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# Flood Routing for Continuous Simulation Models

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# Contents

# Motivation

- Continuous simulation models like APEX and SWAT operate on a daily time step and offer options for simulating some processes on shorter time steps.
- However, they are not adequate for applications like designing flood control structures or estimating flood damages.
- Computationally efficient and robust flood routing methods can provide flood analysis capabilities as well as other potential advantages like more accurate sediment and pollutant transport

# Project Goals

- ❑ Develop reliable routing methods in HYMO model
  - ❑ Muskingum-Cunge (M-C)
  - ❑ Variable Storage Coefficient (VSC)
  - ❑ Storage with Variable Slope (SVS)
- ❑ Test these methods for accuracy, efficiency and reliability on various hydraulic conditions
  - ❑ Various channel lengths and slopes
  - ❑ Channel flow, channel flow + floodplain flow
  - ❑ Rectangular and trapezoidal cross sections
- ❑ Compare results with the Dynamic Wave Flow routing method (HEC-RAS) as a test of accuracy

# Saint-Venant Equations

## ❑ Continuity

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

## ❑ Momentum equation

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t} - \frac{v}{g}\frac{\partial v}{\partial x}$$

- Kinematic wave
- Diffusion wave
- Dynamic wave

# Muskingum-Cunge (M-C) Method

- A diffusion wave model

$$\frac{I_1 + I_2}{2} \cdot \Delta t - \frac{O_1 + O_2}{2} \cdot \Delta t = S_2 - S_1 \qquad S = K\{X \cdot I + (1 - X) \cdot O\}$$

- K and X determined from hydraulic properties of the reach
- K is a timing parameter, seconds
- X is a diffusion parameter, no dimensions

$$X = f(peak\ inflow,\ bottom\ width,\ slope,\ wave celerity,\ \Delta x)$$

- Based on NRCS WIN TR-20 Program

# Variable Storage Coefficient (VSC) Method

- A diffusion wave model

$$\frac{I_1 + I_2}{2} \cdot \Delta t - \frac{O_1 + O_2}{2} \cdot \Delta t = S_2 - S_1 \qquad T = S / O$$

- Storage routing is calculated using a dimensionless storage coefficient (SC)
- Every time step, SC is updated iteratively

$$SC = f(wetted\ area,\ channel\ length,\ water\ surface\ slope,\ normal\ velocity)$$

- Based on Williams (1969)

# Storage with Variable Slope (SVS) Method

- A variation of the VSC method in which the continuity equation is directly solved with no coefficients

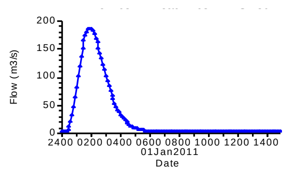
$$O_t = I_1 - O_1 + 2 \cdot \sum_{j=2}^{t-1} \left( I_j - O_j \right) - 2 \cdot \frac{S_t - S_1}{\Delta t}$$

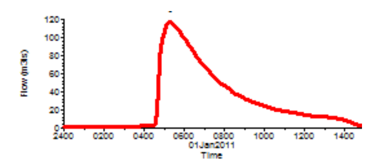
- The storage term is equal to the average water volume in the channel

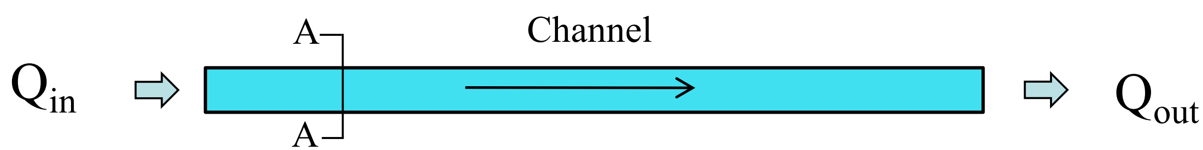
$$S_t = RCHL \cdot \frac{AI_t + AO_t}{2}$$

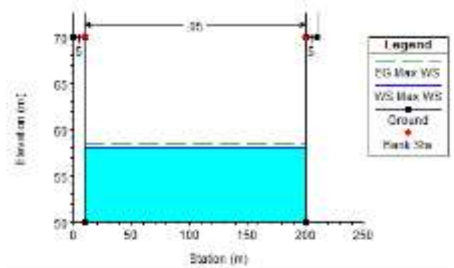
- An iterative solution is used to solve these equations considering variable water surface slope

