Continental Scale Heterogeneous Channel Routing Strategy for Operational Forecast Models

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0 500 1,000 km

Acknowledgements

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National Water Model (NWM)

- Short (18 hr), Medium (10 day) and, and Long (30 day) range forecasts
- Atmospheric forcings from a variety of sensor and model datasets (e.g., UFS)
- Hydrologic surface and subsurface routing
- Hydraulic channel routing (WRF-Hydro) uses Muskingum-Cunge in NHDPlusV2 network

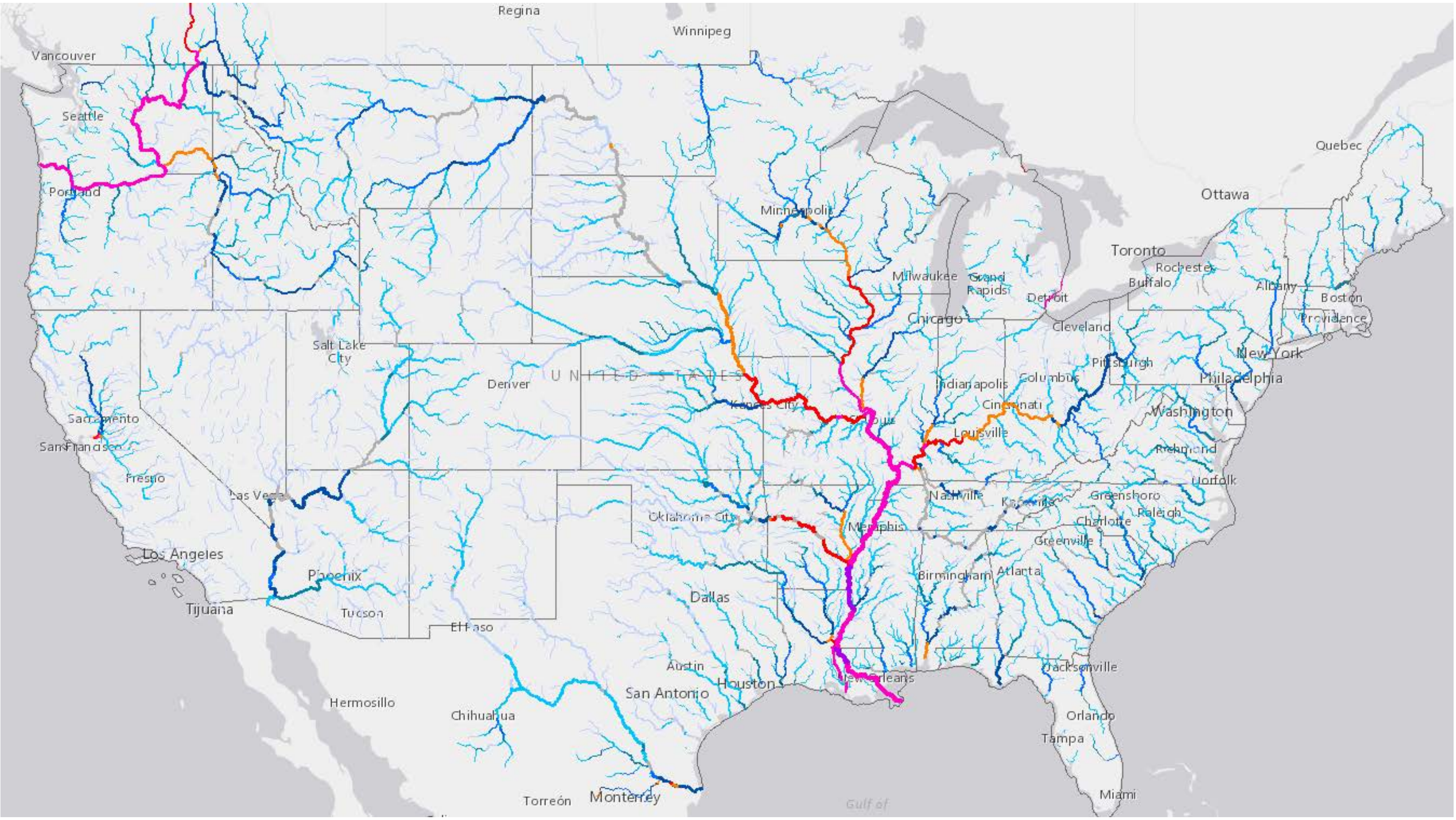


Figure from: https://water.noaa.gov/map

St. Venant Equations

- Conservation of Volume:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

- Conservation of Momentum:

Inertia | Pressure | Gravity | Friction

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} - gA(S_0 - S_f) = 0$$

Kinematic Wave
Muskingum-Cunge
Diffusive Wave
Dynamic Wave

Dimensionless Scaling Parameters (DSP)

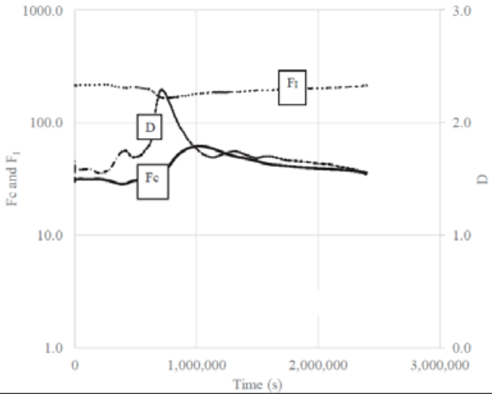
- Ferrick (1985) identified several parameters to estimate relative influence of dynamic vs diffusive & kinematic waves.
- Meselhe et al. (2020) revisited this approach to quantify need for dynamic wave routing in the NWM.
- The magnitude of each momentum term was also analyzed.

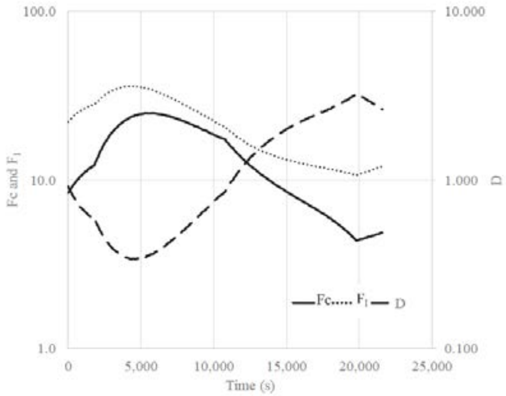
DSP	Equation	Physical interpretation
C_r	$C_r = v_0\left(\frac{\Delta t}{\Delta x}\right)$	Courant number: Ratio of mean flow velocity to measured wave celerity
F_0	$F_0 = \frac{v_0}{\sqrt{g y_0}}$	Froude number: Ratio of surface wave to mean flow velocity
S	$S = \frac{S_0}{S_f}$	Ratio of channel bed slope to energy gradient
D_I	$D_I = \left(\frac{C_r}{F_0}\right)^2$	Ratio of Courant to Froude numbers; or surface wave to measured wave celerity
F_I	$F_I = \frac{2C_r}{(C_*)^2}\left(\frac{k\Delta x}{y_0}\right)$	Friction parameter: influence of friction effects on river flow
F_c	$F_c = F_I C_r$	Friction parameter: reflecting influence of F_I and Courant number
D	$D = \frac{D_I}{F_c}$	Dimensionless diffusion coefficient: ratio of wave diffusion to wave advection

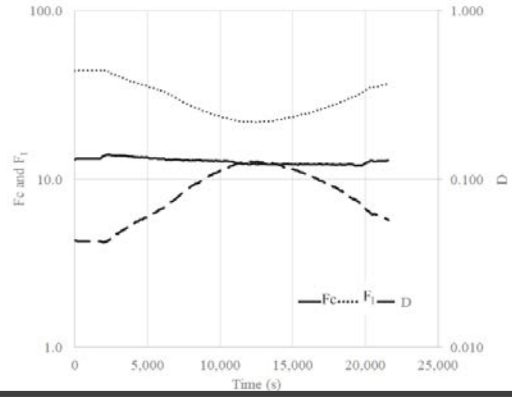
Table (after Ferrick, 1985) from Meselhe et al. (2020)

Test cases from Meselhe et al. (2020)

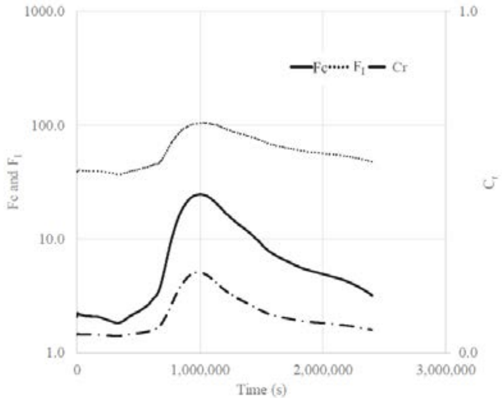
Normal Depth @ Downstream

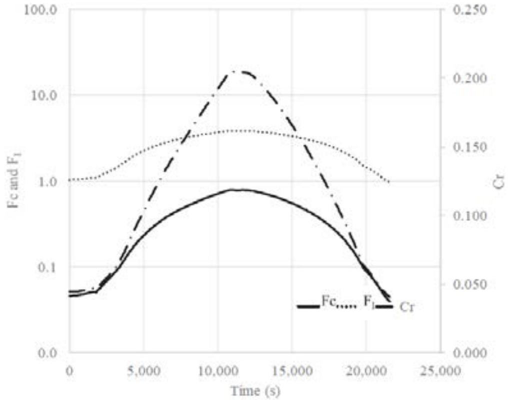






Backwater Curve





Flow state	Back water	Downstream stage (m)	Range of changing variables: Q_{peak} (m^3/s)	Slope	$1/n$
Unsteady	Yes	2 × ND	200–700	—	—
	Yes	2 × ND	—	5×10^{-5}–1×10^{-3}	—
	Yes	2 × ND	—	—	10–90
	No	ND	200–700	—	—
	No	ND	—	5×10^{-5}–1×10^{-3}	—
	No	ND	—	—	10–90

‘100-yr’ Flood in Red River @ Shreveport, LA

Idealized channel geometry and hydrographs

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Test cases from Meselhe et al. (2020)

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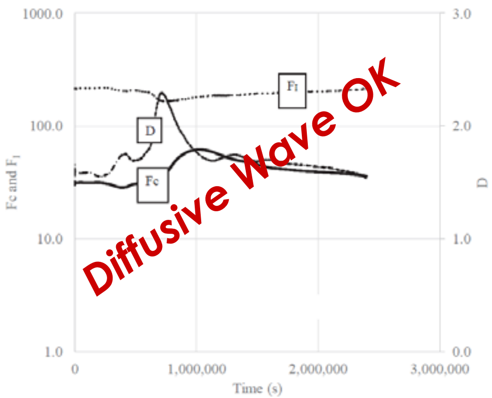

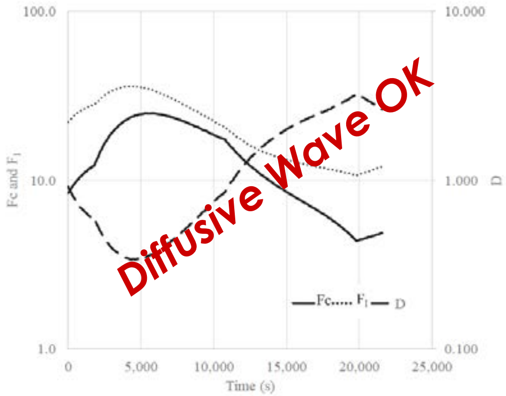

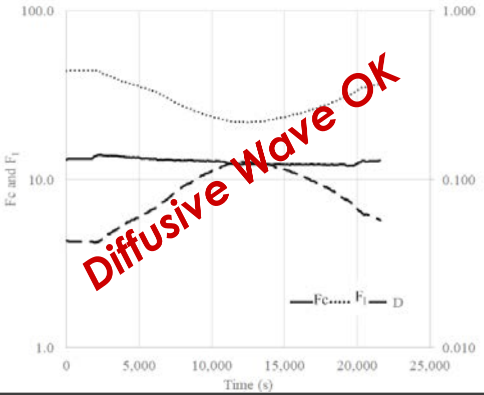

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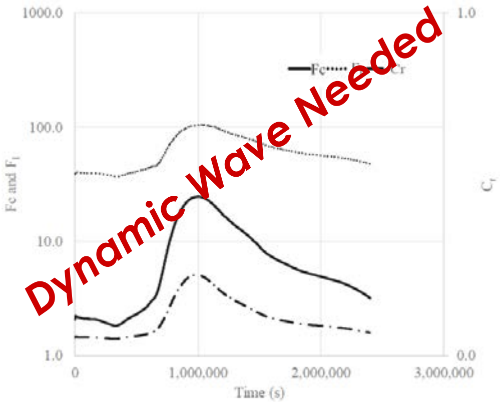

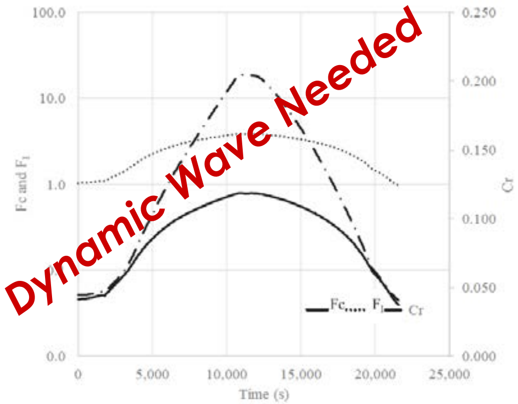

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	Yes	$2 \times$ ND	—	5×10^{-5}–1×10^{-3}	—
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	No	ND	—	—	10–90

