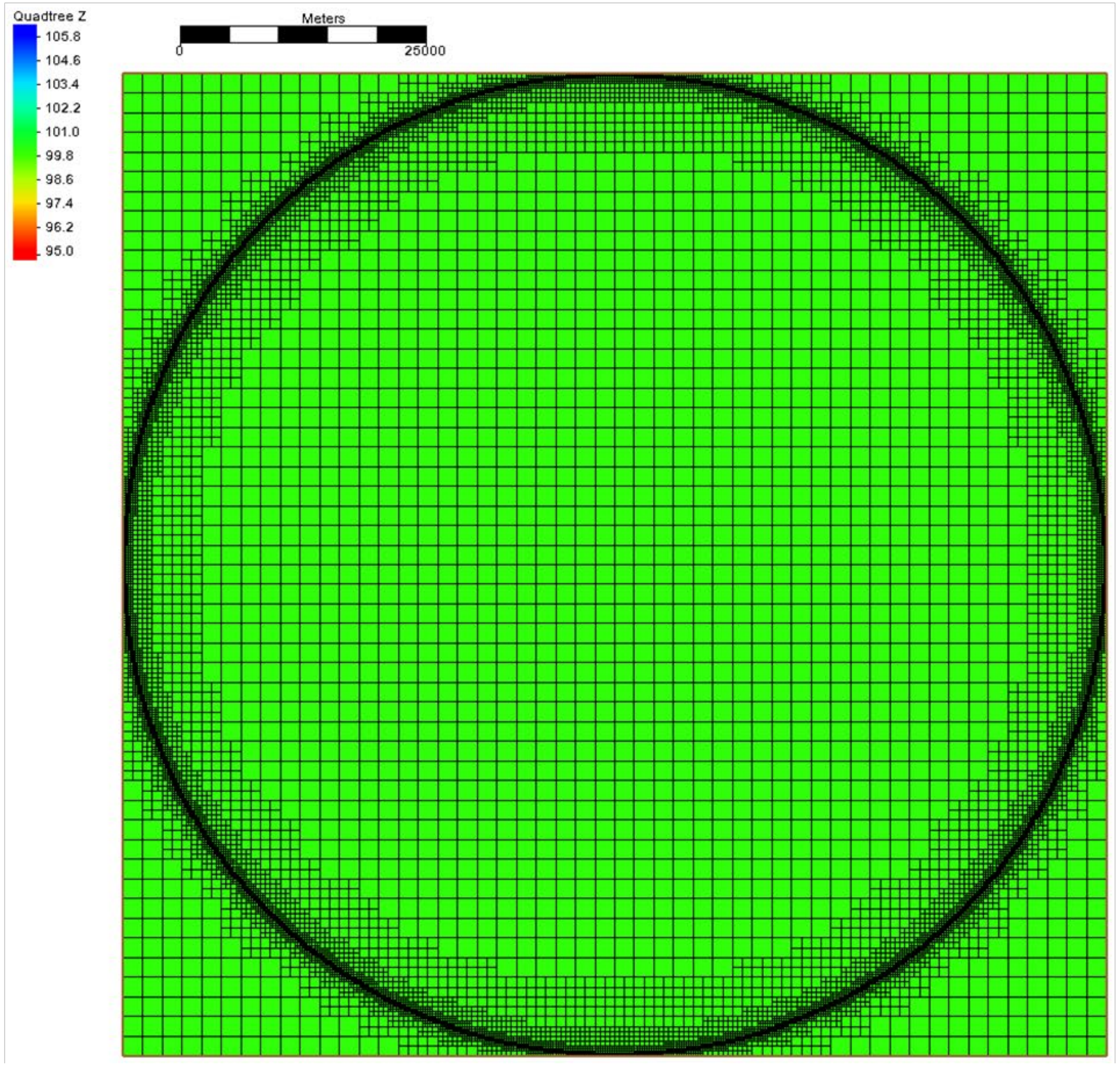




Statistics	Northern Wind
NRMSE [%]	0.109
RMSE [m]	0.00015
NMAE [%]	0.425
R^2 [-]	0.99998
Bias [m]	0.00014

Statistics	Western Wind
NRMSE [%]	0.061
RMSE [m]	0.00007
NMAE [%]	0.314
R^2 [-]	0.99999
Bias [m]	0.00070

Wind-driven Flow in a Circular Basin



Parameter	Value
Numerical Scheme	Implicit
Time step	1800 s
Simulation duration	216 hr
Ramp duration	1 hr
Water depth	100 m
Bottom friction coefficient	0.01
Coriolis frequency	1.0e-4 Hz
Wind gradient	1.0e-4 m^2 s^{-2}
Mixing terms	Off
Advection terms	Off
Wall friction	Off
Resolution	2000 – 125 m

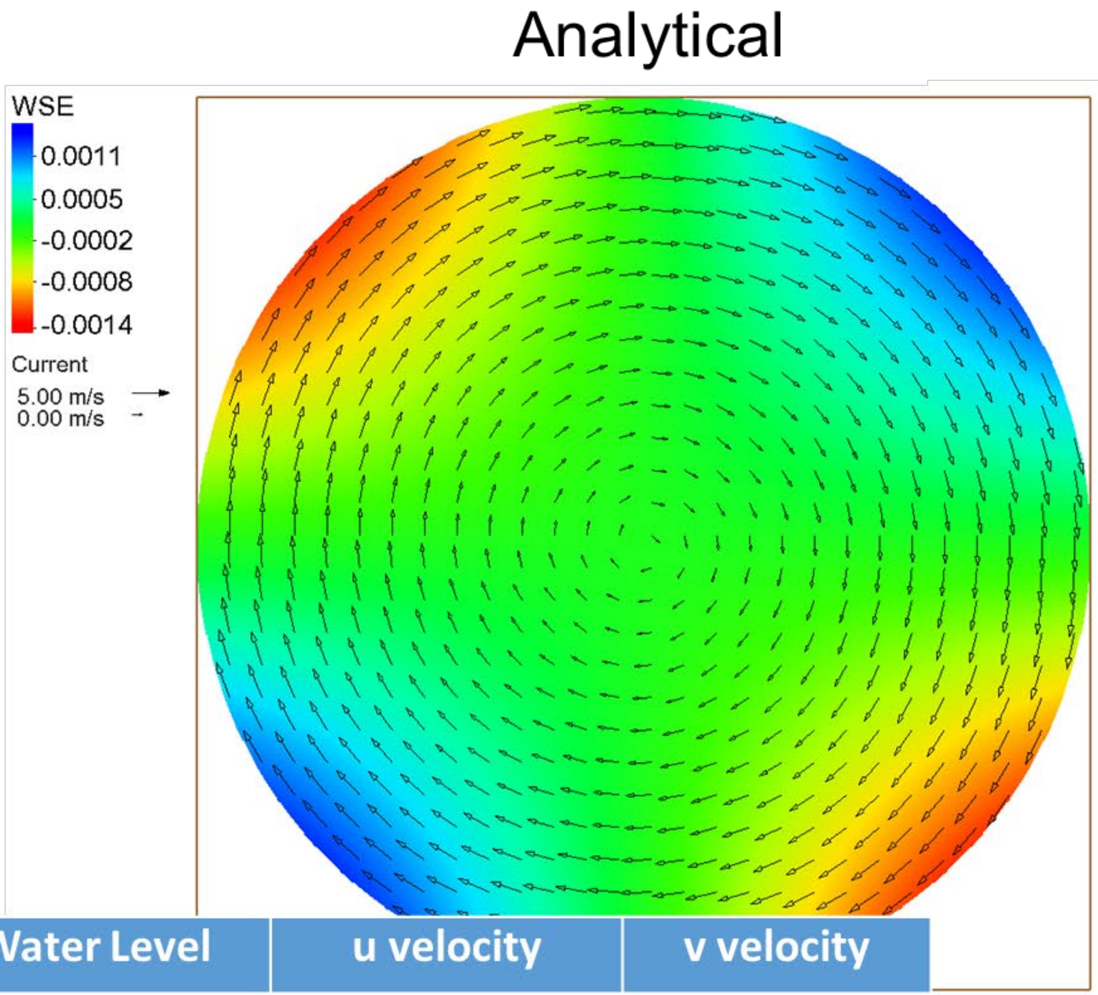
$$gh\frac{\partial \eta}{\partial x} = f_c hv + \frac{y\widehat{W}}{R} - \hat{\kappa}hu$$

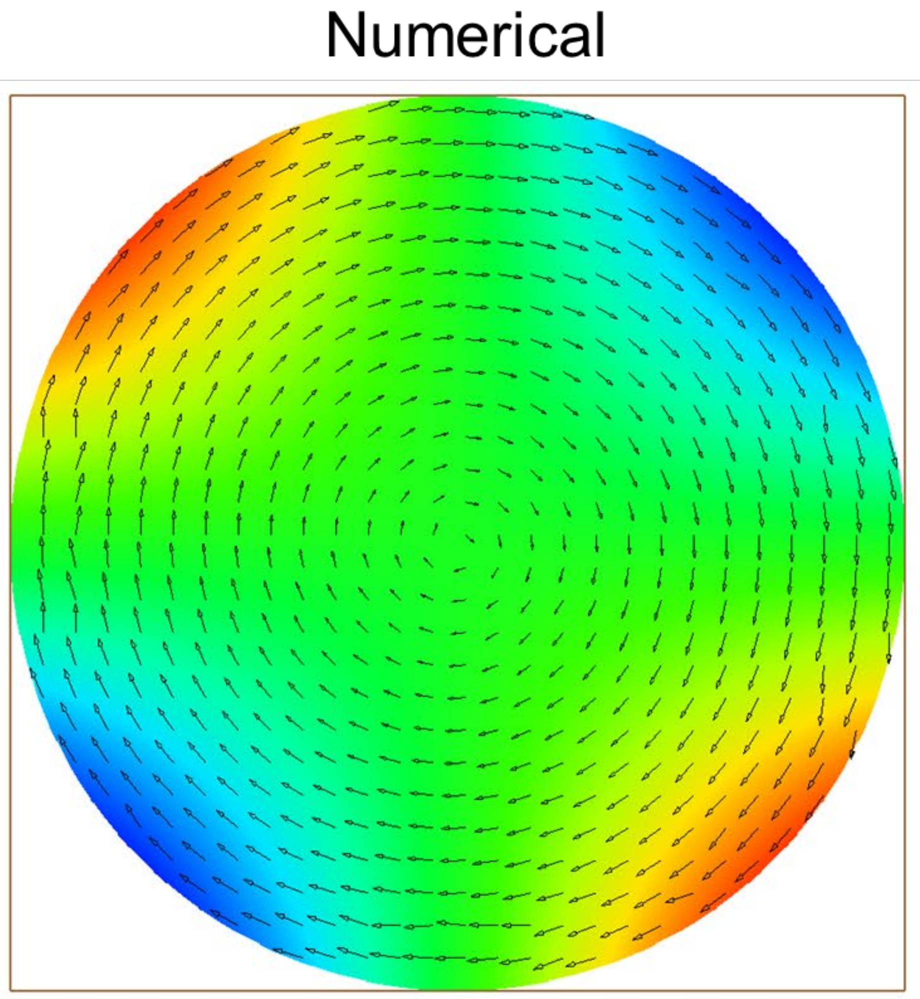
$$\eta = \begin{cases} \dfrac{Wxy}{2ghR}, & f_c \quad = 0 \\ \dfrac{Wf_c}{gh\hat{\kappa}R}\left[\dfrac{R^2}{8} + \dfrac{1}{4}\left(\dfrac{2\hat{\kappa}xy}{f_c} - x^2 - y^2\right)\right], & f_c \neq 0 \end{cases}$$

$$u = \frac{yW}{2h\hat{\kappa}R}$$

(DuPont, 2001)