# Test Configuration

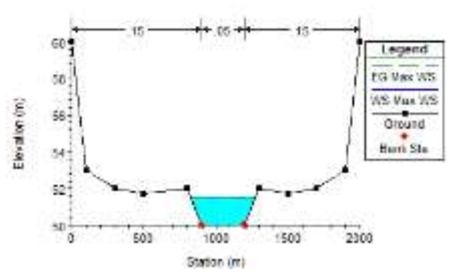


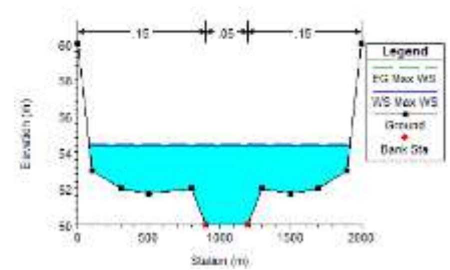




Rectangular (T1, T3)




Trapezoidal (T2)
Channel flow




Trapezoidal (T4,T5,T6)
Floodplain flow

(A-A)

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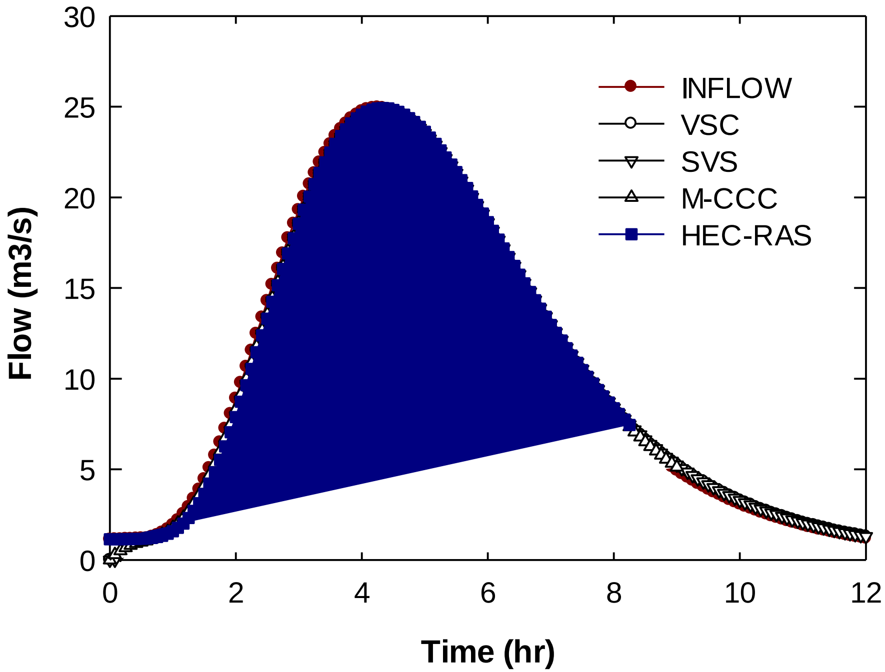
# Hydraulic Properties of Test Cases

| | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 |
|---|---|---|---|---|---|---|
| ***Channel*** | | | | | | |
| Length (km) | 0.335 | 5.785 | 1.830 | 13.635 | 50.000 | 50.000 |
| Top Width (m) | 12.2 | 12.6 | 12.2 | 9.7 | 30.0 | 30.0 |
| Bottom Width (m) | 12.2 | 6.6 | 12.2 | 7.6 | 18.0 | 18.0 |
| Depth (m) | 2.8 | 1.6 | 3.1 | 1.0 | 3.0 | 3.0 |
| Slope (m/ m) | 0.0006 | 0.001 | 0.002 | 0.001 | 0.001 | 0.0001 |
| Manning's n | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 |
| ***Floodplain*** | | | | | | |
| Width (m) | 0.0 | 0.0 | 0.0 | 92.7 | 1900.0 | 1900.0 |
| Depth (m) | 0.0 | 0.0 | 0.0 | 1.0 | 6.0 | 6.0 |
| Manning's n | 0.0 | 0.0 | 0.0 | 0.049 | 0.15 | 0.15 |
| ***Routing*** | | | | | | |
| Reaches | 1 | 4 | 2 | 10 | 50 | 50 |
| Time interval (h) | 0.083 | 0.167 | 0.1 | 0.1 | 0.5 | 0.5 |