'100-yr' Flood in Red River @ Shreveport, LA

Idealized channel geometry and hydrographs

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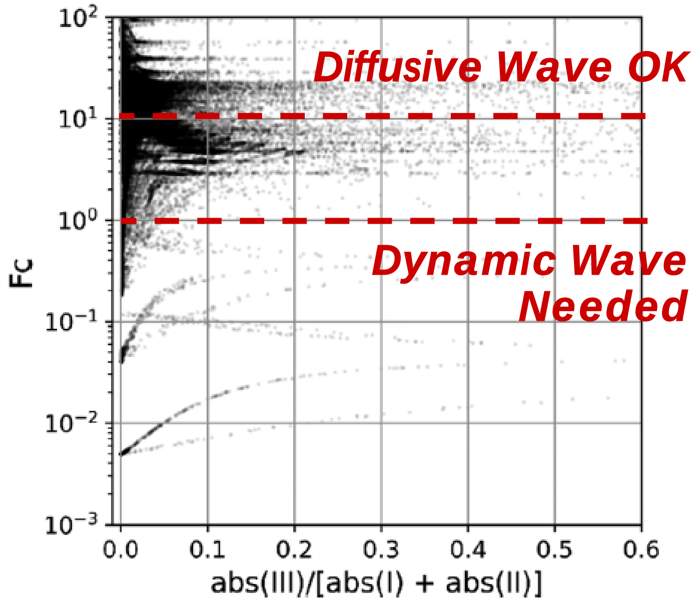
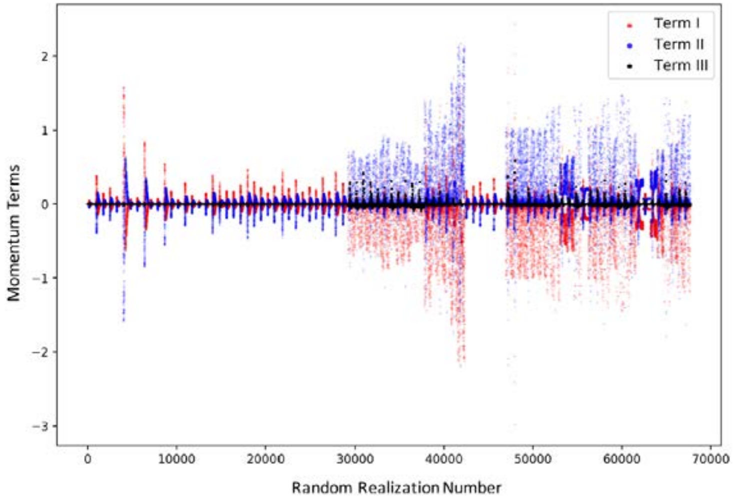
Prevalence of Dynamic Waves

- Pressure gradient is non-negligible[1] in 97% of sampled points in test cases
  - Kinematic Wave only useful in 3% of cases

- Inertia terms are negligible[2] in 76% of sampled points in test cases
  - Dynamic Wave needed in 24% of cases
  - Therefore, Diffusive Wave appropriate in roughly 73% of cases

- Ferrick's F_C indicates inertia is negligible in 60%–80% of sampled points in test cases





Figures from Meselhe et al. (2020)

[1]considered negligible when momentum term due to pressure is less than 10% of that due to friction
[2]considered negligible when momentum term due to inertia is less than 10% of that due to friction

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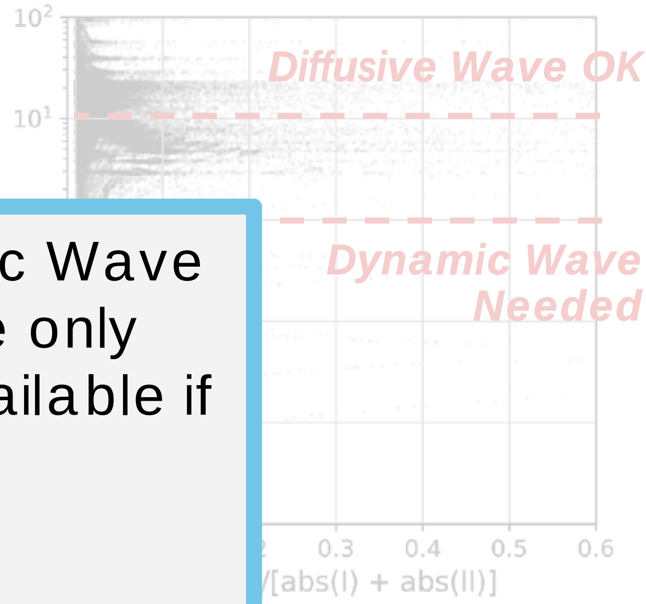
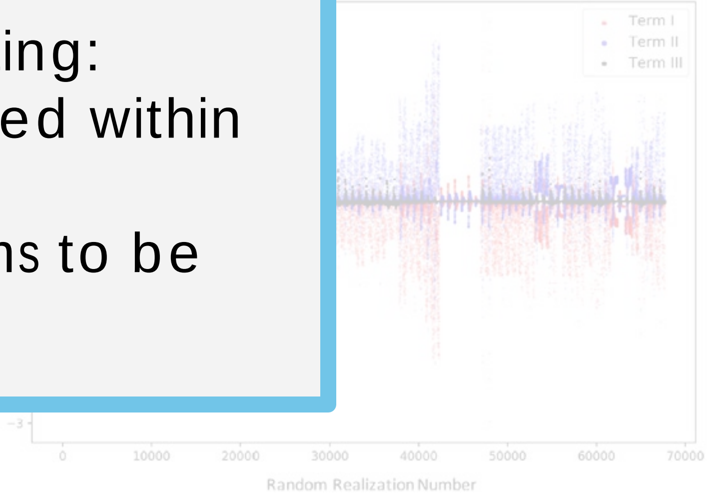
Prevalence of Dynamic Waves



We want to know *a priori* whether we need to run the Dynamic Wave or can 'make do' with Diffusive Wave. But the inertia terms are only calculated via the full Dynamic Wave model; they are not available if Diffusive Wave, Muskingum-Cunge, or Kinematic wave routing algorithms are used. We must rely on the DSPs.

For the ~ 25% of conditions that require Dynamic Wave routing:

- can we identify **where** these channel reaches are located within CONUS, and
- **when** conditions will allow for simplified routing algorithms to be used without loss of accuracy?



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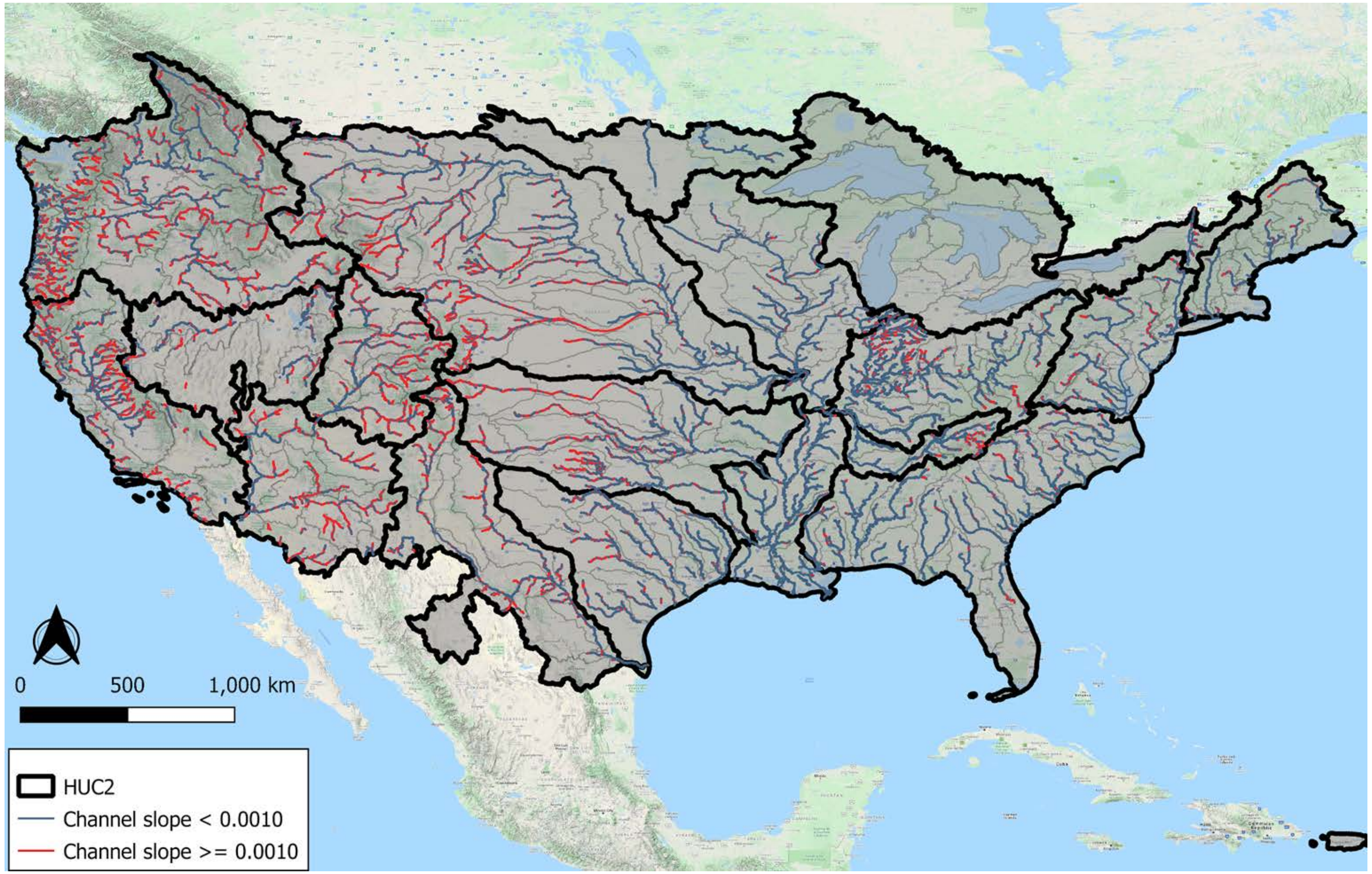
Work Flow: Continental Scale Properties

National Hydrography Dataset - NHDPlusV2
- channel alignment
- channel slope

Network is reduced to channel reaches that have the two highest stream orders within each HUC04



Workflow: Continental Scale Properties

Estimate bankfull channel width from:

- contributing drainage area (Wilkerson et al., 2014)
- corresponds to '2-yr' peak flowrate, which is calculated via USGS StreamStats

Bankfull width chosen so that channel reach can be represented with a rectangular cross-section

- removes complexities of modeling floodplain connectivity
- no need for cutting cross-sections from DEMs
- only using in order to flag need for Dynamic vs Diffusive wave algorithms, ultimately flood inundation will be modeled with the operational model/cross-sections

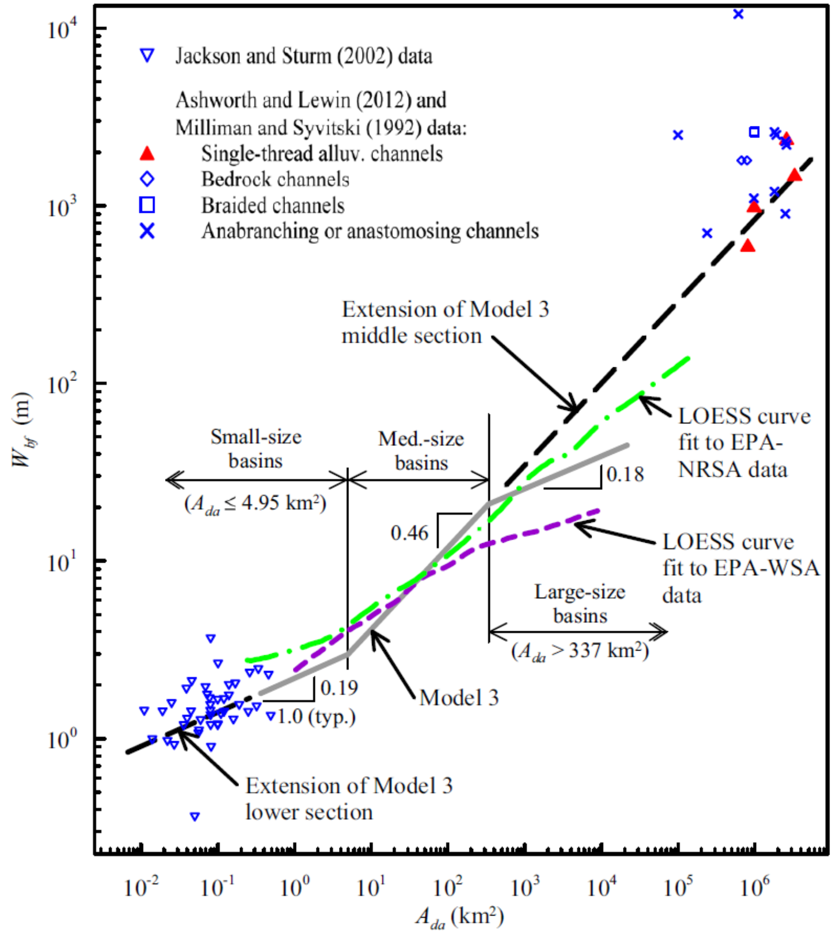


Figure from Wilkerson et al. (2014)