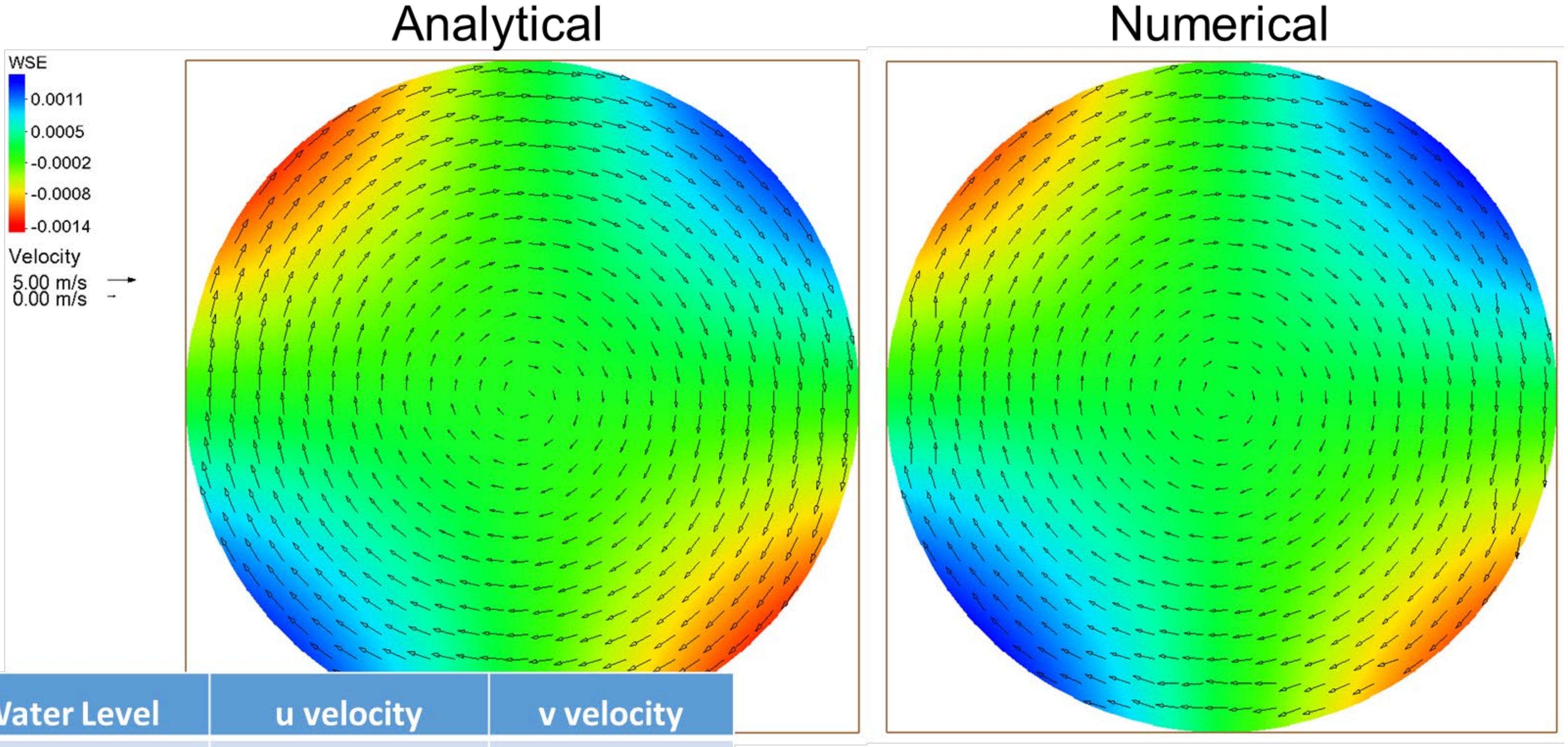
No Coriolis





Statistics	Water Level	u velocity	v velocity
NRMSE [%]	0.994	10.924	12.404
RMSE [m or ms^{-1}]	0.00003	0.00001	0.00001
NMAE [%]	3.340	0.060	-0.047
R^2 [-]	0.99910	0.91418	0.89189
Bias [m or ms^{-1}]	0.00025	0.00000	0.00000

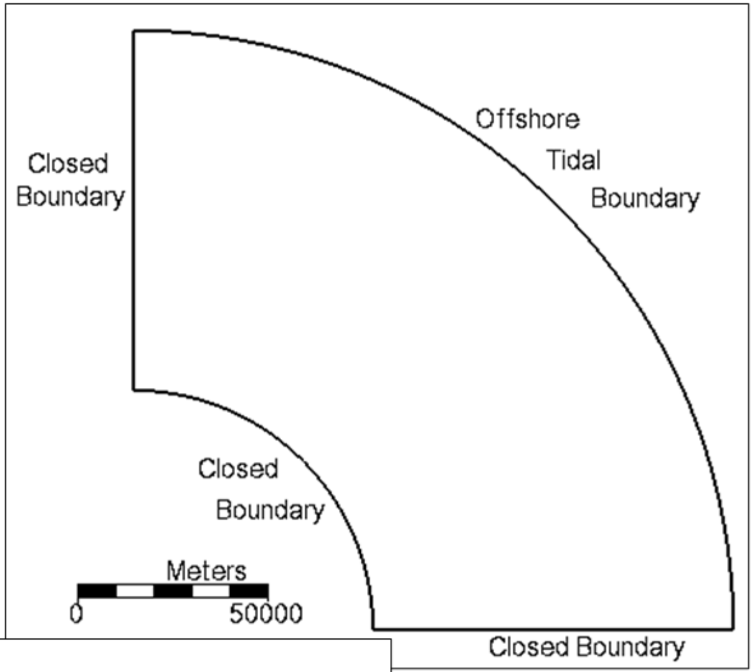
With Coriolis



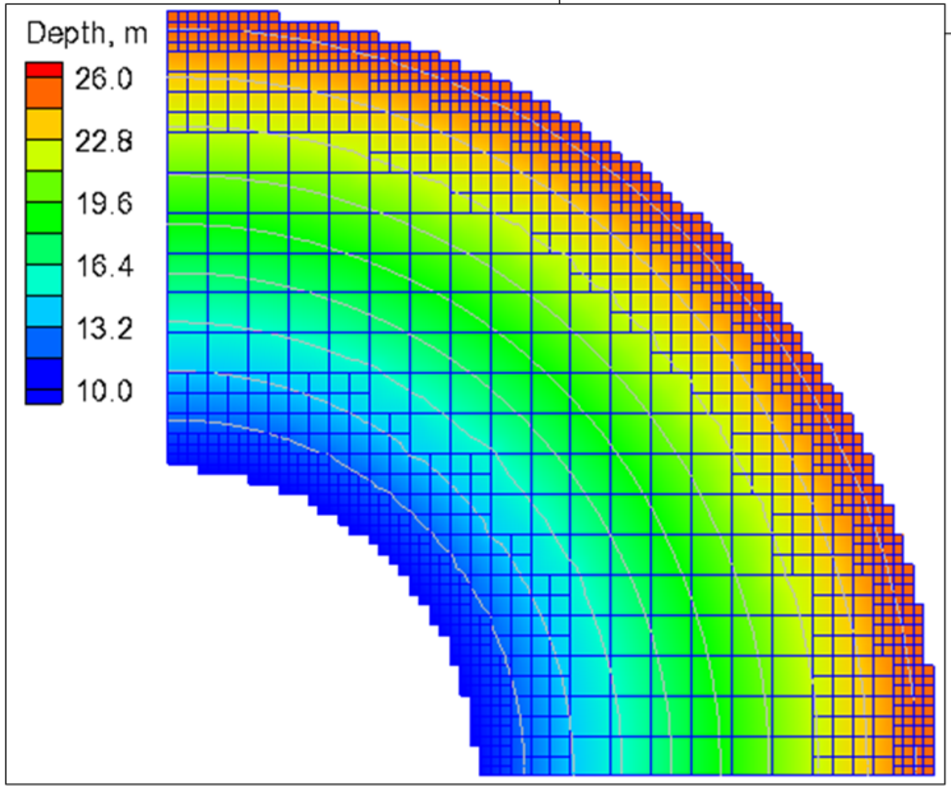
Statistics	Water Level	u velocity	v velocity
NRMSE [%]	4.523	10.934	12.401
RMSE [m or ms^{-1}]	0.00012	0.00001	0.00001
NMAE [%]	15.660	0.062	-0.051
R^2 [-]	0.98086	0.91408	0.89185
Bias [m or ms^{-1}]	0.00012	0.00000	0.00000

Tidal Propagation in a Quarter Annulus

Parameter	Value
Boundary tidal wave amplitude	0.3048 m
Tidal period (M2)	12.42 hr
Annulus inner radius	60.96 km
Annulus outer radius	152.4 km
Annulus inner water depth	10.02 m
Annulus outer water depth	25.05 m



Parameter	Value
Temporal solution scheme	implicit
Time step	600 s
Simulation duration	120 hr
Ramp duration	24 hr
Bottom friction	None
Wall friction	Off
Advection terms	Off
Mixing terms	Off
Coriolis force	Off



$$\frac{\partial hU}{\partial t} + gh\frac{\partial \eta}{\partial x} = 0 \qquad \eta(r_2, t) = \eta_0 \cos \omega t$$