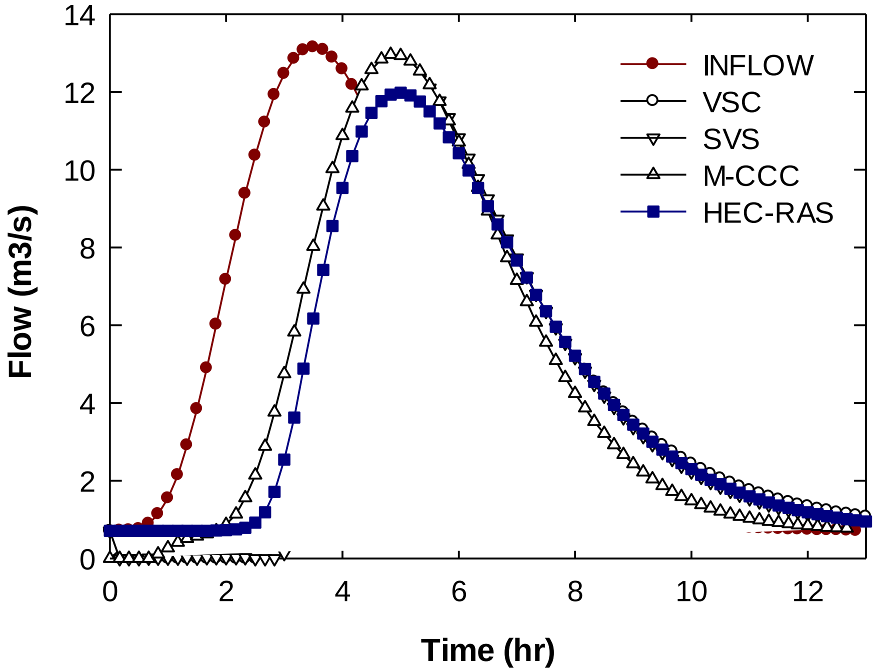
# Routing Result: Test 1




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 24.8 | 4.25 | 0.3 |
| SVS | 24.8 | 4.33 | 0.3 |
| M-C | 24.8 | 4.32 | 0.2 |
| HEC | 24.9 | 4.33 | n/a |

(L=0.335km, S=0.0006, Rectangular shape, Channel flow)

# Routing Result: Test 2




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 11.0 | 5.0 | 4.5 |
| SVS | 12.4 | 5.2 | 3.3 |
| M-C | 13.0 | 4.9 | 5.2 |
| HEC | 12.0 | 5.0 | n/a |

(L=5.8km, S=0.001, Trapezoidal shape, Channel flow)

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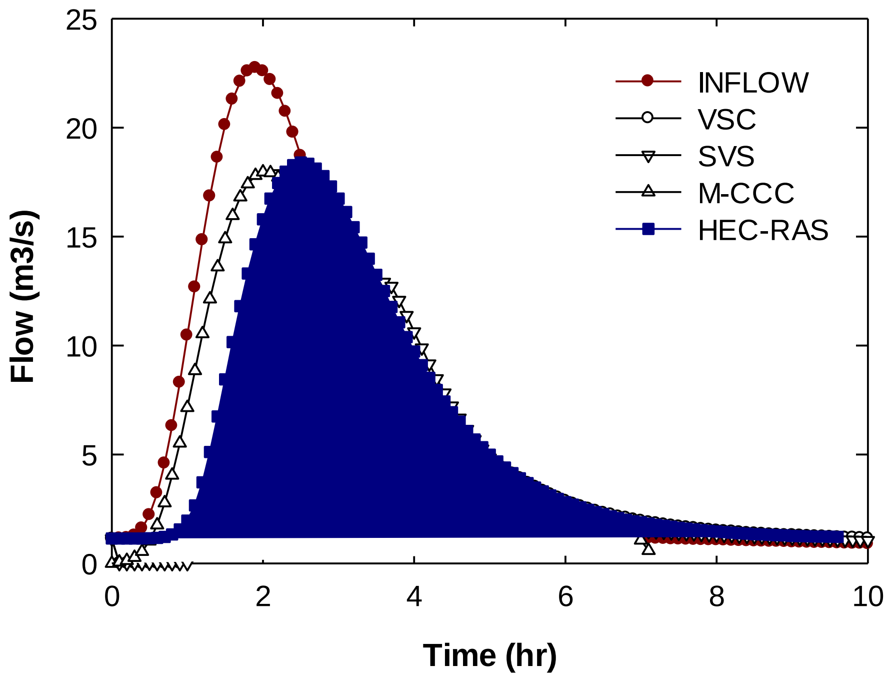
# Routing Result: Test 3