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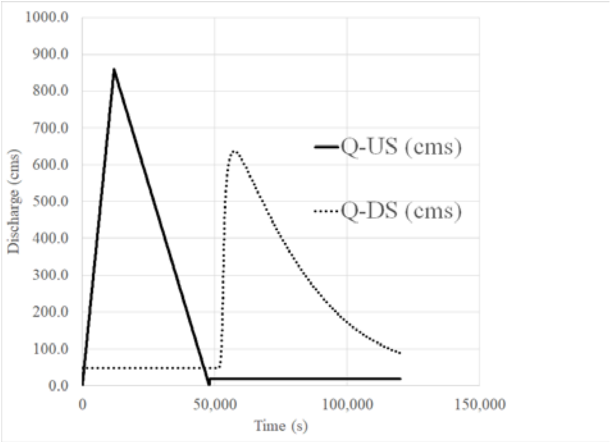
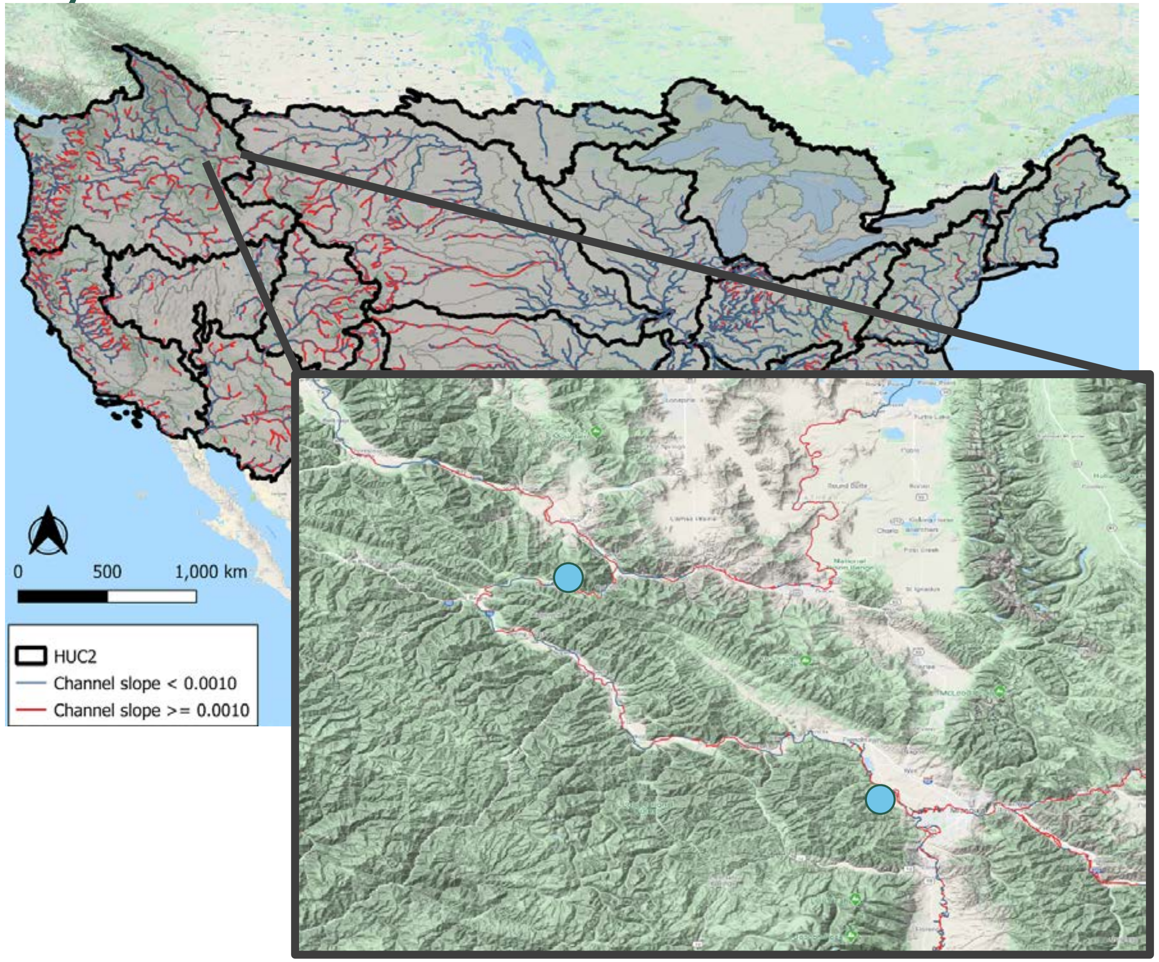
Test case: Clark Fork River, Montana

- ‘2-yr’ Peak Discharge = 858 cms
- Basin area = 23,310 km^2
- Bankfull width = 45 m
- Mean channel slope = 0.0012
- Manning’s roughness = 0.03
- Channel reach length = 165 km
- No backwater or drawdown





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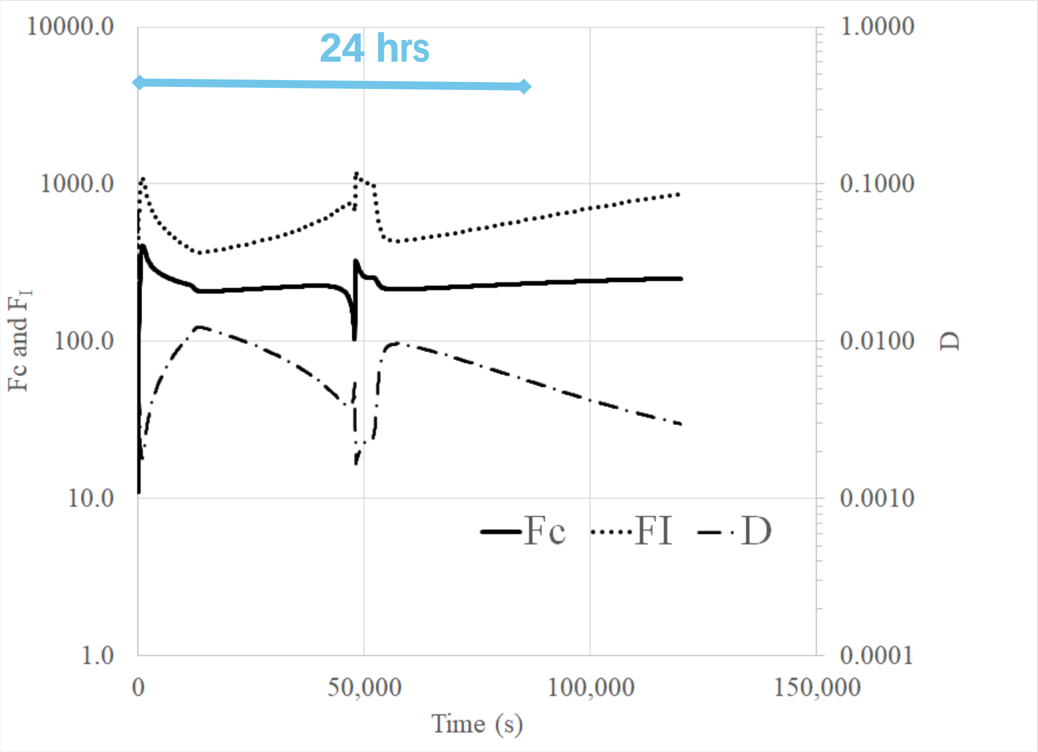
Dynamic wave not required (F_C >> 10)

Kinematic wave would suffice (D << 0.1)



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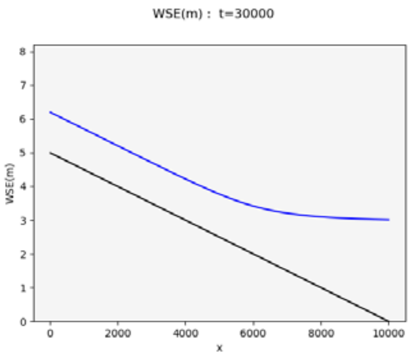
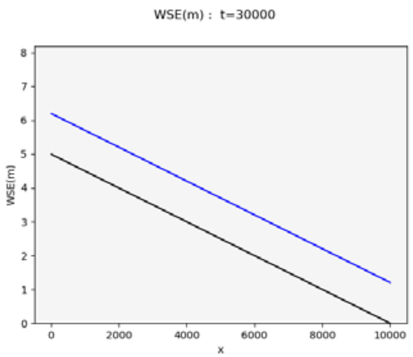
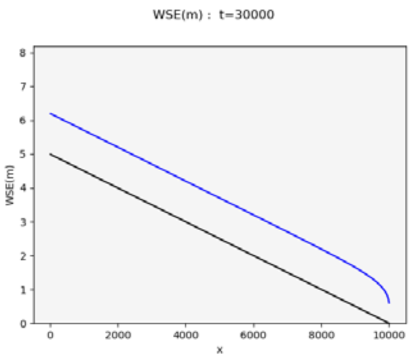
Next Steps for CONUS analysis:

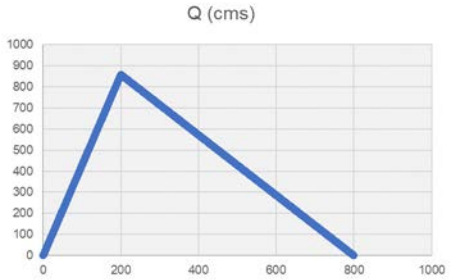
- For mainstem reach within each HUC04 model:
  - more frequent flowrates than bankfull (e.g., 1-year flood and smaller)
  - bankfull flowrates with varying downstream boundaries

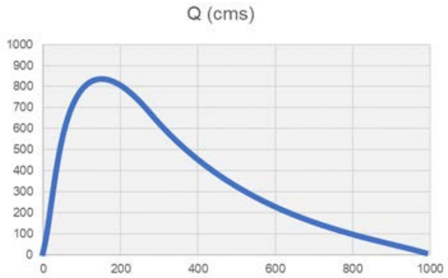


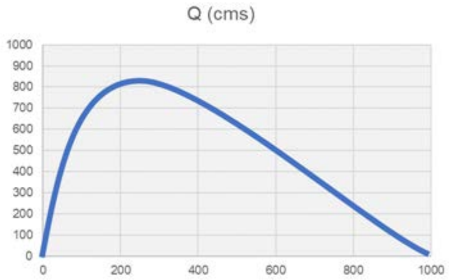




  - varied hydrograph shapes and durations







Next Steps for CONUS analysis :

- Repeat above analysis with detailed slopes (as opposed to average slope per reach)

- Repeat above analyses with varying channel roughness values

- Analyze variations in increasing downstream water levels (e.g., tidal)
  - Important for tidal channels with large tidal ranges (but how large?)
  - Observed tidal amplitude and period will be used to set realistic/operational bounds
    - More on this in following slides
  - Also likely to be important for accurate modeling in headwater networks with intense rainfall (e.g. flashy hydrographs in neighboring basins)

Additional test cases

- Analyze sensitivity of complex channel cross-sectional geometry
    - will be done for select basins with detail cross-sections available
        - Vermilion River, LA; Goodwin Creek, MS; more
- Compare simulations of Dynamic & Diffusive wave to assess accuracy and computational costs of different methods
    - More on this in following slides

Lower Mississippi River Model Domain

- U/S Boundary at Baton Rouge
- D/S boundary at East Jetty (South West Pass)
- River length 411.8 km

LMR Experiment: Model Performance

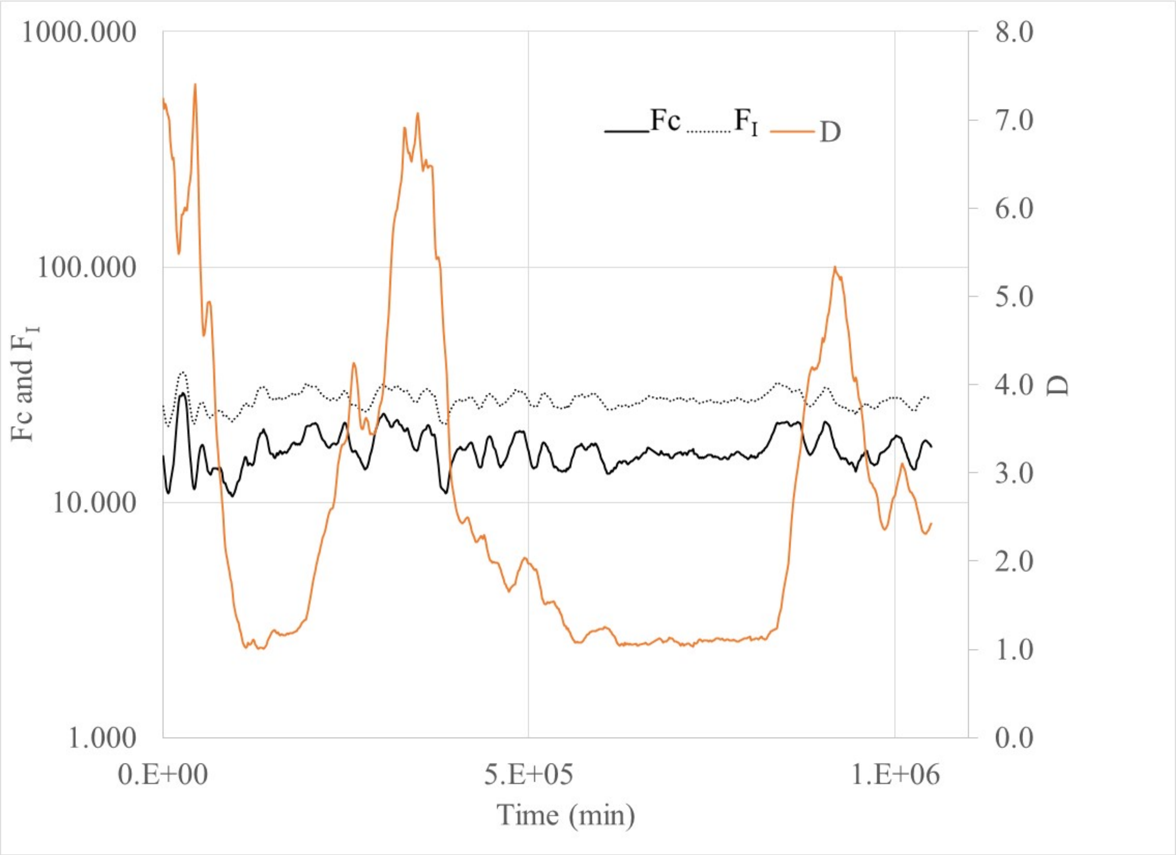
- Simplified cross section representations
- Simplified bed slope (only positive/downward slope)

	No of X-secs	Max Dx (m)	Min Dx (m)	Ave Dx (m)
Model Domain Attributes	280	2,184	796	1,423