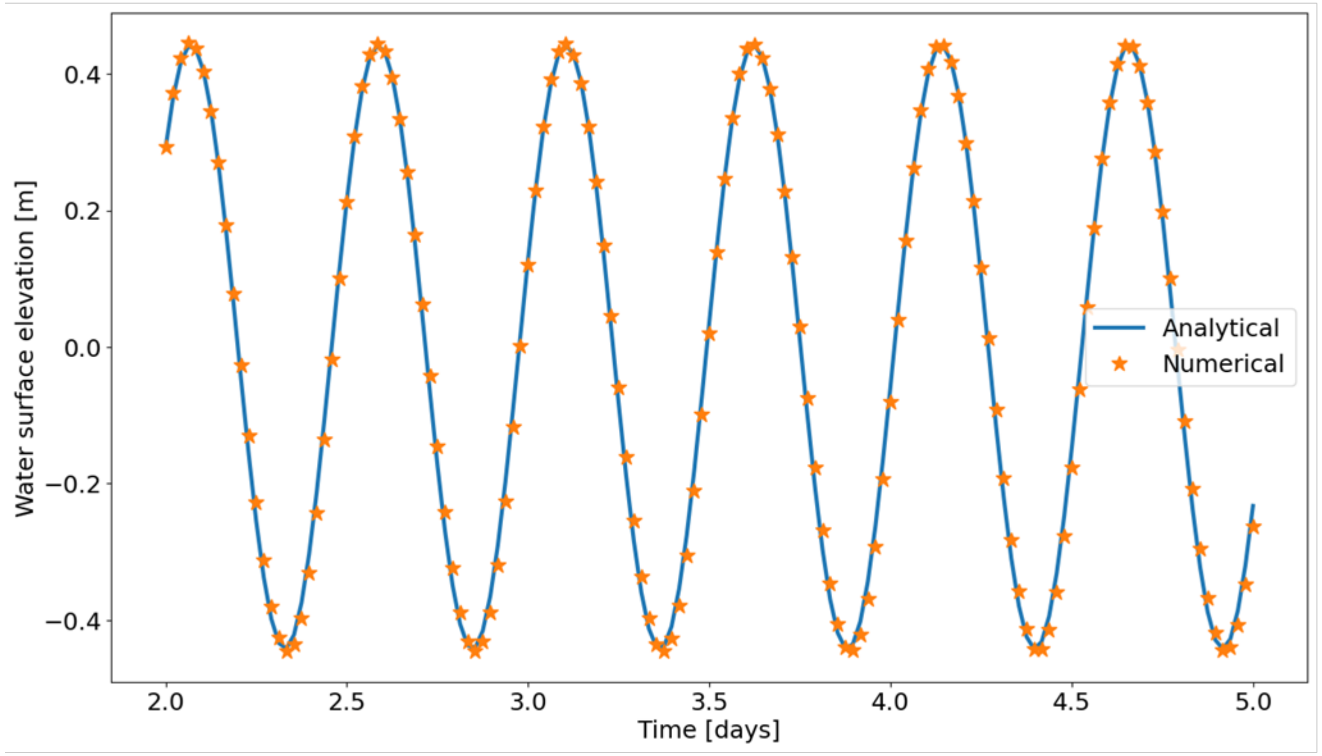
$$\eta(r,t) = [AJ_0(\beta r) + BY_0(\beta r)] \cos \omega t$$

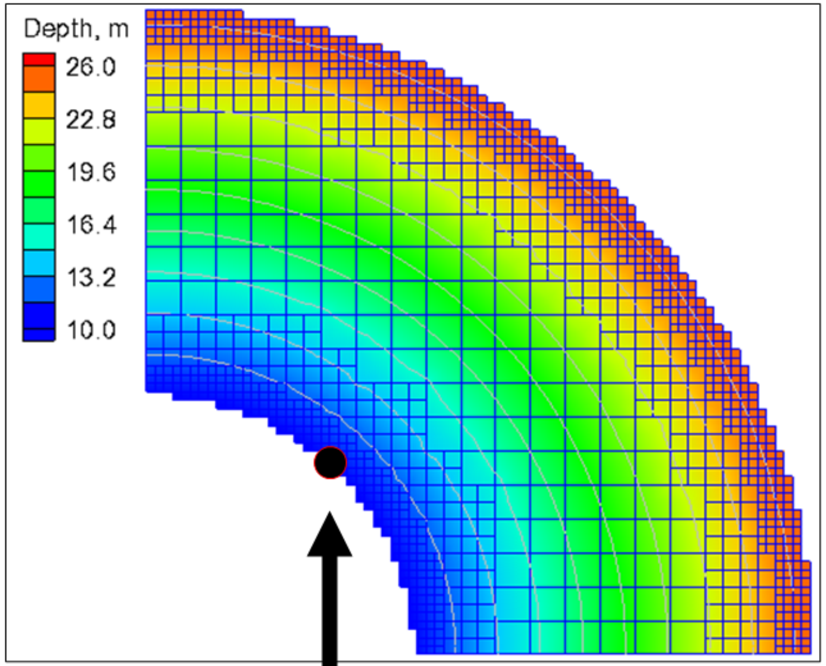
$$A = \frac{\eta_0 Y_1(\beta r_1)}{J_0(\beta r_2)Y_1(\beta r_1) - J_1(\beta r_1)Y(\beta r_2)} \qquad B = -\frac{\eta_0 J_1(\beta r_1)}{J_0(\beta r_2)Y_1(\beta r_1) - J_1(\beta r_1)Y_0(\beta r_2)}$$

$$\beta^2 = \frac{\omega^2}{gh} \qquad J_\alpha \; and \; Y_\alpha = Bessel \; functions \; of \; 1^{st} \; and \; 2^{nd} \; kind$$

$$r = \sqrt{x^2 + y^2} \qquad r_1, r_2 = inner \; and \; outer \; radius$$

(Lynch and Gray, 1979)

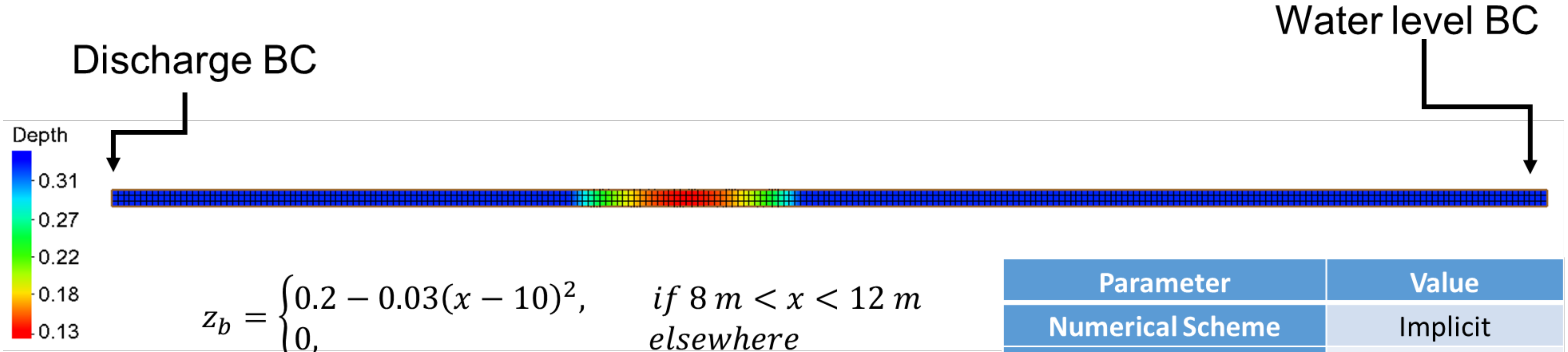




Sample Point

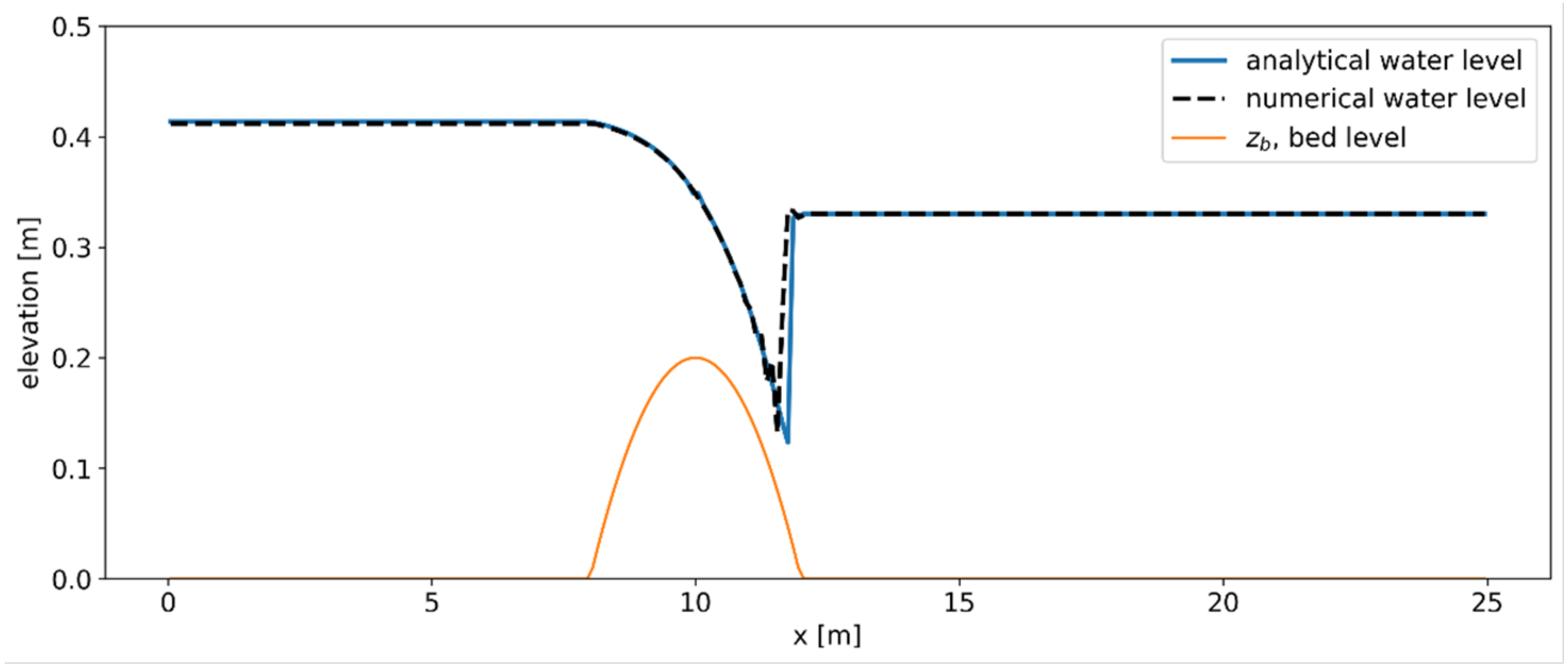
Statistics	Water Level
NRMSE [%]	1.9
RMSE [m]	0.017
NMAE [%]	0.3
R^2 [-]	0.997
Bias [m]	0.001

Transcritical flow over a bump



$$z_b = \begin{cases} 0.2 - 0.03(x-10)^2, & if\ 8\,m < x < 12\,m \\ 0, & elsewhere \end{cases}$$

Parameter	Value
Numerical Scheme	Implicit
Time steps	0.05s -- 0.062 s
Simulation duration	2 hr
Ramp duration	1 hr
Flow discharge	0.18 $m^2\ s^{-1}$
Downstream depth	0.33 m
Bottom friction	None
Mixing terms	Off
Wall friction	Off