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 17.8 | 2.16 | 8.5 |
| SVS | 17.9 | 2.23 | 6.7 |
| M-C | 18.0 | 2.03 | 10.6 |
| HEC | 18.4 | 2.50 | n/a |

(L=1.83km, S=0.002, Rectangular shape, Channel flow)

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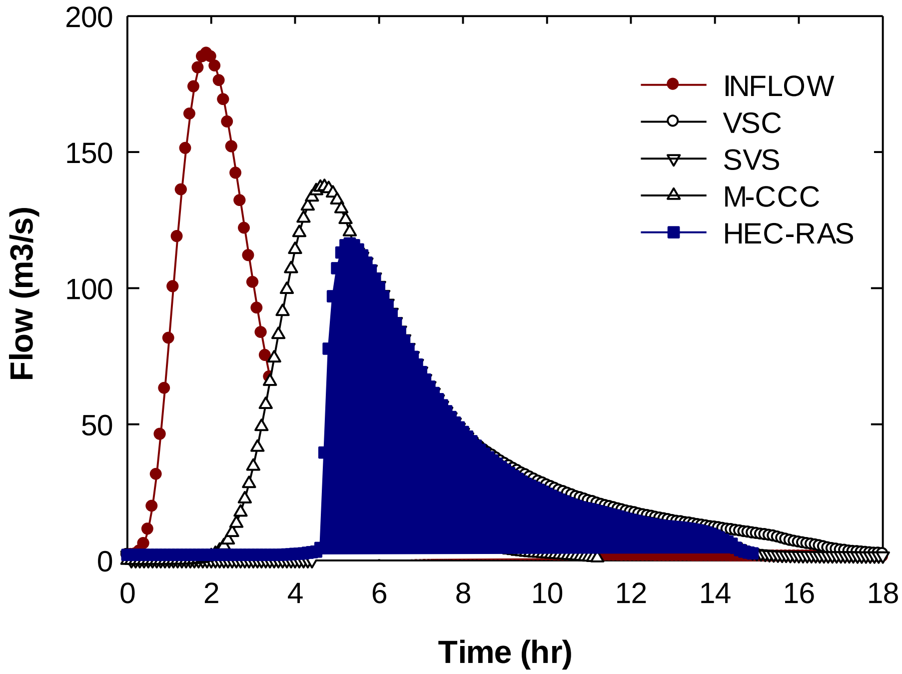
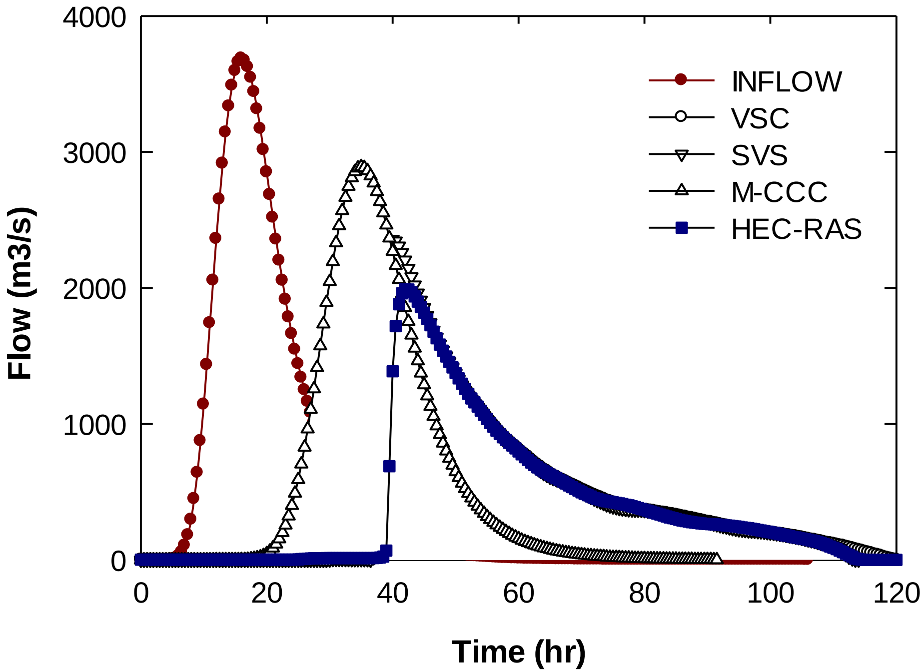
# Routing Result: Test 4