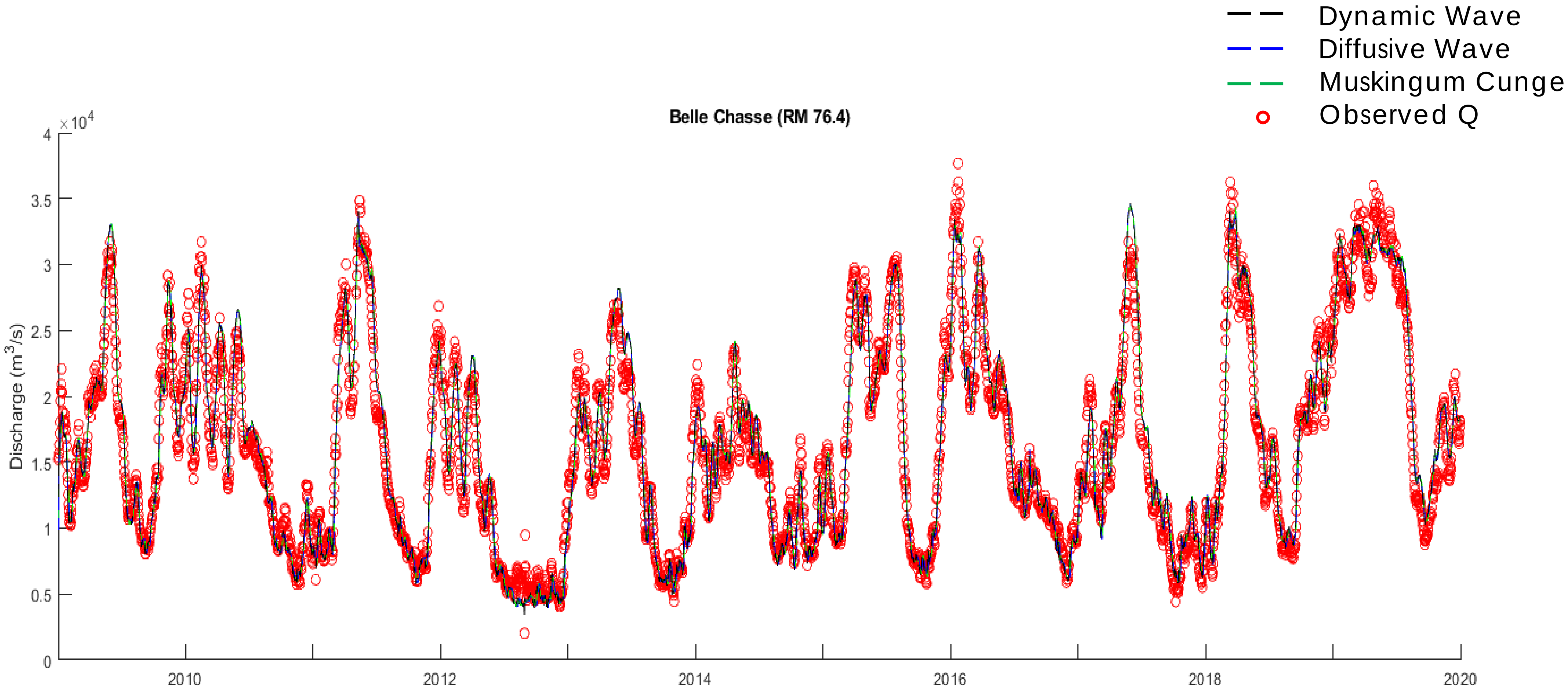
	Dt (s)	Simulation Duration (yrs)	Run Time (s)	Courant No (-)	Run Time for NHD+/per hour(s)
Dynamic Wave	240	11	1,590	0.706	200
Diffusive Wave	Var	11	370	1.0	47
Muskingum Cunge	240	11	536	--	67

Channel Flow Routing: Scaling Parameters

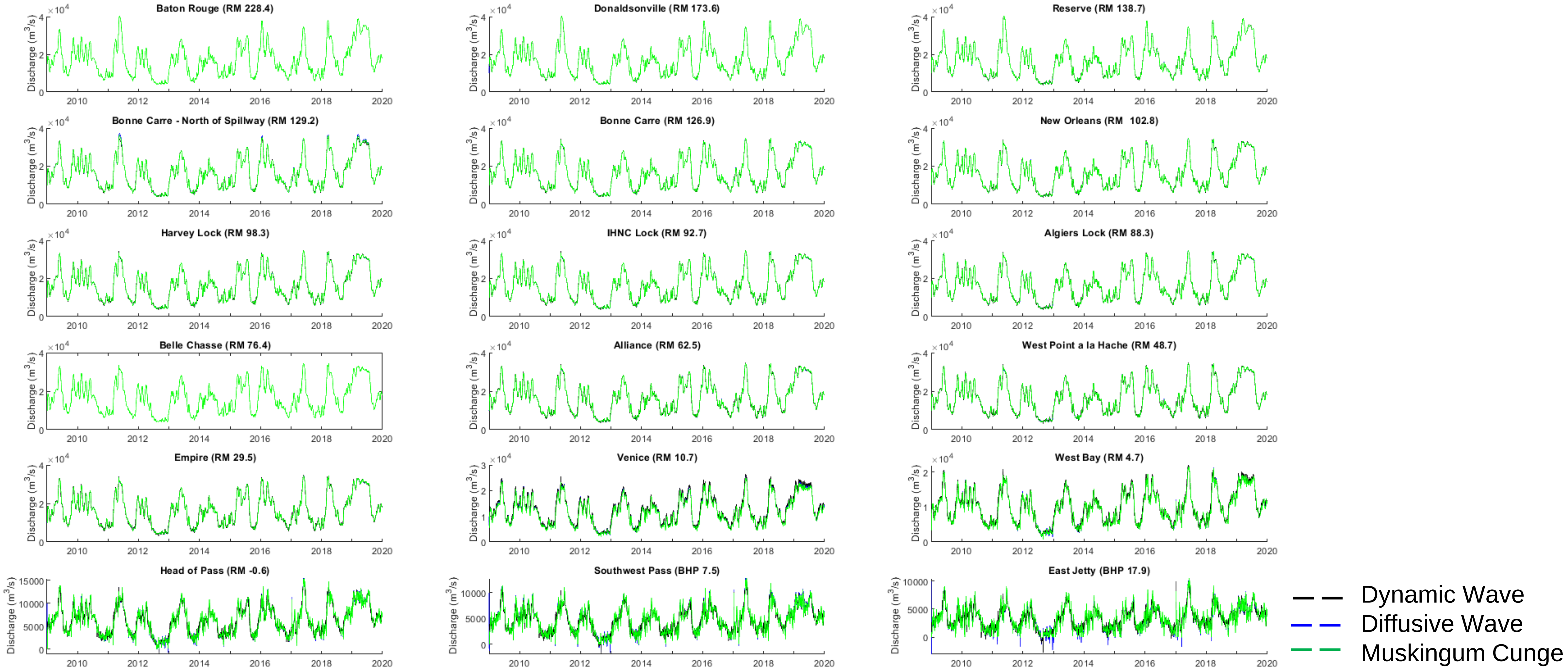
- Friction Parameters (F_c & F_I) >> 1
  - Bulk Waves
- Diffusion Coefficient (D) >1
  - Diffusive Wave



Discharge at Belle Chasse



Discharge Along the River Length



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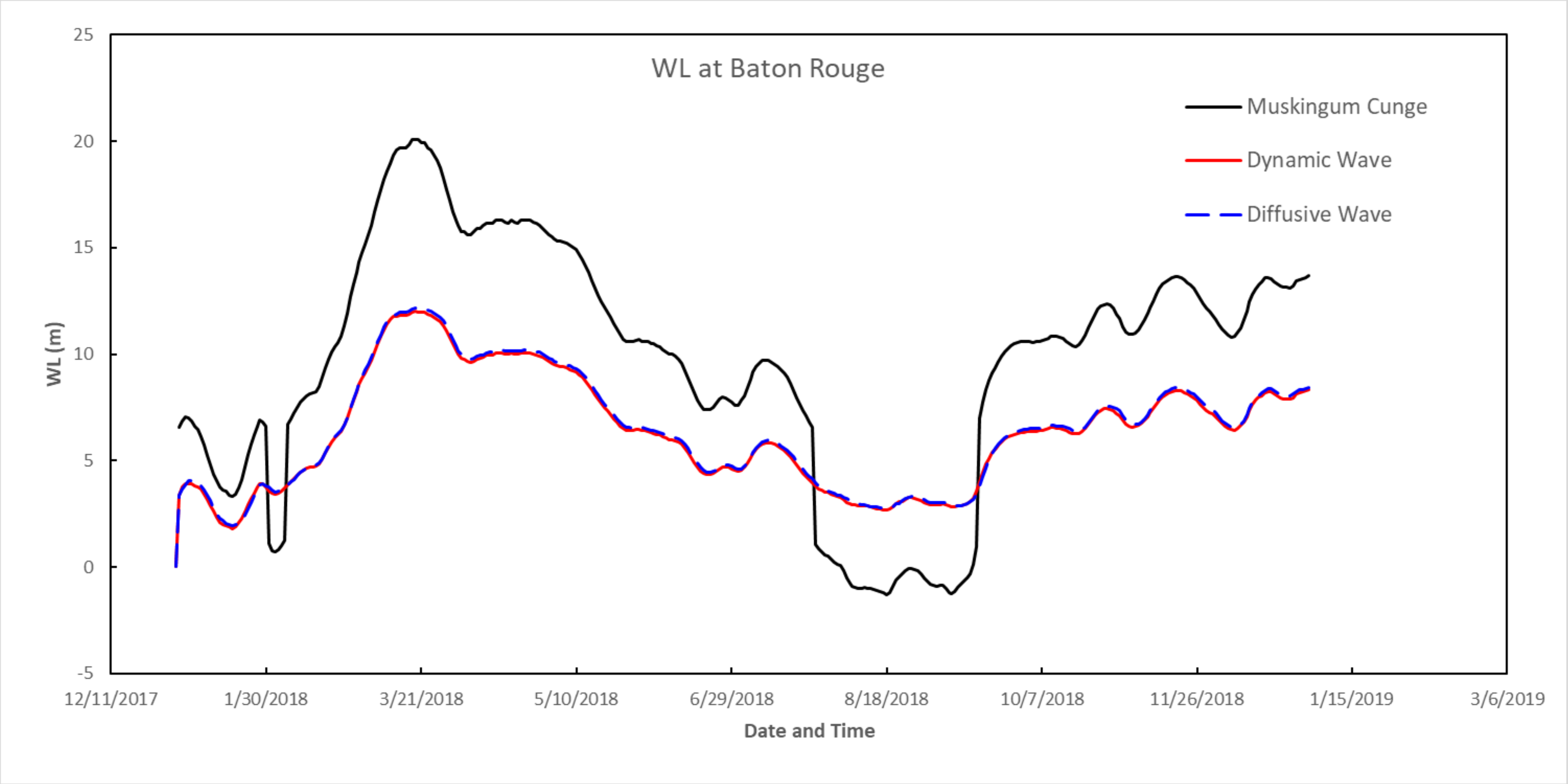
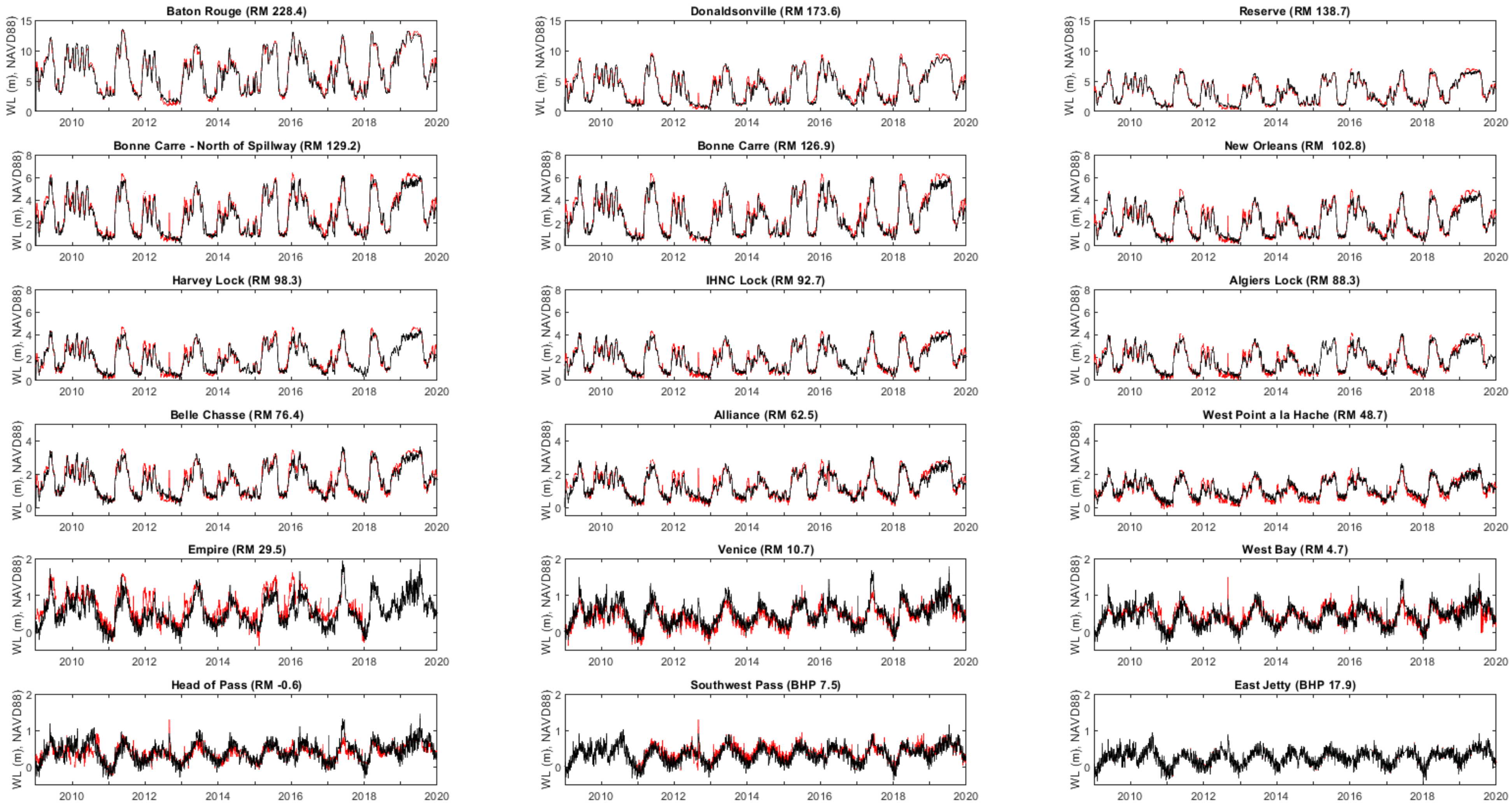
Water Level at Baton Rouge