(Delestre, 2013)

$$
\begin{cases}
h^3 + \left(z_b - \dfrac{q_0^2}{2gh_c^2} - h_c - z_{b,max}\right)h^2 + \dfrac{q_0^2}{2g} = 0 & for\ x < x_{shock} \\
h^3 + \left(z_b - \dfrac{q_0^2}{2gh_L^2} - h_L\right)h^2 + \dfrac{q_0^2}{2g} = 0 & for\ x > x_{shock} \\
q_0^2\left(\dfrac{1}{h_1} - \dfrac{1}{h_2}\right) + \dfrac{g}{2}(h_1^2 - h_2^2) = 0 &
\end{cases}
$$

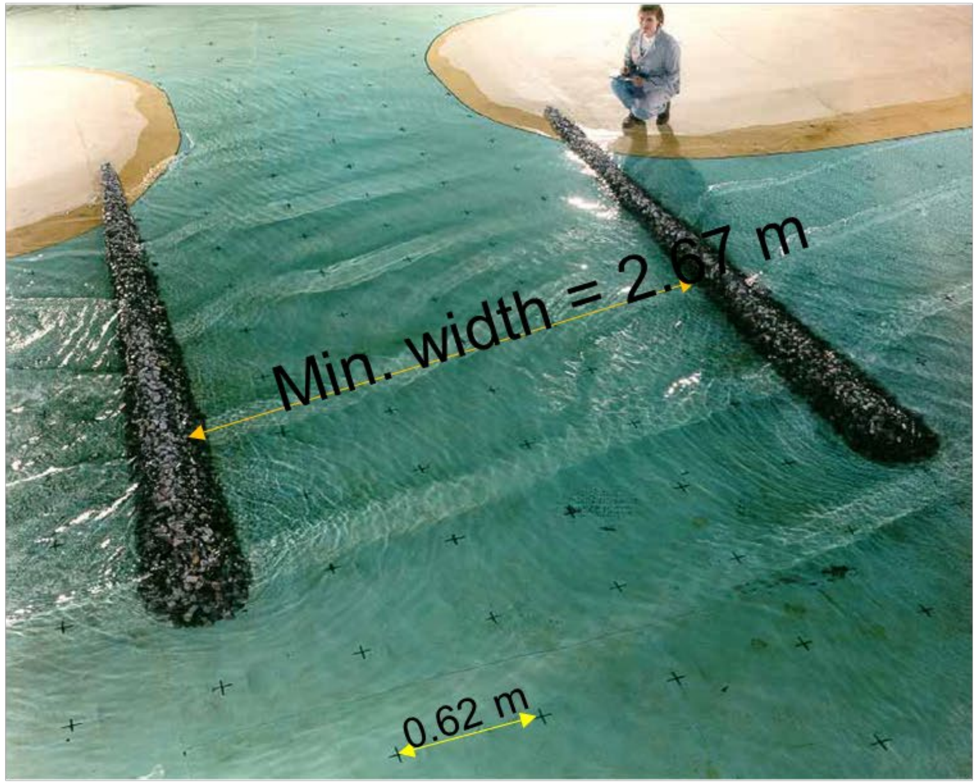
Statistics	Water Level
NRMSE [%]	5.388
RMSE [m]	0.01509
NMAE [%]	0.142
R^2 [-]	0.91535
Bias [m]	0.00051

Summary

- The hydrodynamic model performed well simulating a range of processes at different physical scales.
- Water level RMSEs were less than 5% and on the order of centimeters. This indicates proper formulation. Perhaps investigating the discretization could improve results.
- Current velocity magnitude errors were typically ~10%. This is in accordance with the previous VVUQ effort.
- Computational efficiency and grid size/timestep sensitivity tests are logical further developments for this work.

Laboratory Cases

Laboratory Study of Hydrodynamics Near Absorbing and Fully Reflecting Jetties
(Seabergh, Lin, & Demirbilek, ERDC/CHL TR-05-8, 2005)



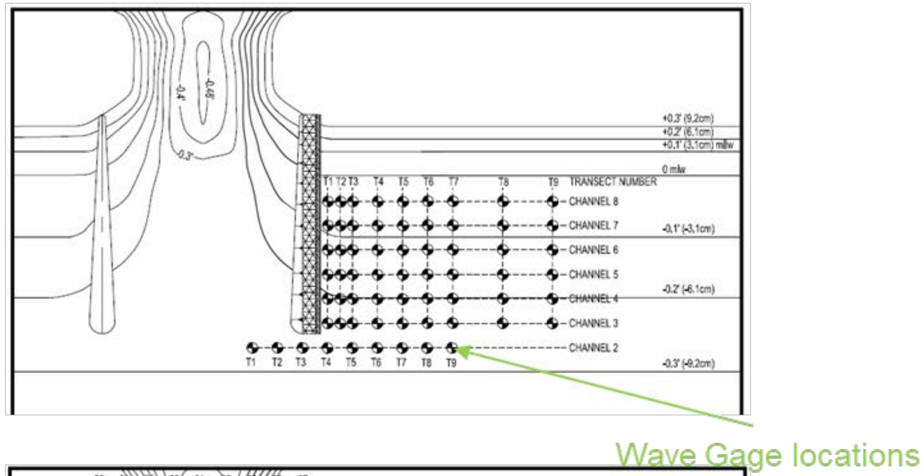
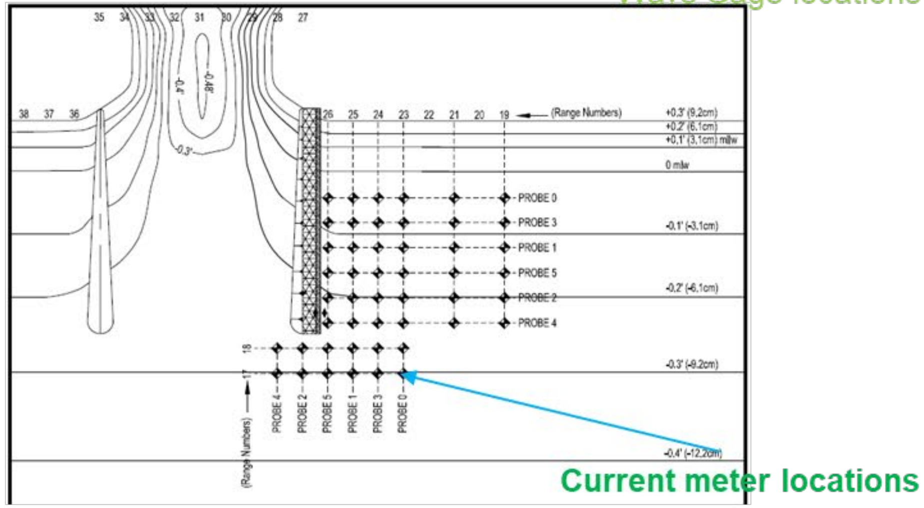


Table 1
Model-Prototype Scale Relations at 1:50 Undistorted Scale

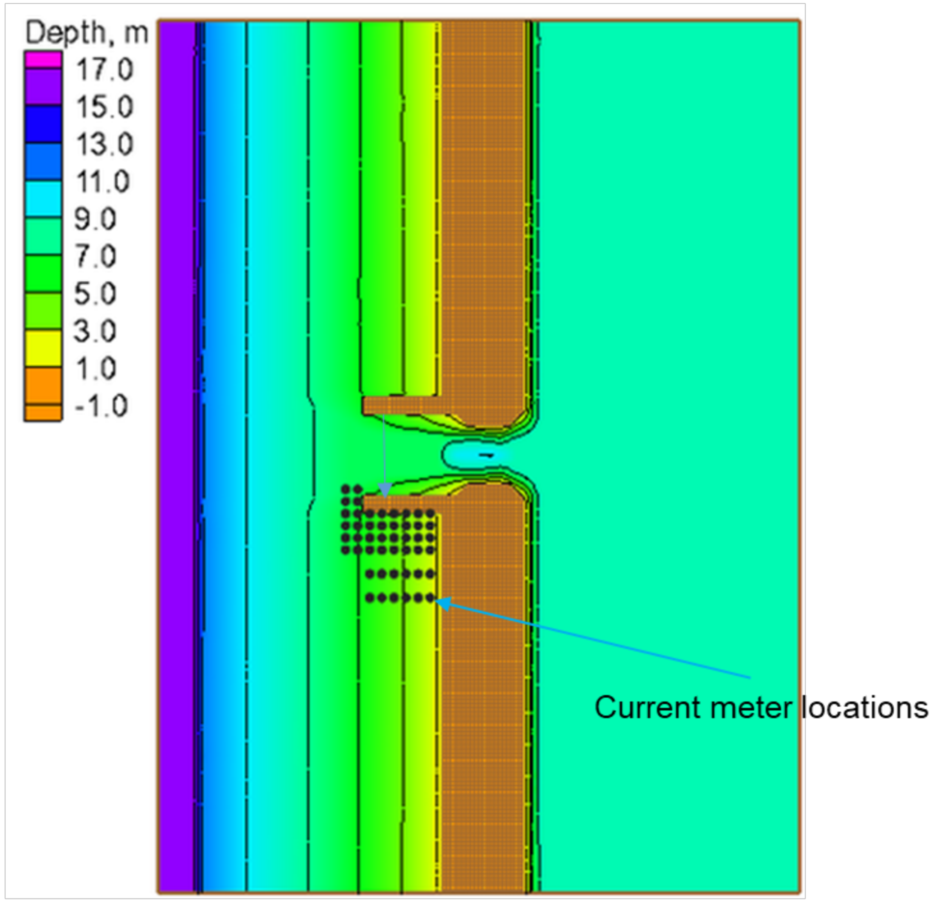
Characteristic	Dimension	Model-Prototype Scale Relation
Length	ℓ	ℓ_r = 1:50
Area	ℓ^2	Ar = ℓ_r^2 = 1:2,500
Volume	ℓ^3	Vr = ℓ_r^3 = 1:125,000
Time	t	Tr = $\sqrt{\ell_r}$ = 1:7.07
Velocity	ℓ/t	Ur = ℓ_r/t_r = 1:7.07