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 70 | 5.8 | 24.7 |
| SVS | 114 | 5.4 | 1.9 |
| M-C | 137 | 4.7 | 14.9 |
| HEC | 116 | 5.3 | n/a |

(L=13.6km, S=0.001, Trapezoidal shape, Floodplain flow)

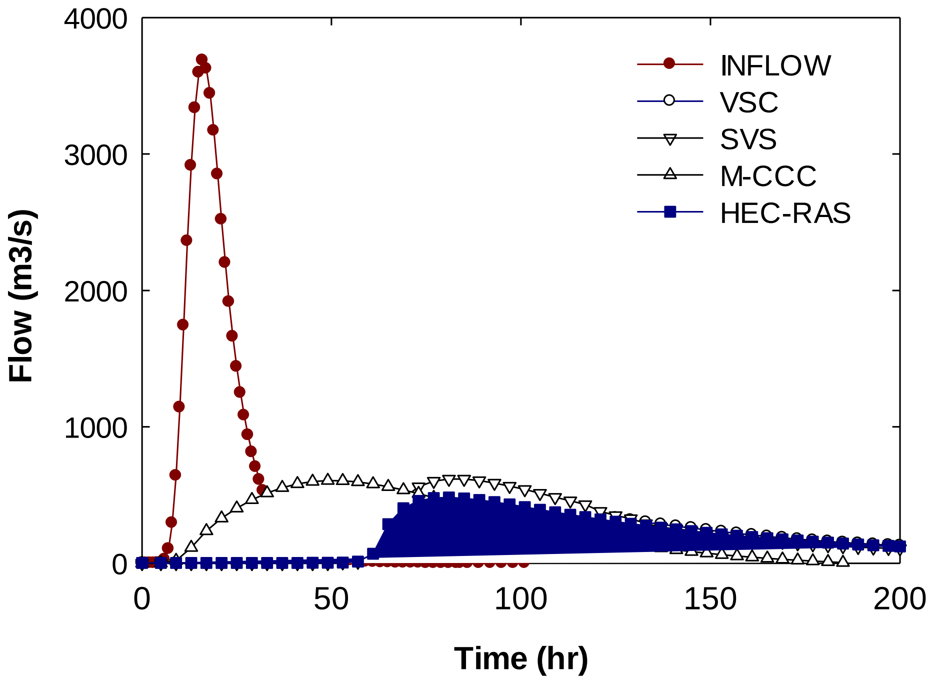
# Routing Result: Test 5




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 1,943 | 41.7 | 1.6 |
| SVS | 2,359 | 40.0 | 11.7 |
| M-C | 2,891 | 35.0 | 30.9 |
| HEC | 1,990 | 42.0 | n/a |

(L=50km, S=0.001, Trapezoidal shape, Floodplain flow)

# Routing Result: Test 6




| | $Q_p$ (m3/s) | $t_p$ (hr) | Error (%) |
|---|---|---|---|
| VSC | 454 | 81.7 | 3.8 |
| SVS | 619 | 82.5 | 15.6 |
| M-C | 606 | 50.4 | 31.5 |
| HEC | 482 | 80.3 | n/a |

(L=50km, S=0.0001, Trapezoidal shape, Floodplain flow)