Dynamic/Diffusive Wave: 11-Year Validation



Black: Simulated data

Red: Observed data

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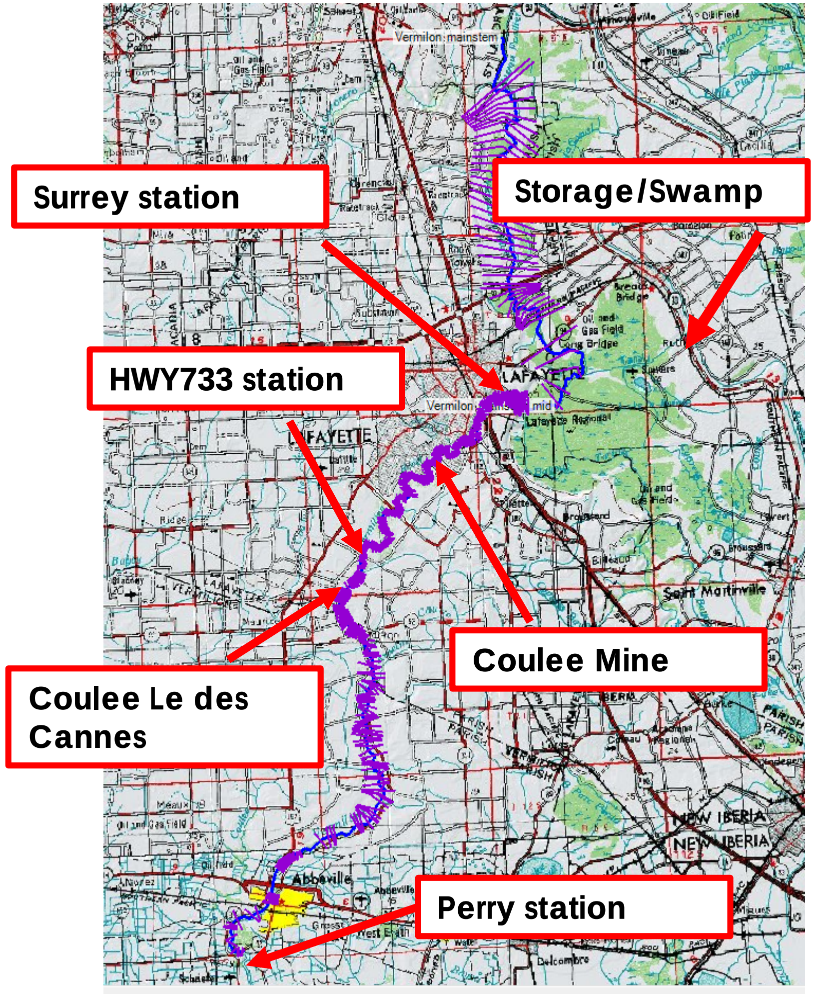
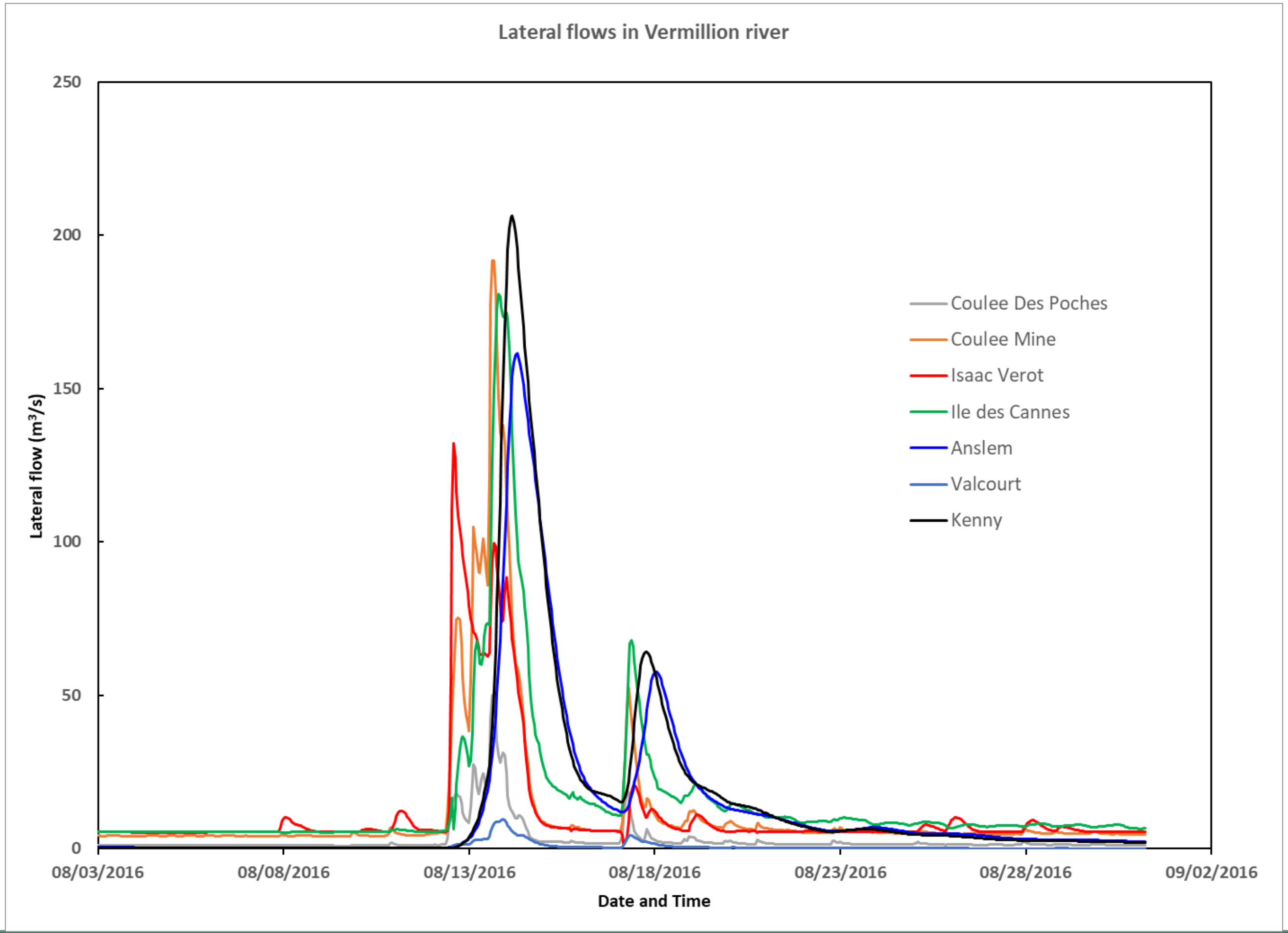
Vermilion River Experiment



- Primary stream for a HUC-8 in South Central Louisiana
- Upstream at river station 281,095
- Downstream at river station 90,452
- Data source: UL Lafayette (Dr. Habib)
- River reach length: 58.1 km
- Upstream Boundary: Q (time series)
- Downstream Boundary: WL (time series)

No of cross sections	Maximum dx (m)	Minimum dx (m)	Average dx (m)
373	457.2	42.2	156.2

Vermilion River: Tributaries and Lateral Flow



Connection Name	Distance from U/S (m)
Coulee Des Poches	14,340
Coulee Mine	16,760
Isaac Verot	28,790
Ile des Cannes	30,300
Anslem	36,350
Valcourt	53,080
Kenny	55,980

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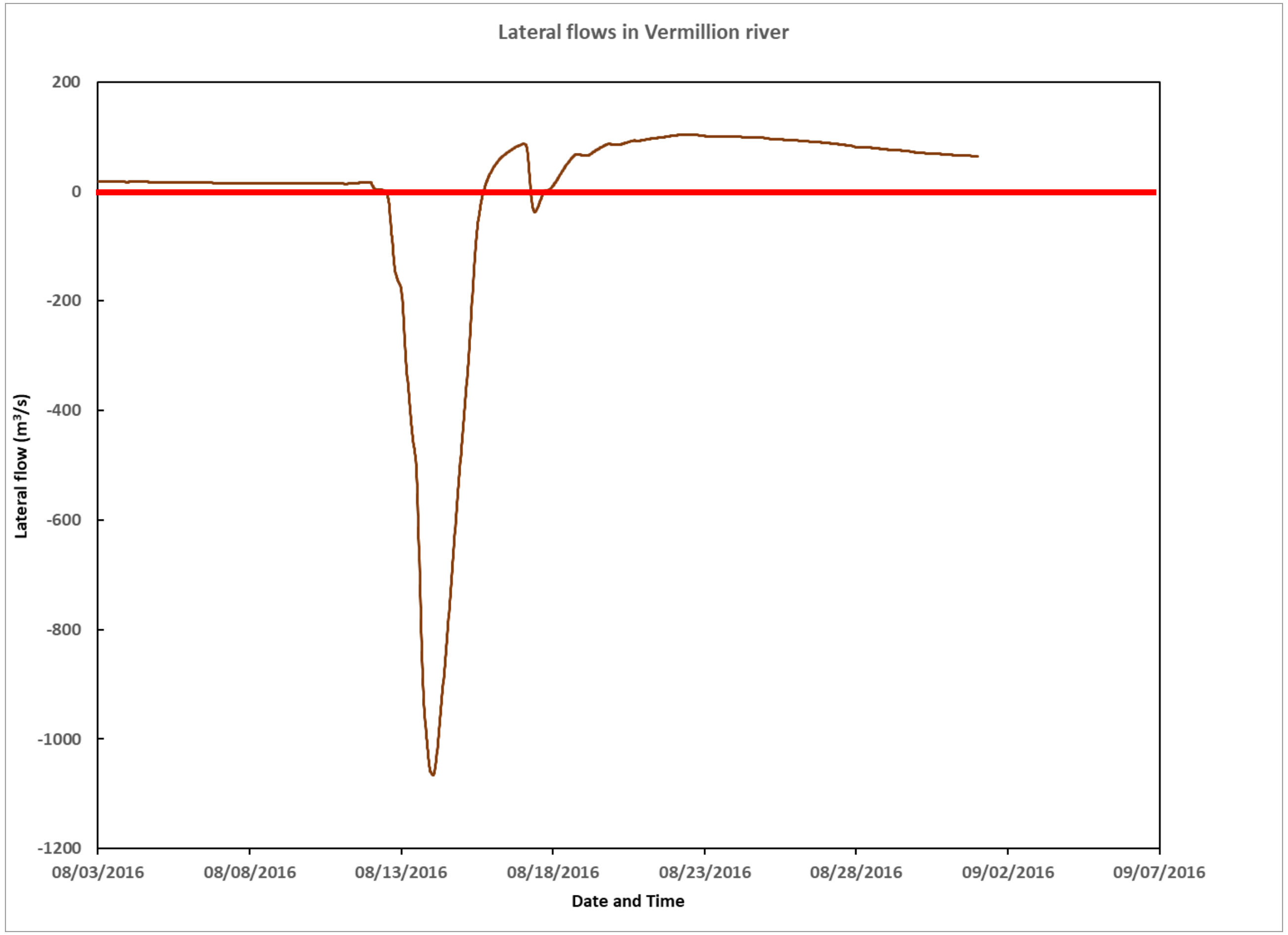
Storage Area (Swamp): Bi-directional Flow (distance: 3,436-11,154 m from U/S)