CMS2D Model Configuration

Domain: 1:50 to a prototype dimension of the inlet

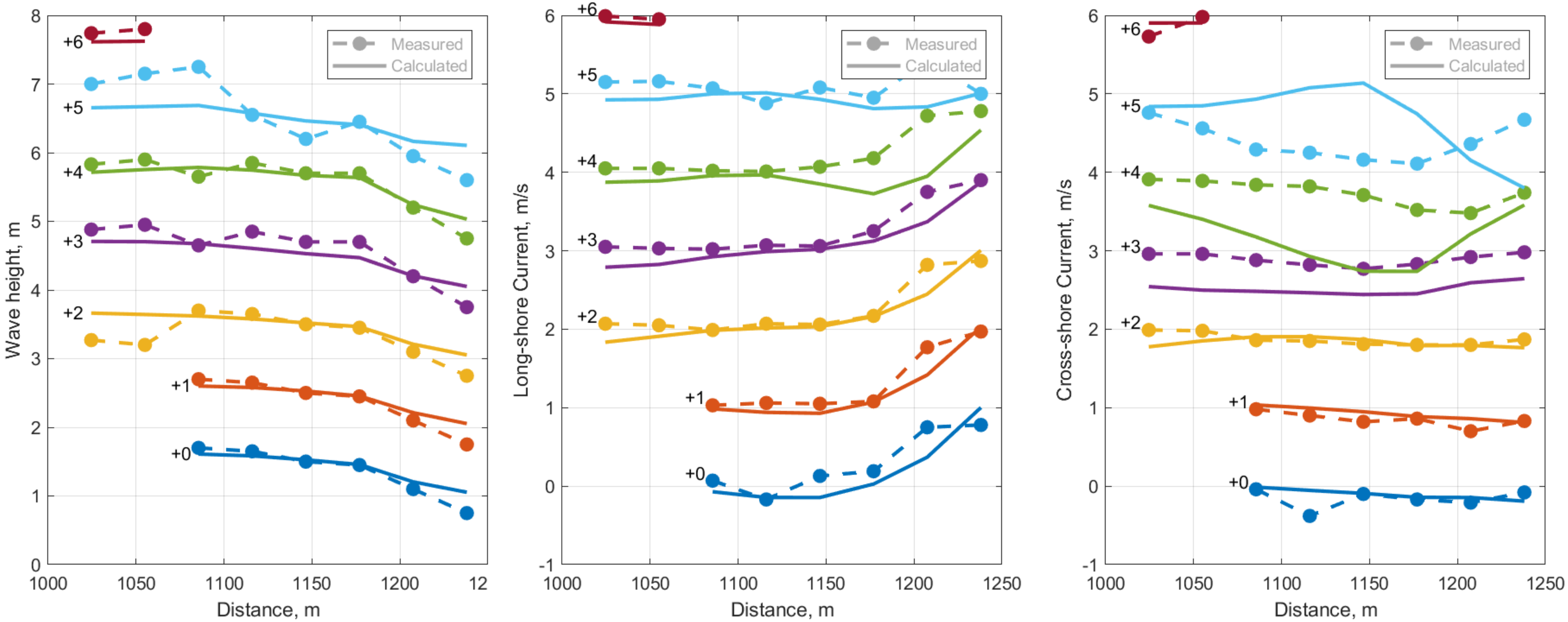
Parameter	Value
Model	CMS2D_v5p1.exe, (10/25/2019)
Grid size	Δx=Δy=10.0 m
Flow time step	10 min
Simulation duration	10 hr
Ramp period duration	3 hr
Manning's n (both flow and wave grids)	0.025 s/$m^{1/3}$
Steering interval	1 hr
Roller	On
Roller dissipation coefficient	0.05 (default for regular waves)
Stokes velocities	On
Wave reflection coefficient	0.0
Breaking Criterion	Battjes & Janssen
Wave-to-Flow Coupling	Linear Temporal Interpolation



Case	Hs (m)	Tp (s)	Angle (°)
1	1.65	11.0	-20.0
2	2.0	11.0	-20.0
3	3.25	8.0	-20.0
4	0.95	11.0	-20.0
5	1.10	8.0	-20.0

Case 1

Case	Hs (m)	Tp (s)	Angle (°)
1	1.65	11.0	-20.0



Error Analysis (Case 1)

Current Results (by CMS2D_V5p1.exe)

	RRMSE %	RMAE %	R2	Bias
Longshore current (U)	25.95	19.62	0.485	-0.070
Cross-shore current (V)	27.80	18.26	0.713	-0.149
Wave Height	15.23	12.71	0.825	-0.076

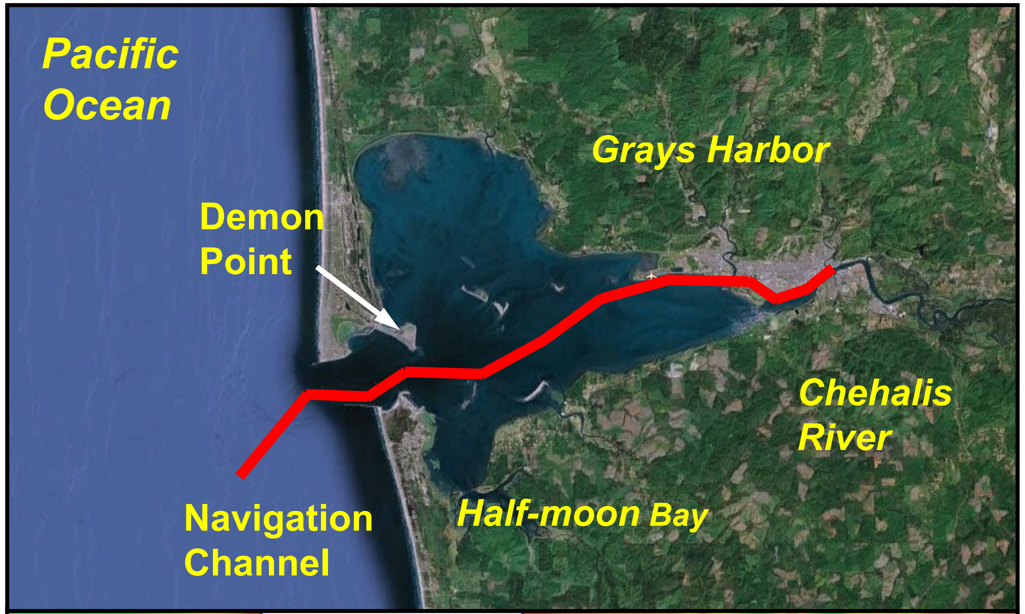
Alex's Results on CirpWiki

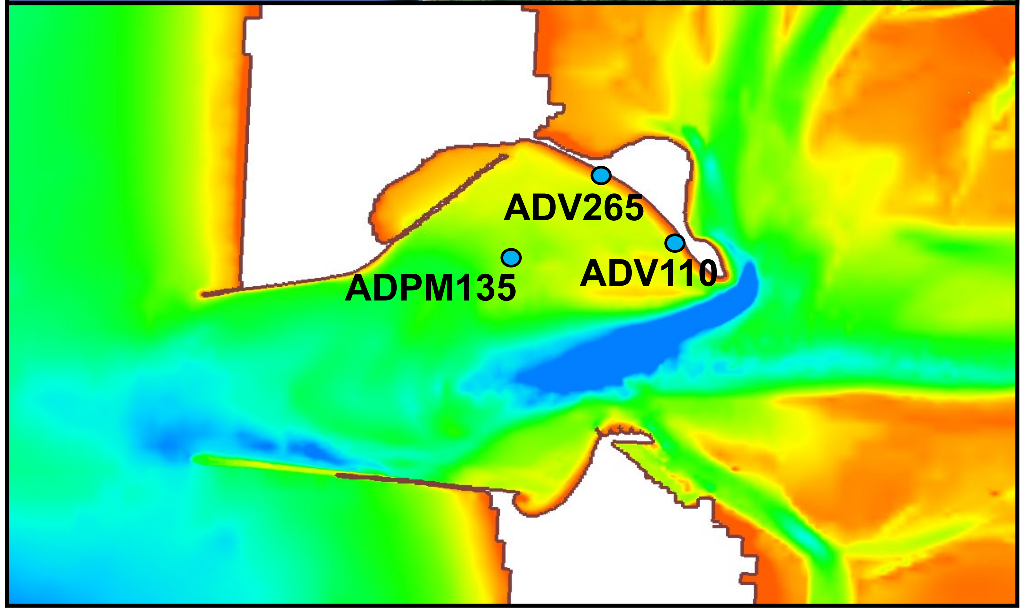
Variable	NRMSE,%	NMAE,%	R2	Bias
Longshore current	24.11	18.74	0.836	-0.141
Cross-shore current	14.27	10.30	0.907	0.017
Wave Height	13.96	10.62	0.826	0.051

Field Cases

Grays Harbor, WA

- Grays Harbor estuary is located on the southern coast of WA. A natural inlet on the west connects the harbor to Pacific.
- The federal navigation channel is 39.1 km long, 300 m wide outside the inlet and 100 m near the Port.
- Damon Point at the harbor entrance has experienced continued evolution towards the navigation channel. Spit encroachment on the channel may lead to increased maintenance requirements.
- The purpose of the study is to develop and calibrate a hydrodynamic and sediment transport model to evaluate potential shoaling in the navigation channel.
- A field survey program collected wave, water level, current, and sediment data in the region of Damon Point and were used for model calibration and validation (two Beach Pods, ADV265 and ADV110, and one bottom-mounted ADP).





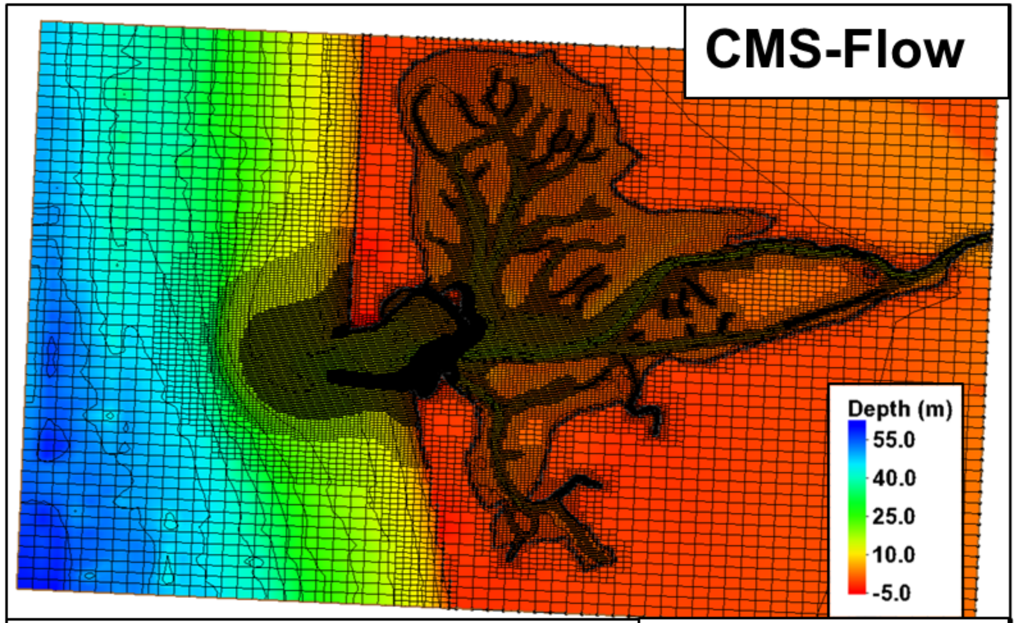
CMS Set up

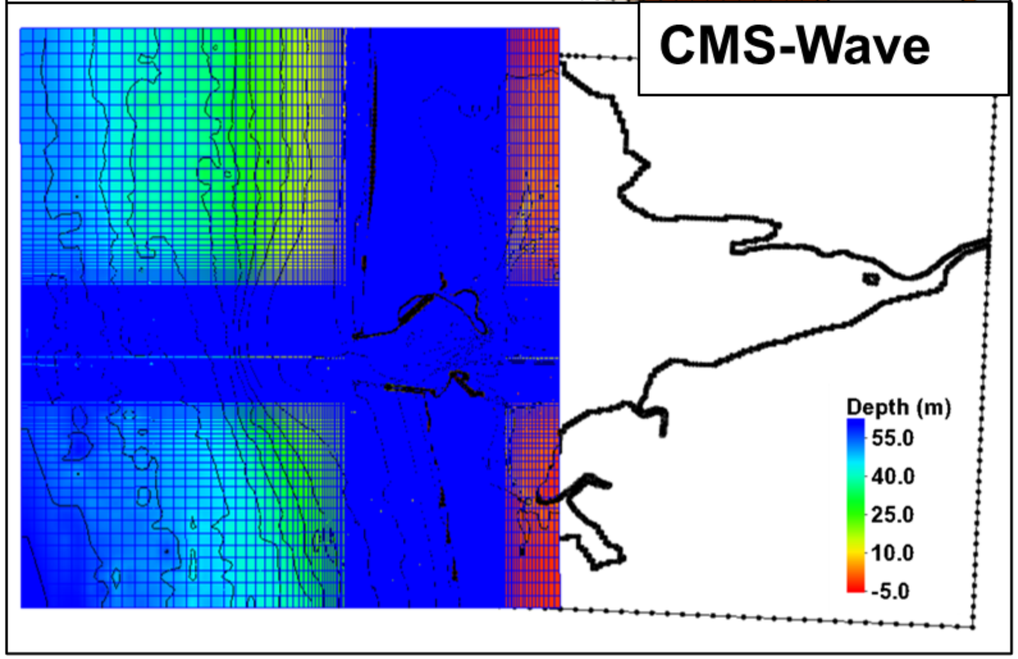
CMS-Flow:

Grid – telescoping grid
Domain - 25 km alongshore and 50 km cross shore
Computational grid - 57,500 ocean cells
Grid resolution - 8 × 11 to 480 × 720 m
Hydro time step - 900 sec.

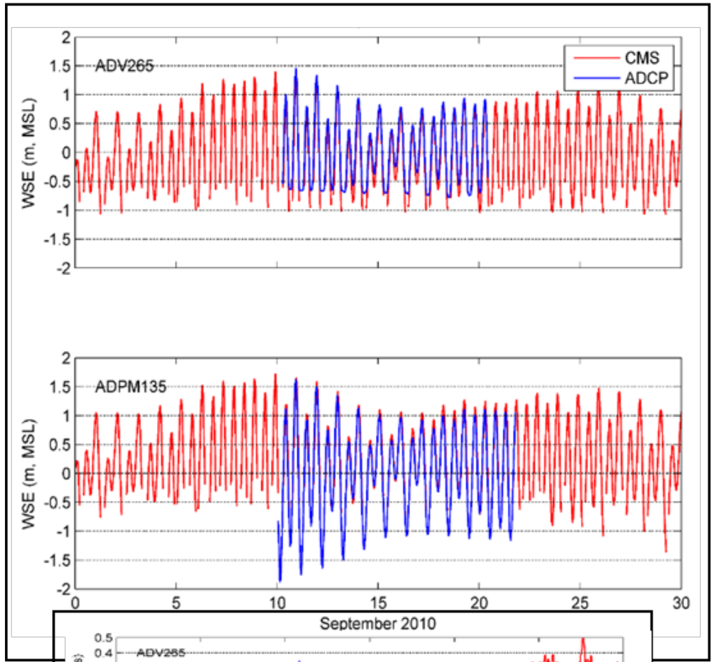
CMS-Wave:

Grid - non-uniform rectangular grid
Domain - 25 × 26 km
Computational grid - 81,300 cells
Grid resolution - 20 × 20 to 600 × 600 m

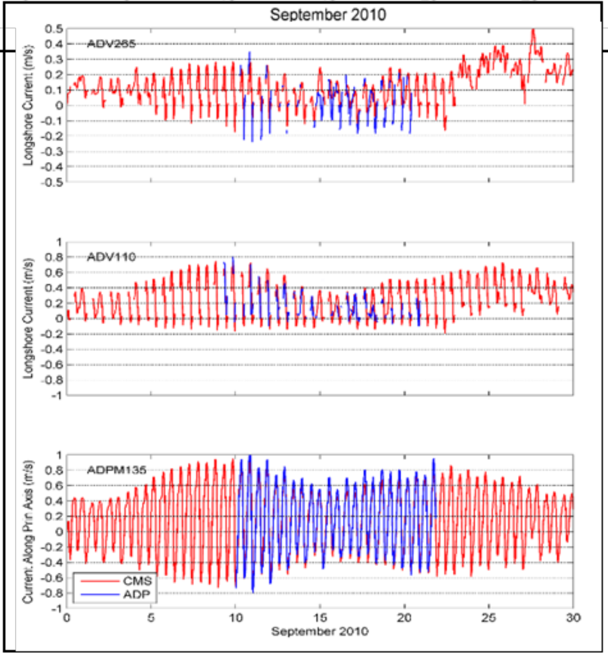




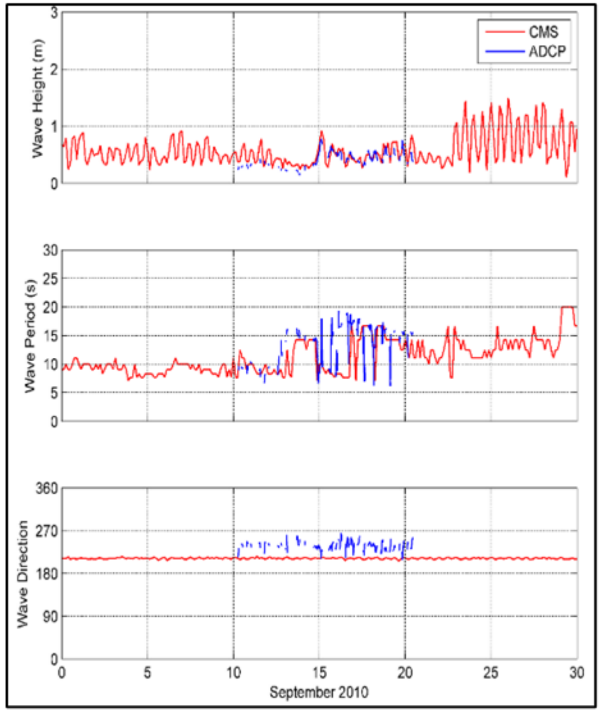
CMS Results - Goodness-of-fit Statistics

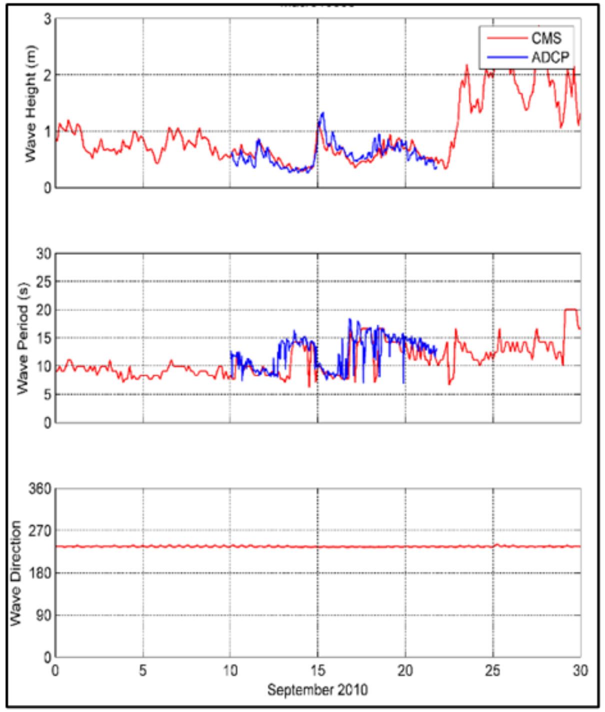


Water Surface Elevation		
Statistics	ADV265	ADPM135
NRMSE [%]	8.082	2.983
RMSE [m]	0.178	0.104
NMAE [%]	7.195	2.386
R^2	0.981	0.984
Bias [m]	-0.156	0.034



Principle Current Velocity		
ADV265	ADV110	ADPM135
14.483	17.056	5.200
0.087	0.154	0.094
11.067	13.422	4.150
0.542	0.531	0.966
0.029	0.032	-0.013

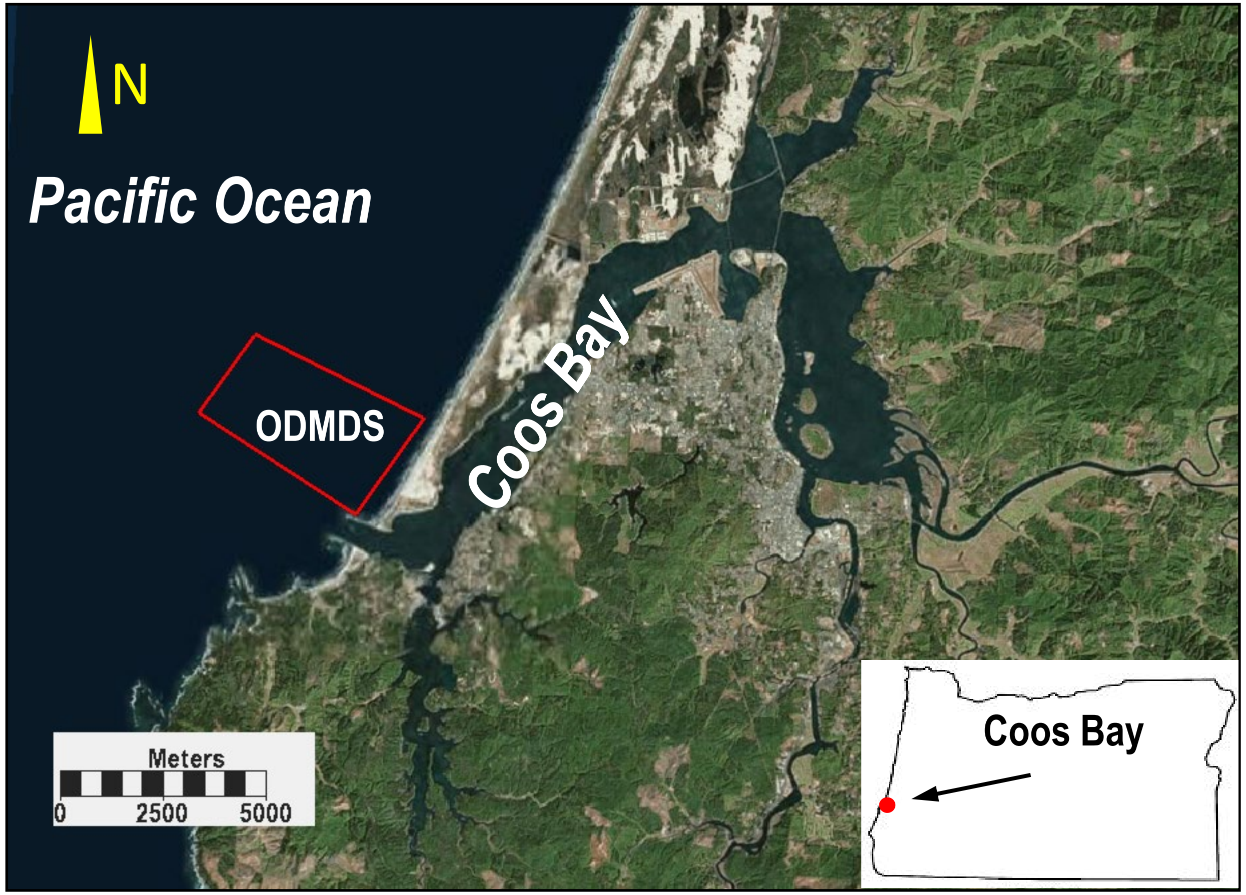




Wave Parameters				
Statistics	ADV265		ADPM135	
	Significant Wave Height (m)	Peak Wave Period (s)	Significant Wave Height (m)	Peak Wave Period (s)
NRMSE [%]	16.688	22.078	10.169	14.917
RMSE	0.134	4.195	0.132	2.685
NMAE [%]	12.775	14.995	7.815	10.006
R^2	0.424	0.111	0.582	0.412
Bias	0.069	-1.860	0.010	-1.180