# Routing Result: Summary

| | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Rank |
|---|---|---|---|---|---|---|---|
| VSC | 0.3 | 4.5 | 8.5 | 24.7 | **1.6** | **3.8** | 2 |
| SVS | 0.3 | **3.3** | **6.7** | **1.9** | 11.7 | 15.6 | 1 |
| M-C | **0.2** | 5.2 | 10.6 | 14.9 | 30.9 | 31.5 | 3 |

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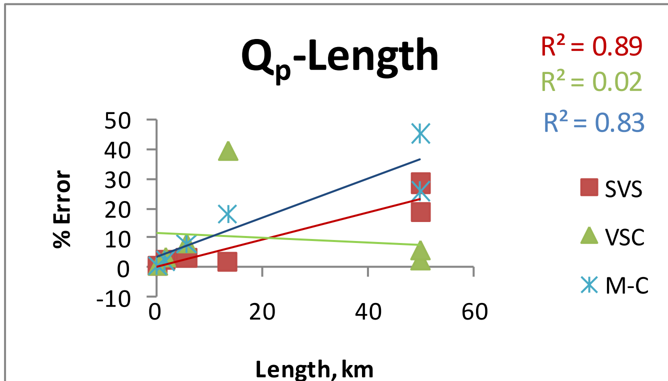
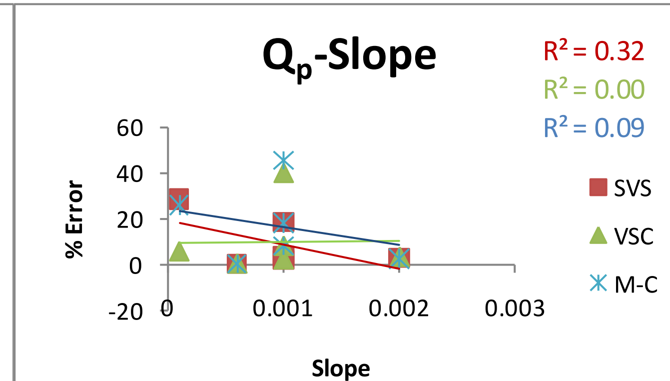
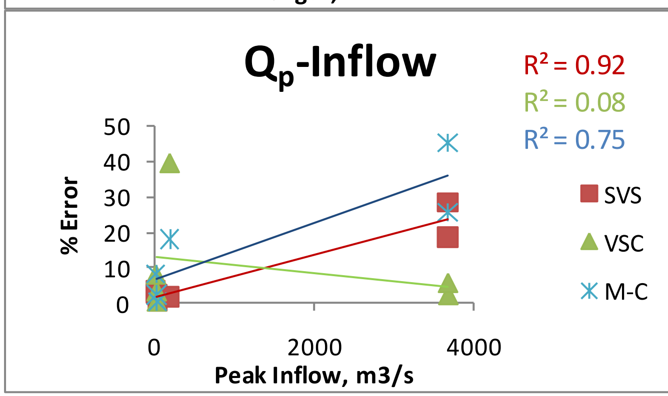
# Correlation Analysis




**SVS** shows typical responses of kinematic wave models (e.g. error increases as slope decreases or with larger inflow-meaning higher surface slope)