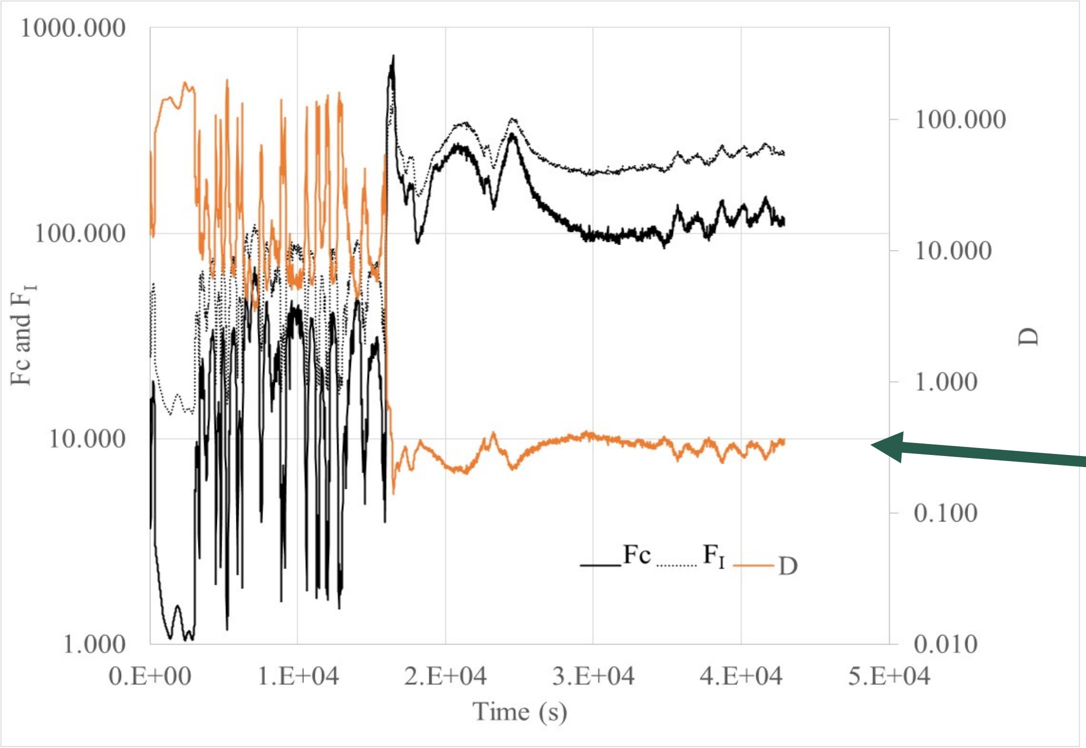


Negative Flow: Flow from River to Storage

Positive Flow: Flow from Storage to River

Channel Flow Routing: Scaling Parameters

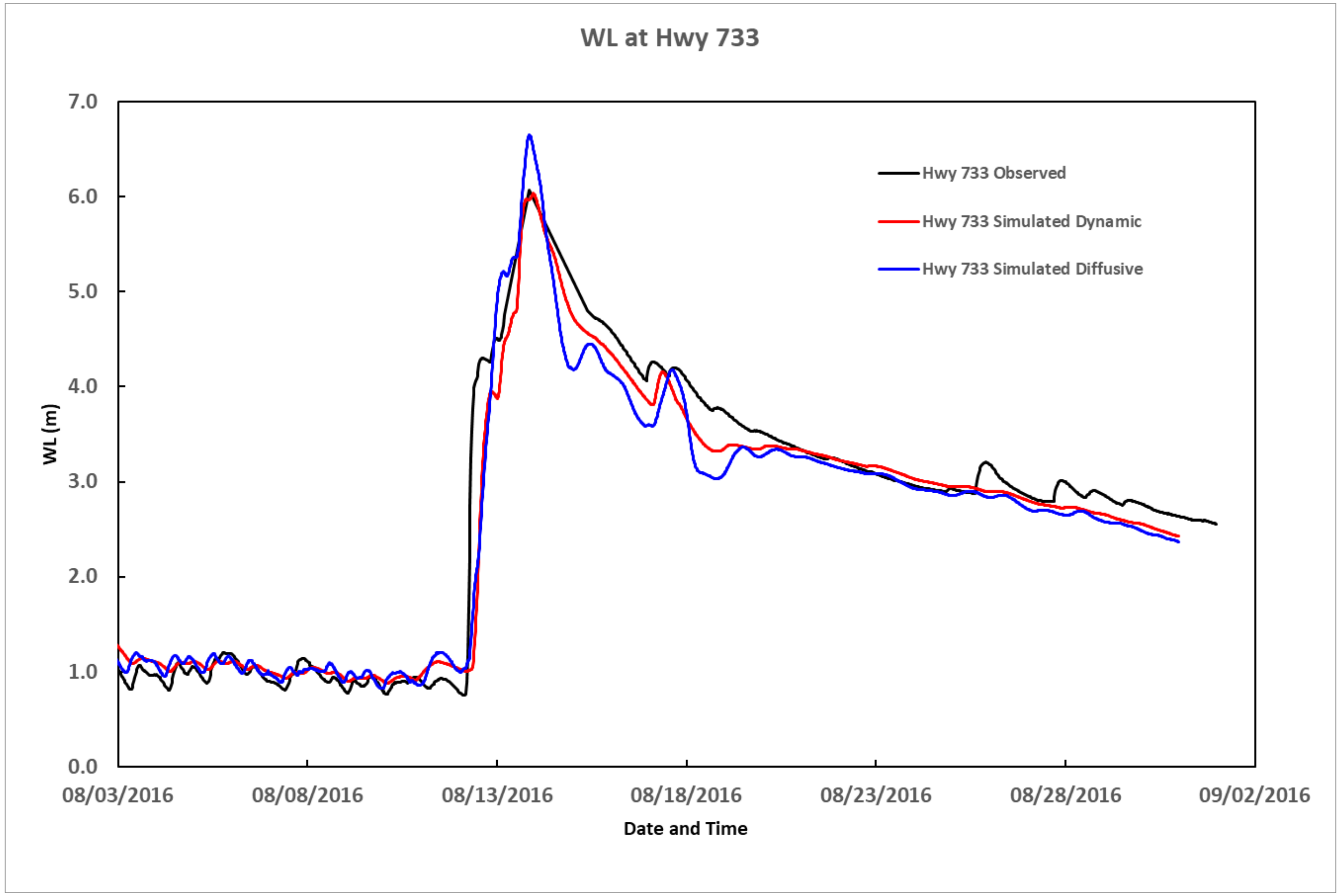
- Friction Parameters (F_c & F_l) ~ 1: Dynamic Waves
- Friction Parameters (F_c & F_l) >> 1: Bulk Waves
  - Diffusion Coefficient (D) >1: Diffusive Wave

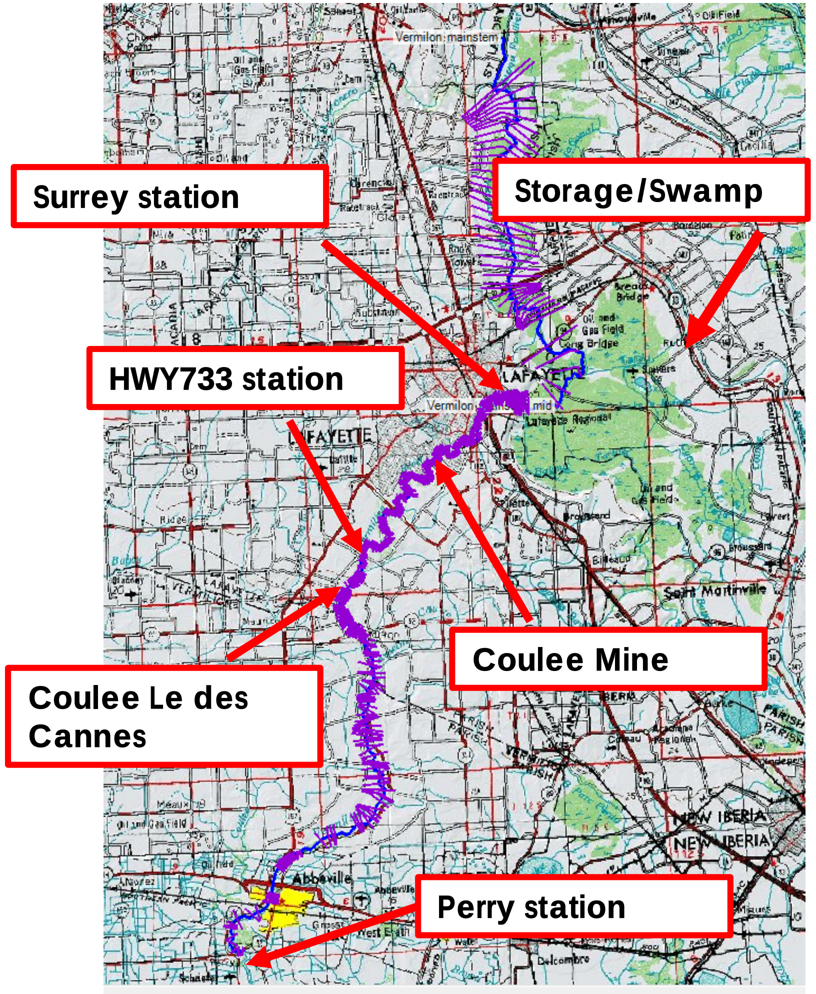


Dynamic Routing Needed

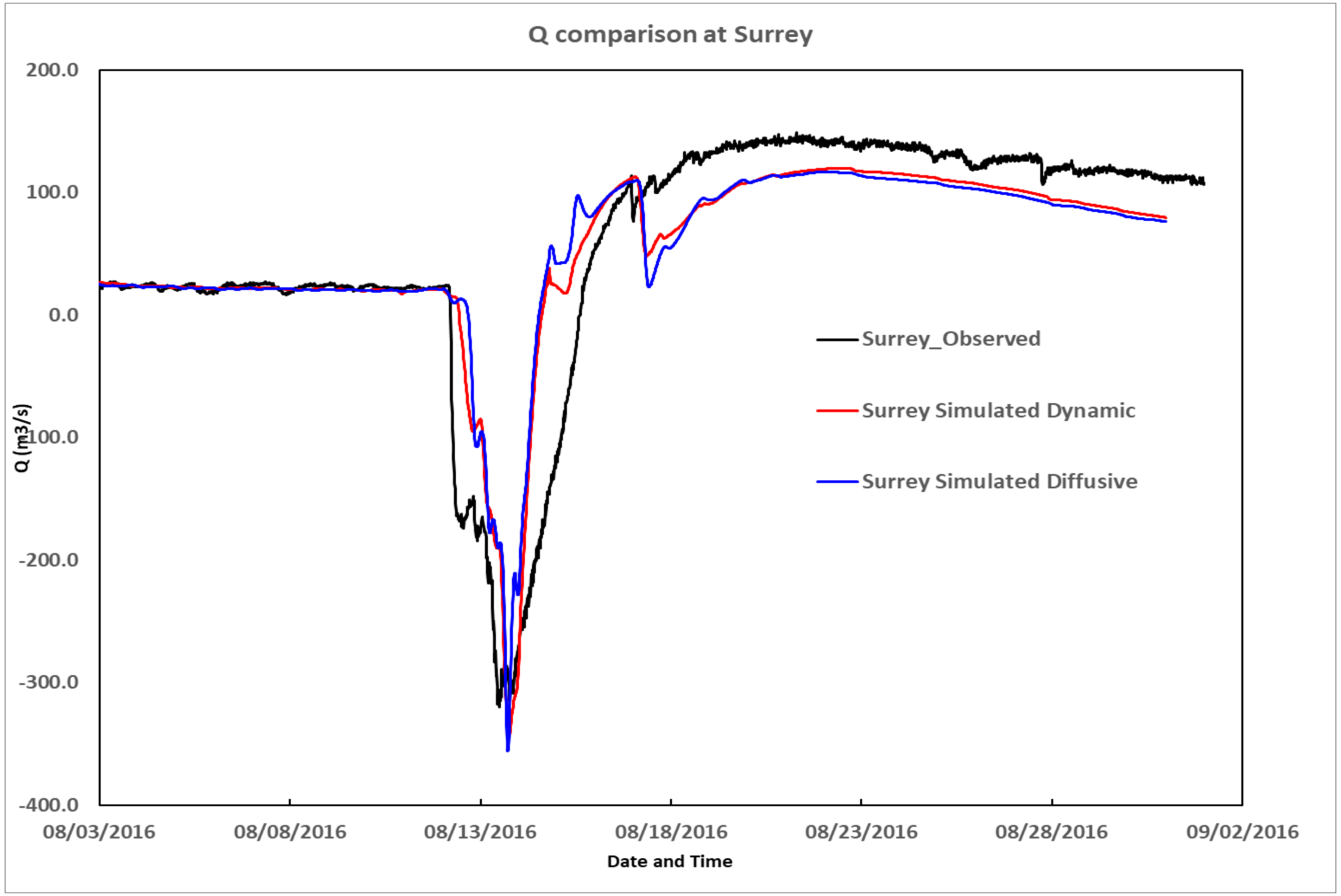
Diffusive Routing Sufficient

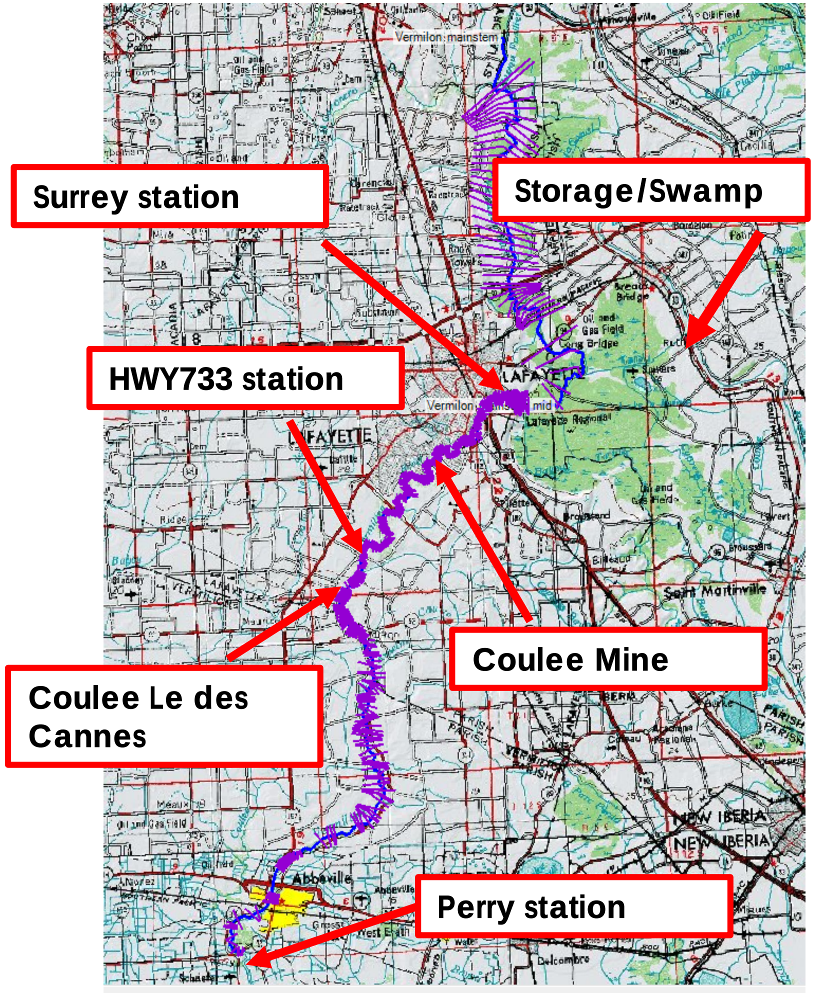
WL comparison: Observation vs Simulated





Discharge comparison: Observation vs Simulated





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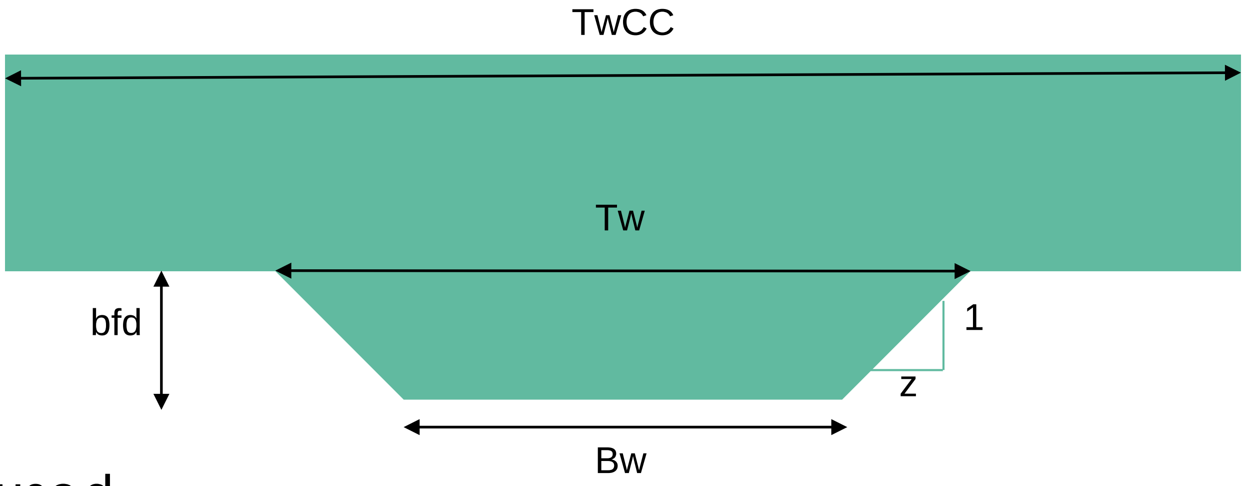
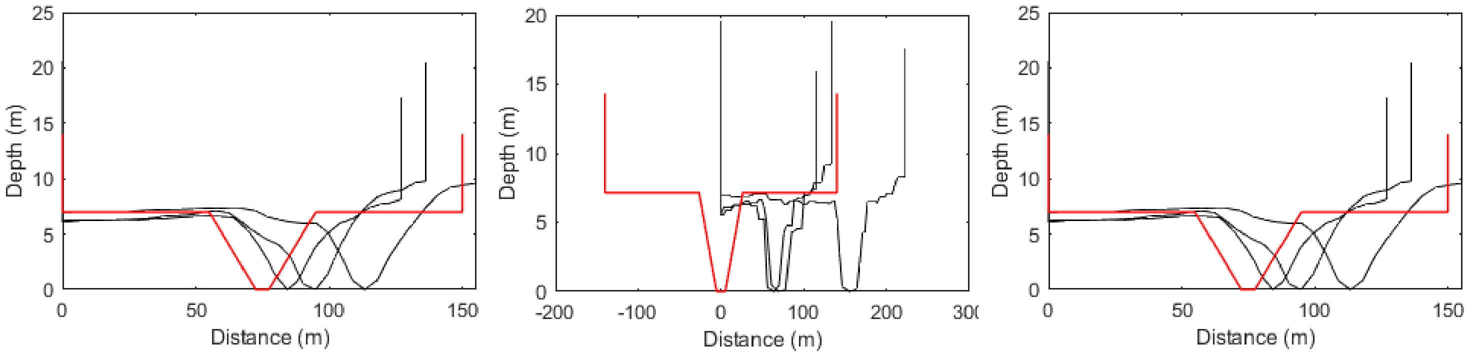
Compound Trapezoidal Section