Coos Bay, OR

- Coos Bay Inlet System: large waves and strong tidal current in the system
- Annual maintenance dredging of the navigation channel and sand material is placed in nearshore ocean dredged material disposal site (ODMDS) to supplement the littoral sediment budget
- Sediment interaction with waves and current induces channel backfilling and decreases channel navigability
- Sediment tracer study and numerical model to investigate littoral sediment transport for the Coos Bay inlet and estuarine system and to evaluate the effects and the short- and long-term response of nearshore dredged material placement to coastal wave and hydrodynamic environment.



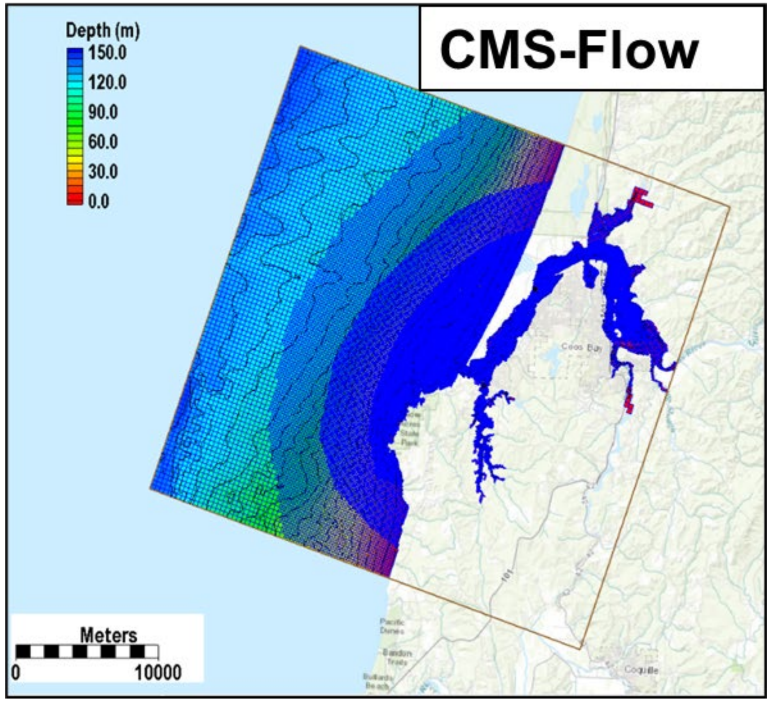
CMS Set up

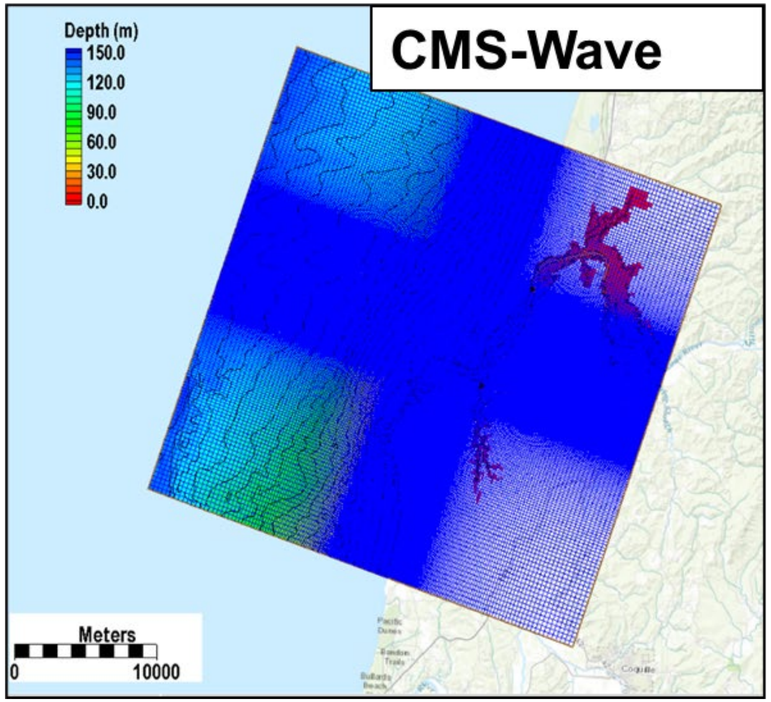
CMS-Flow:

Grid – telescoping grid
Domain – 31 × 32 km
Computational grid - 132,000 ocean cells
Grid resolution - 20 × 20 to 320 × 320 m
Hydro time step - 600 sec.

CMS-Wave:

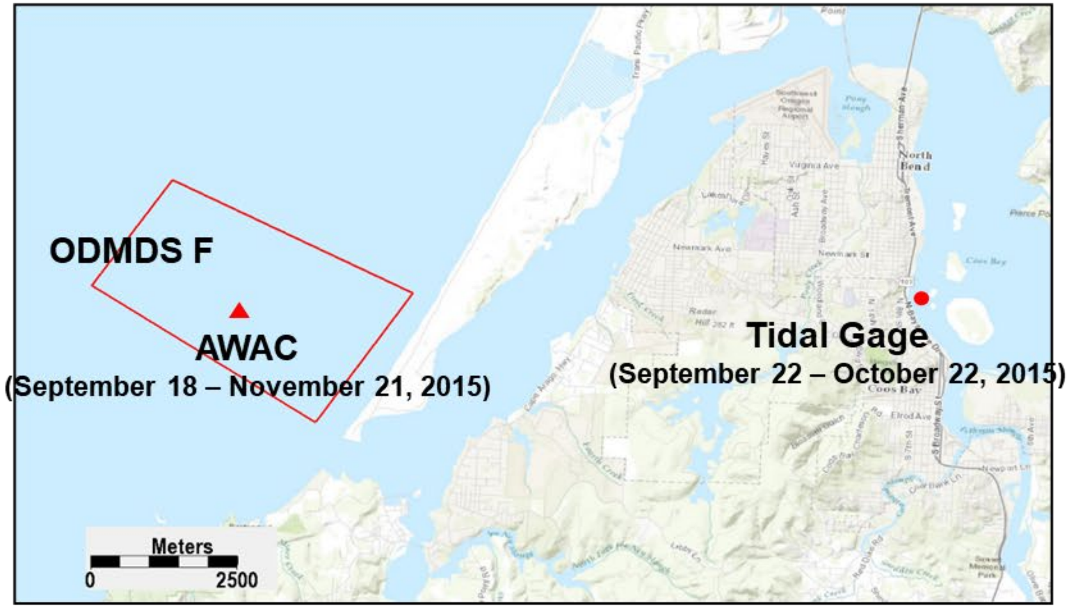
Grid - non-uniform rectangular grid
Domain - 31 × 32 km
Computational grid - 212,700 cells
Grid resolution - 20 × 20 to 320 × 320 m

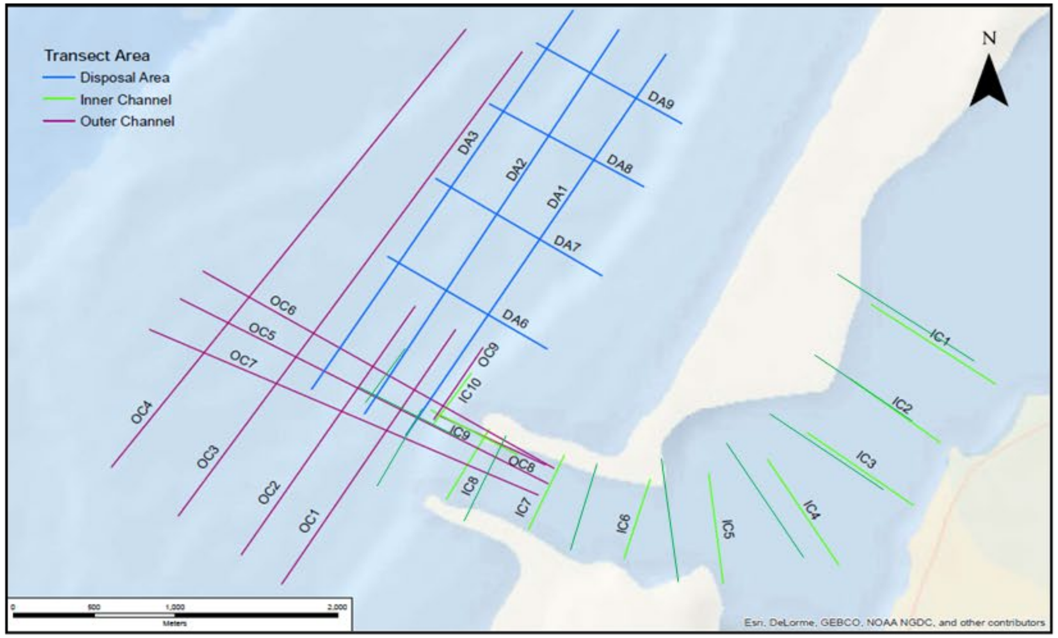




Model Calibration/Validation

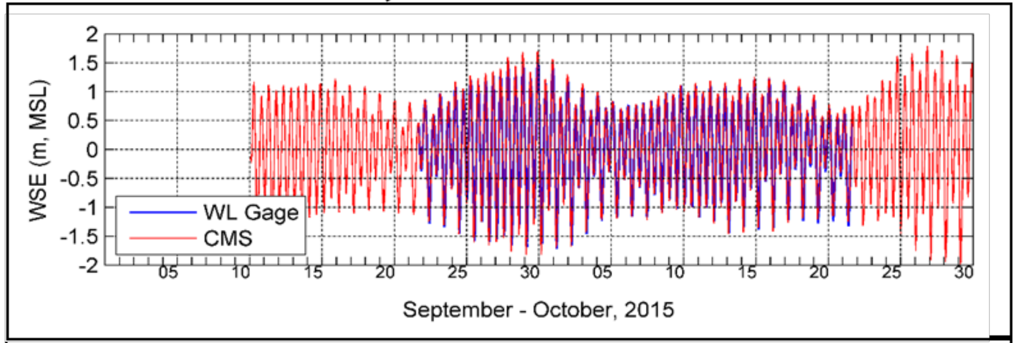
- Time series measurements: acoustic wave and current profiler (AWAC) and tidal gage
- Instantaneous measurements: vessel mounted ADCP along transects