**M-C** shows similar trends to **SVS** ?

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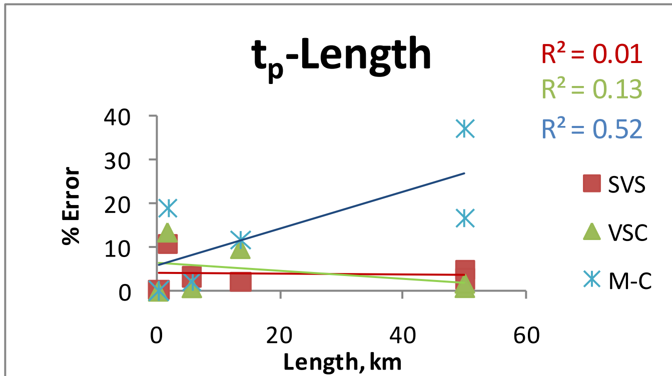
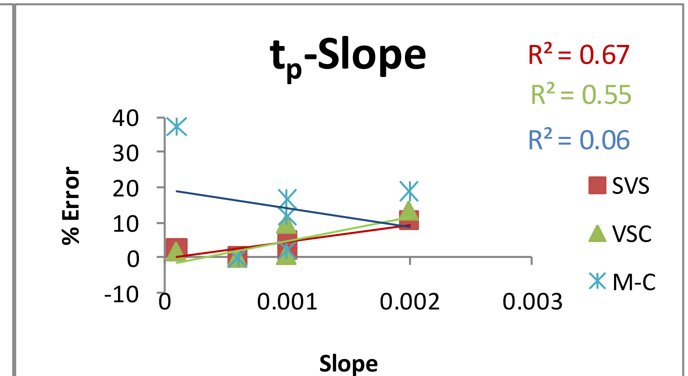
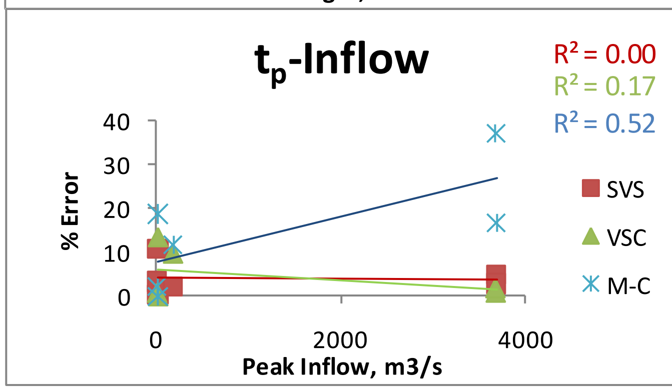
# Correlation Analysis




**SVS** and **VSC** show similar patterns while **M-C** behaves differently

**SVS** and **VSC** use the same algorithm for calculating flow velocity and travel time

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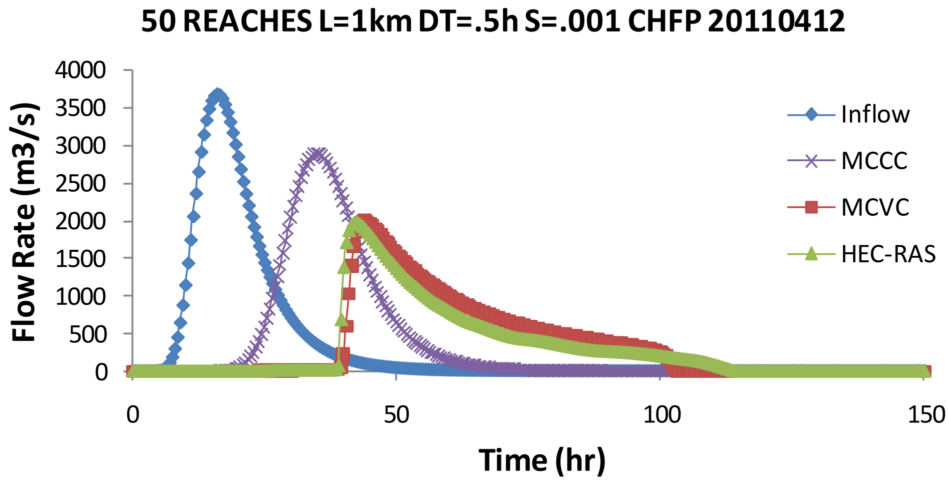
# Conclusion

- All methods (M-C, VSC, and SVS) were computationally stable and maintained mass balance in all of the tests
- No prevailing advantage was found for the diffusion models over kinematic wave model
- The VSC method performed superior on combined flow (channel flow + floodplain flow) in long channels
- The SVS method was reliable in routing short channels, but showed marginal error on long channels
- The M-C method showed limited performance. The errors were significant in tests with floodplain flow on long channels
- The peak flows of M-C and SVS showed similar patterns in responding to hydraulic properties.
- The time to peak of VSC and SVS showed similar patterns to hydraulic properties. Both use the same equations to compute flow velocity

# Future work

- The routing methods will be integrated into APEX and SWAT for continuous simulation
- The routing methods within APEX/SWAT will be tested on complex channel networks at the watershed scale
- A preliminary study of the Muskingum-Cunge with Variable Coefficient method shows promising results, so it will be included in the future study




(Test 5)

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# Questions?