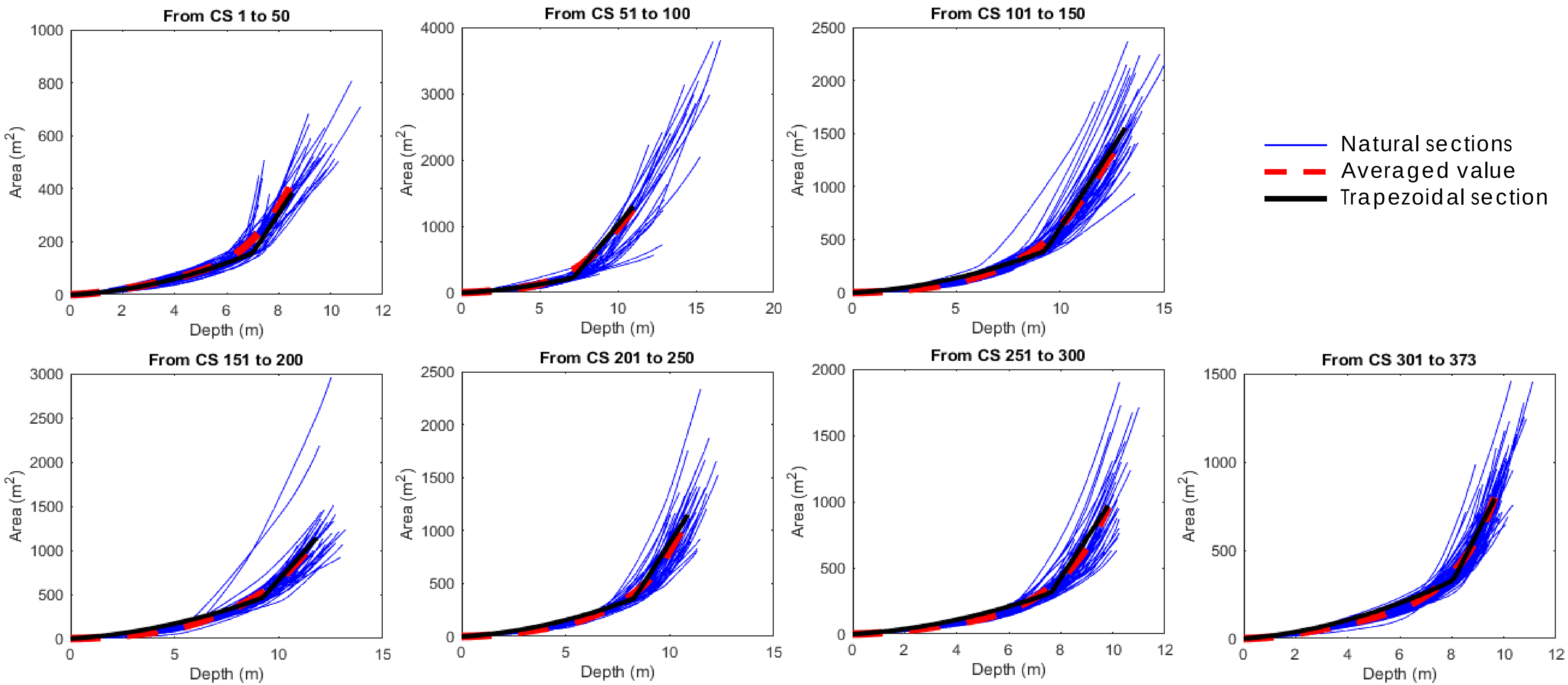
- Side slope: z
- Bottom width: Bw
- Top width at bankfull depth: Tw
- Width of floodplain: TwCC
- Bankfull depth: bfd=(Tw-Bw)/(2z)
- 7 different compound cross sections are used to approximate the geometry



z	Bw	Tw	TwCC	Sections
2.5	5	40	150	1 – 50
3	10	53	280	51 - 100
3.5	10	75	300	101 – 150
3.8	15	85	260	151 – 200
3.8	12	75	305	201 – 250
3.8	12	70	300	251 – 300
3.6	12	70	290	301 - 373



Natural vs Approximated Sections



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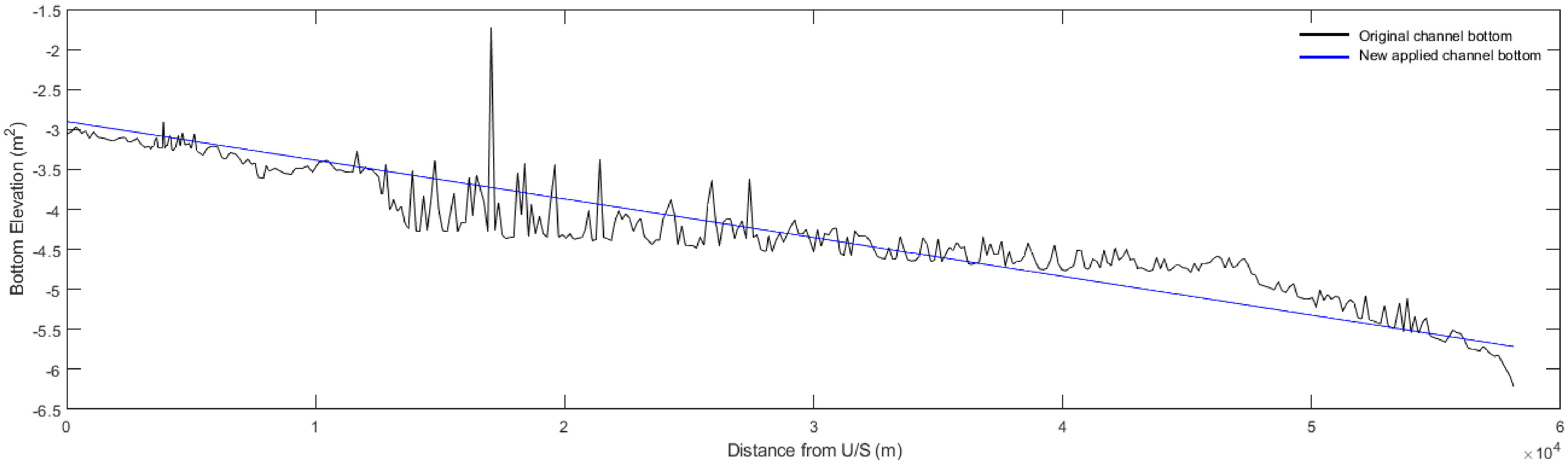
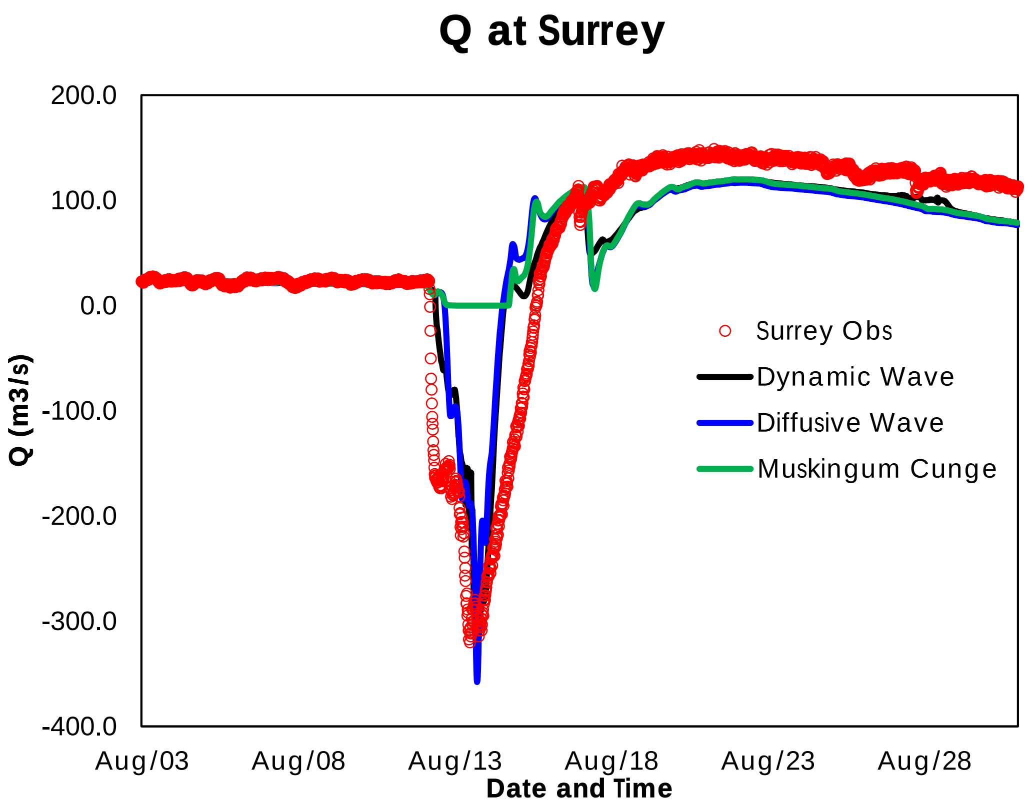
Channel Bed Slope Approximation

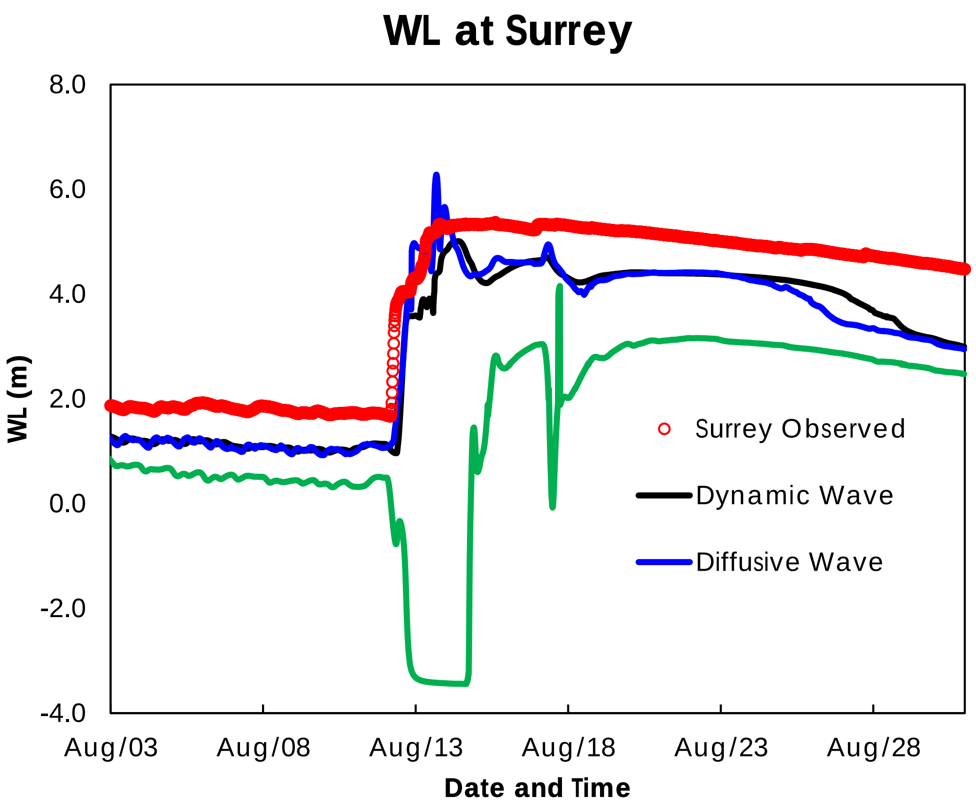
- Muskingum Cunge does not accept zero or adverse bed slope
- Bed slope approximated as shown below