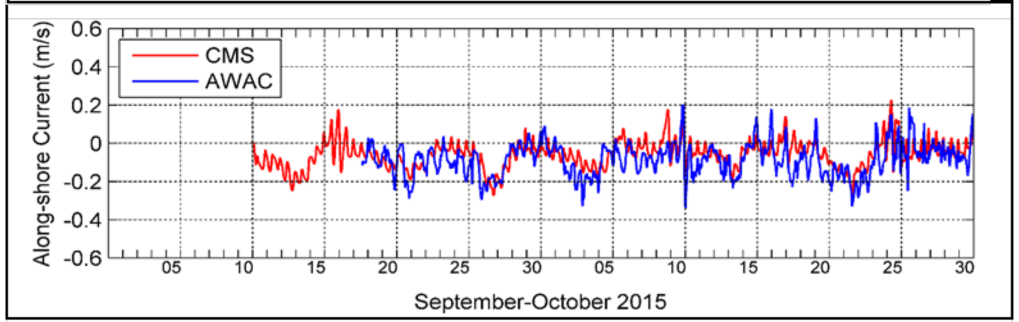




CMS Results - Goodness-of-fit Statistics

Water Level, Current

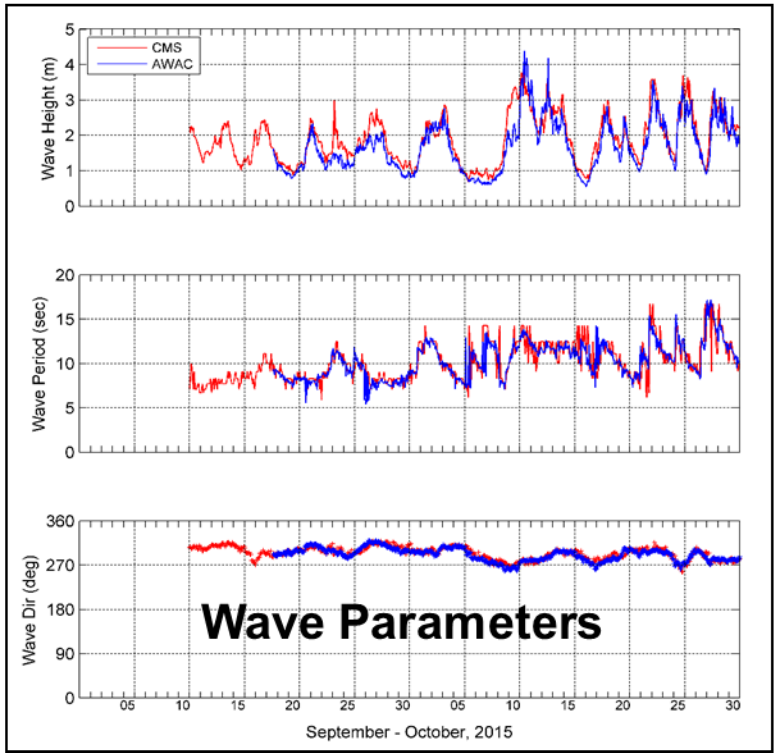




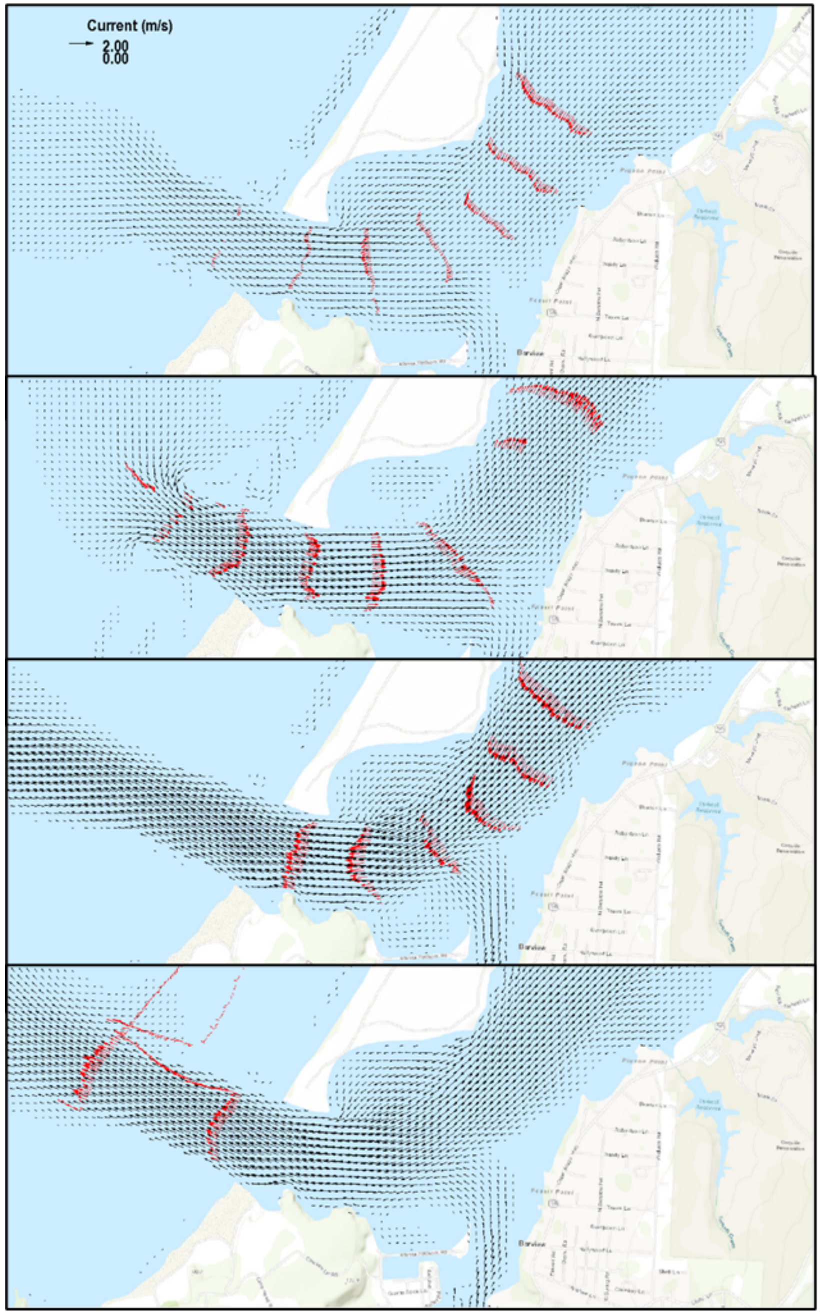
Water surface elevation	
Statistics	**WL Gauge**
NRMSE [%]	6.068
RMSE [m]	0.206
NMAE [%]	4.938
R^2	0.946
Bias [m]	-0.016

Principle current velocity	
Statistics	**AWAC Gauge**
NRMSE [%]	15.840
RMSE [m/s]	0.079
NMAE [%]	12.420
R^2	0.324
Bias [m/s]	0.030

Wave parameters			
Statistics	**AWAC Gauge**		
	Significant Wave Height (m)	**Peak Wave Period (s)**	**Mean Wave Direction (deg)**
NRMSE [%]	8.336	7.158	2.006
RMSE	0.375	1.217	6.418
NMAE [%]	6.380	4.586	1.588
R2	0.834	0.682	0.788
Bias	0.222	0.129	2.228

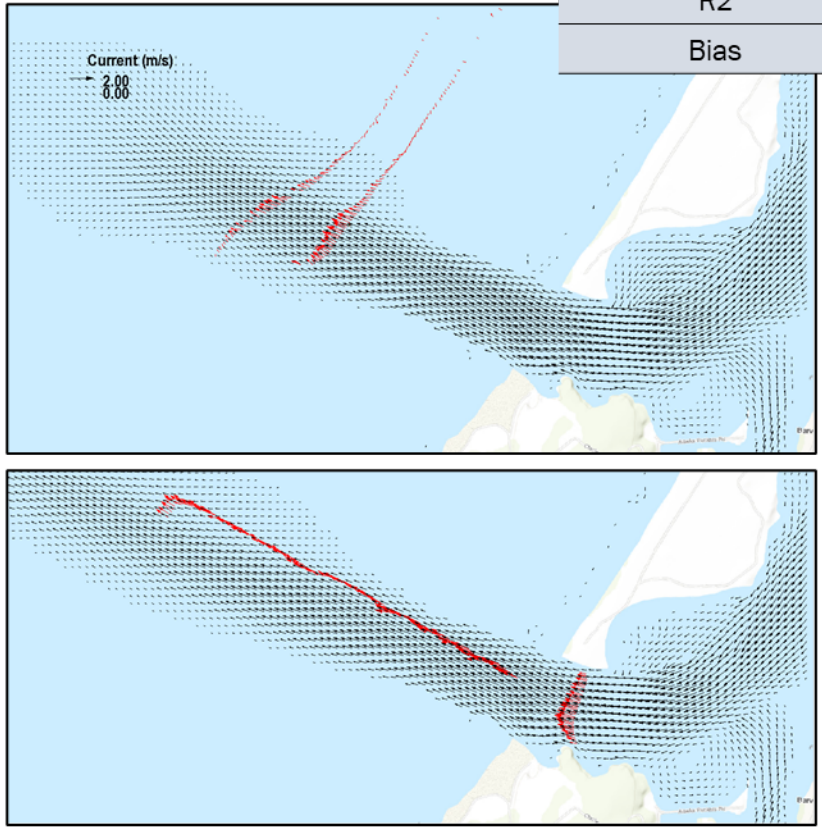


CMS Results - Goodness-of-fit Statistics



Vessel-mounted instantaneous current measurements and CMS calculations in transects from 28 September to 1 October 2015.

Statistics	Current Velocity (m/s)	
	U Component (E-W)	V Component (N-S)
NRMSE [%]	6.393	5.129
RMSE	0.197	0.147
NMAE [%]	4.471	3.669
R2	0.855	0.840
Bias	0.008	0.003



Summary

- The CMS performs well in simulating tidal hydrodynamics at a coastal inlet and estuarine system in the presence of waves and wind.
- Time series measurements of water levels, current velocities, and wave parameters are well reproduced at AWAC (ADCP) and tidal gages.
- The model has also caught instantaneous measured currents along selected transects around the inlet and navigation channel.
- Goodness-of-fit statistics are used to assess the model performance and the model results agree well with measurements in nearshore breaking zone and in offshore deeper area.
- The model results demonstrate that it is reasonable to use large time steps, on the order of 15 min, for similar tidal inlet hydrodynamic studies.

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