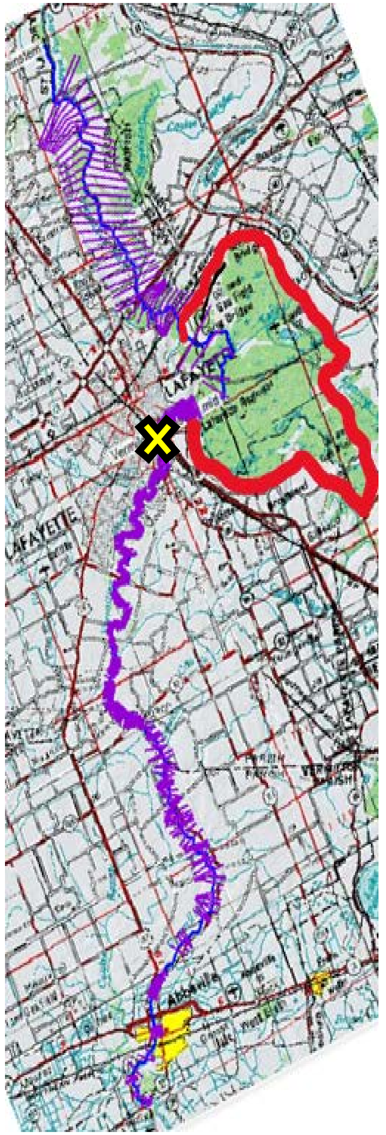
Surrey



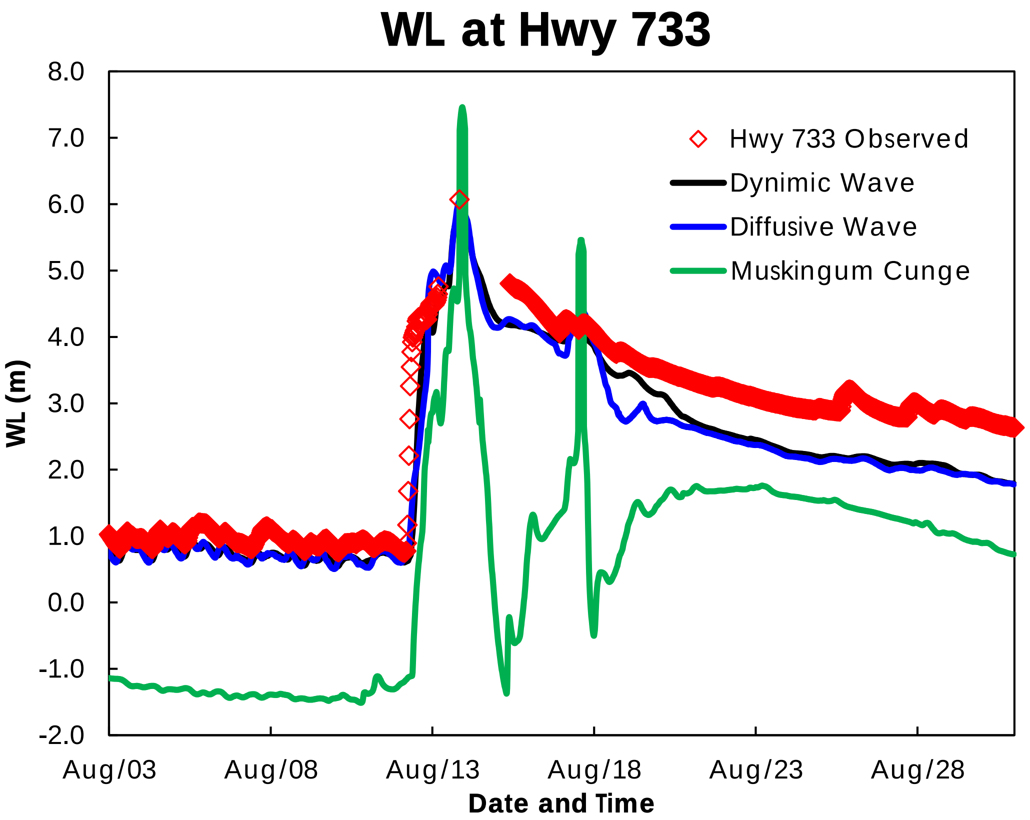
Q at Surrey
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
Q (m3/s)
Aug/03
Aug/08
Aug/13
Aug/18
Aug/23
Aug/28
Date and Time
Surrey Obs
Dynamic Wave
Diffusive Wave
Muskingum Cunge



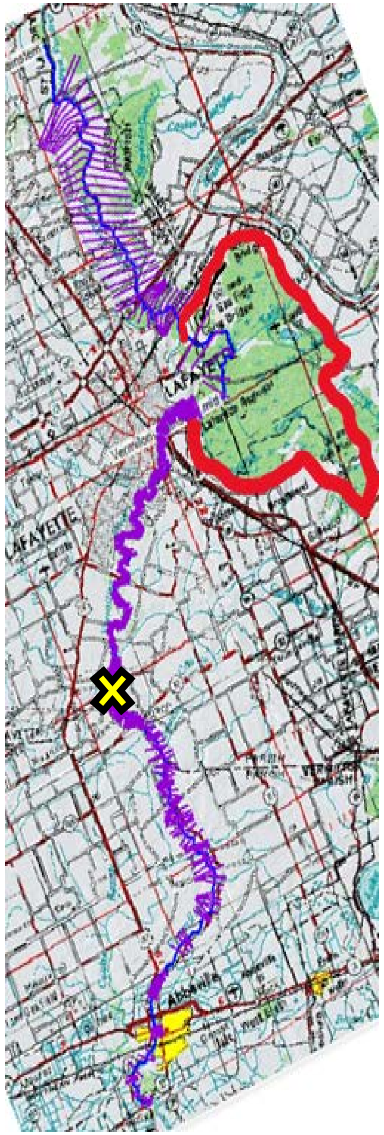
WL at Surrey
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
WL (m)
Aug/03
Aug/08
Aug/13
Aug/18
Aug/23
Aug/28
Date and Time
Surrey Observed
Dynamic Wave
Diffusive Wave



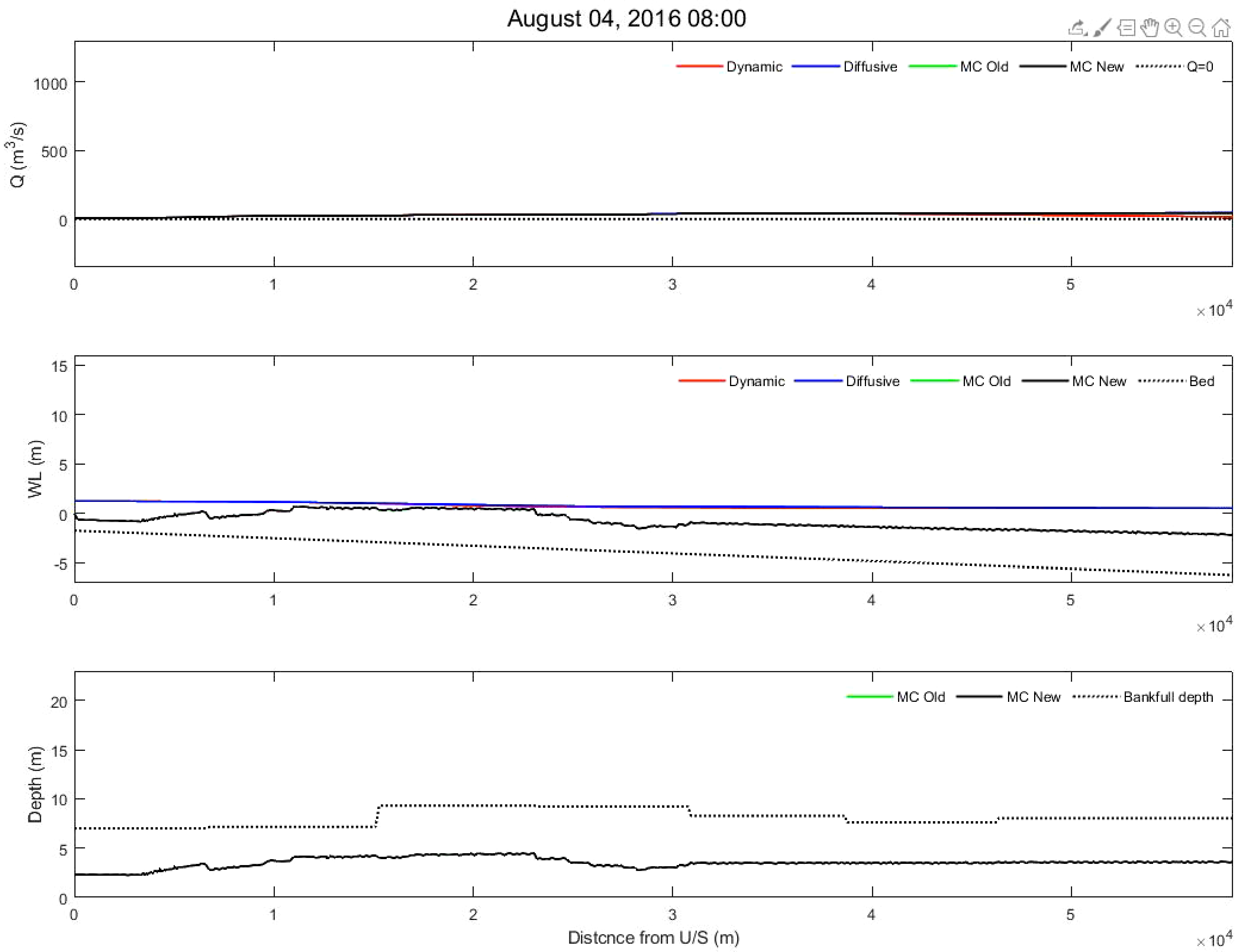
Hwy 733



WL at Hwy 733
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
WL (m)
Hwy 733 Observed
Dynimic Wave
Diffusive Wave
Muskingum Cunge
Aug/03
Aug/08
Aug/13
Aug/18
Aug/23
Aug/28
Date and Time



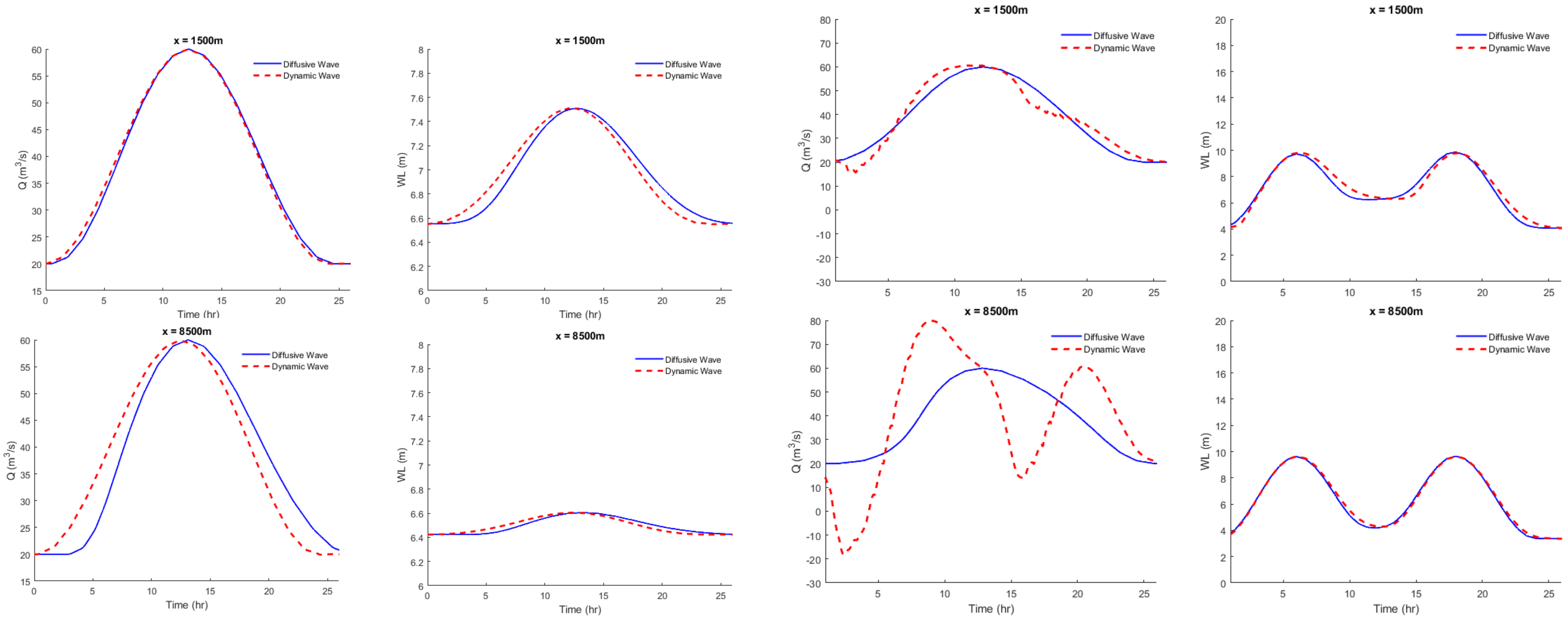
Discharge and Water Level: Animation



https://wavetulane-my.sharepoint.com/:v:/g/personal/mbeg_tulane_edu/ERzqlgcaUaJCsi40RBPNC18BbY3HA8wU2ON3o7n6rh9g6A?e=TN2oZM

Tulane

Channel Flow Routing – D/S WL Variability



Findings

- **Dynamic wave:**
  - Applicable to, but unnecessary and expensive to be used for, all hydraulic conditions
  - Should be limited to transition zone or when flow acceleration is significant
  - Code can be optimized with potential of substantial speedup
- **Diffusive wave:**
  - Applicable to a broad set of conditions: no limits on bed slope (including adverse)
  - Captures backwater effects quite well
  - Provides a stable solution even when acceleration terms are significant but with oscillations
  - Faster than Muskingum-Cunge despite being more rigorous
- **Muskingum-Cunge:**
  - Compound cross section is limiting but can be improved (this will help stability and speed)
  - Slope limitations are problematic
  - Inability to capture downstream effects are also problematic

Thank you.

Questions?

References:

Ferrick, M.G. 1985. “Analysis of River Wave Types.” *Water Resources Research.* 21 (2): 209–20.

Meselhe, E.A., et al., 2020. “Continental scale heterogeneous channel flow routing strategy for operational forecasting models.” *J. American Water Resources Assoc.* 1-13. https://doi.org/10.1111/1752-1688.12847

Wilkerson, G.V., et al., 2014. “Continental-scale relationship between bankfull width and drainage area for single-thread alluvial channels.” *Water Resources Research.* 50: 919-936. https://doi.org/10.1002/2013WR013916

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