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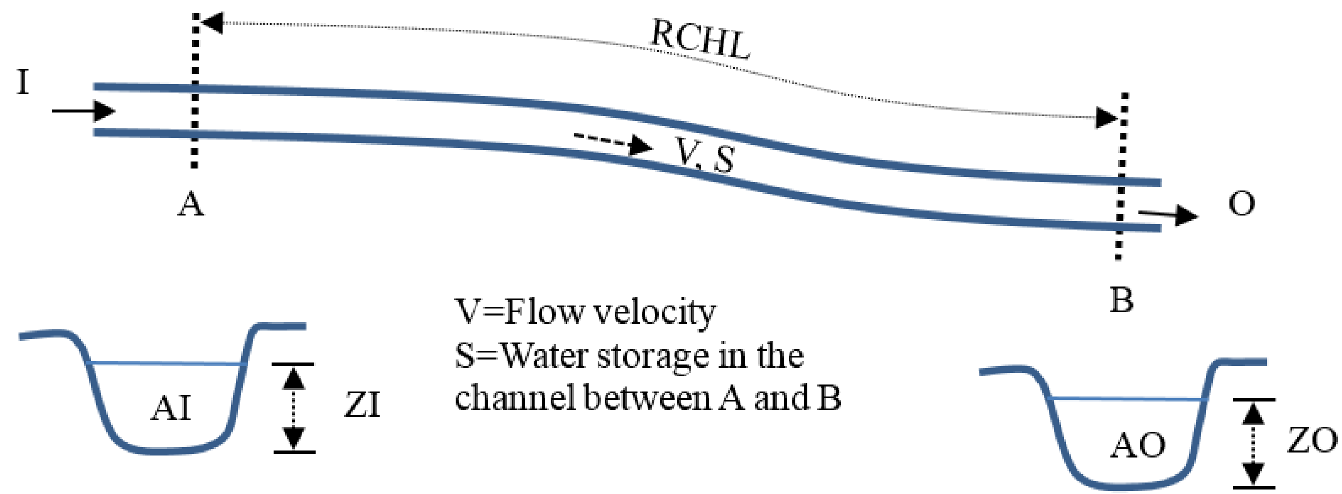
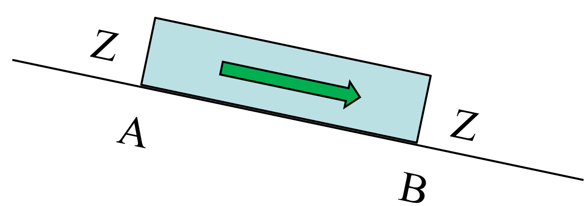
Improving Life through Science and Technology

Enhanced Streamflow Routing Methods for Watershed Models

J. Jeong, J. R. Williams, W. H. Merkel, J. G. Arnold, X. Wang, C. G. Rossi

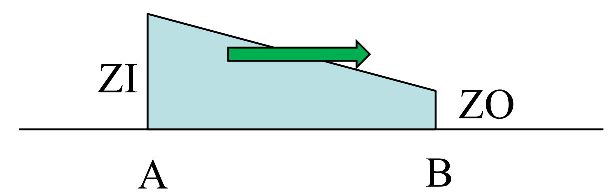
Motivation





Gravity flow

+



Diffusion flow

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Tasks

- ❑ Develop reliable routing methods in APEX model
  - ❑ Muskingum-Cunge (M-C)
  - ❑ Variable Storage Coefficient (VSC)
  - ❑ Storage with Variable Slope (SVS)
- ❑ Test these methods on various hydraulic conditions
  - ❑ Various channel lengths and slopes
  - ❑ Channel flow, channel flow + floodplain flow
  - ❑ Rectangular and trapezoidal cross sections
- ❑ Evaluate APEX flow routing in a case study
  - ❑ Riesel Y2 watershed

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Muskingum-Cunge (M-C) Method

- Definition

$$\frac{I_1 + I_2}{2} \cdot \Delta t - \frac{O_1 + O_2}{2} \cdot \Delta t = S_2 - S_1$$

$$S = K\{X \cdot I + (1 - X) \cdot O\}$$

- K is a timing parameter, seconds
- X is a non-dimensional diffusion coefficient

$$X = f(QI_{peak}, W_{bed}, S, c, \Delta x)$$

- Based on NRCS's TR-20 Program

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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

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

- Based on Williams (1969)

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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

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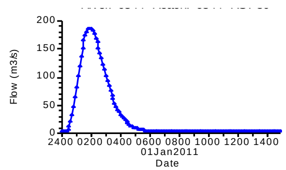
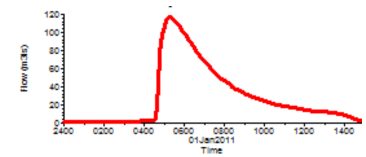
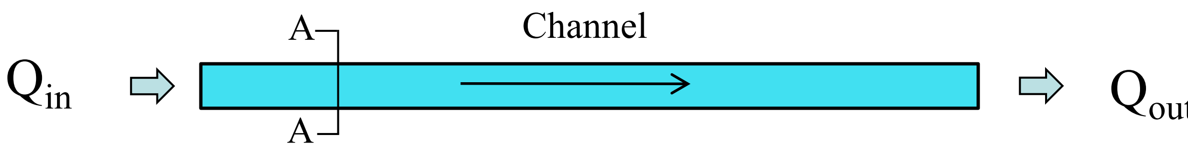
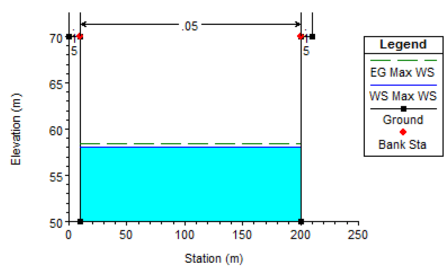
Test Configuration

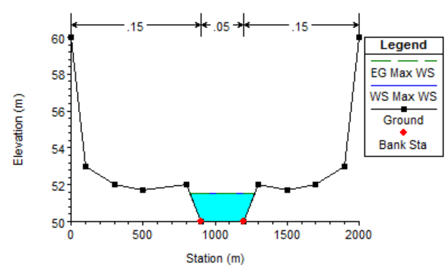




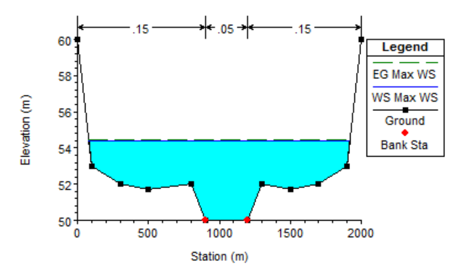




Rectangular (T1, T3)



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

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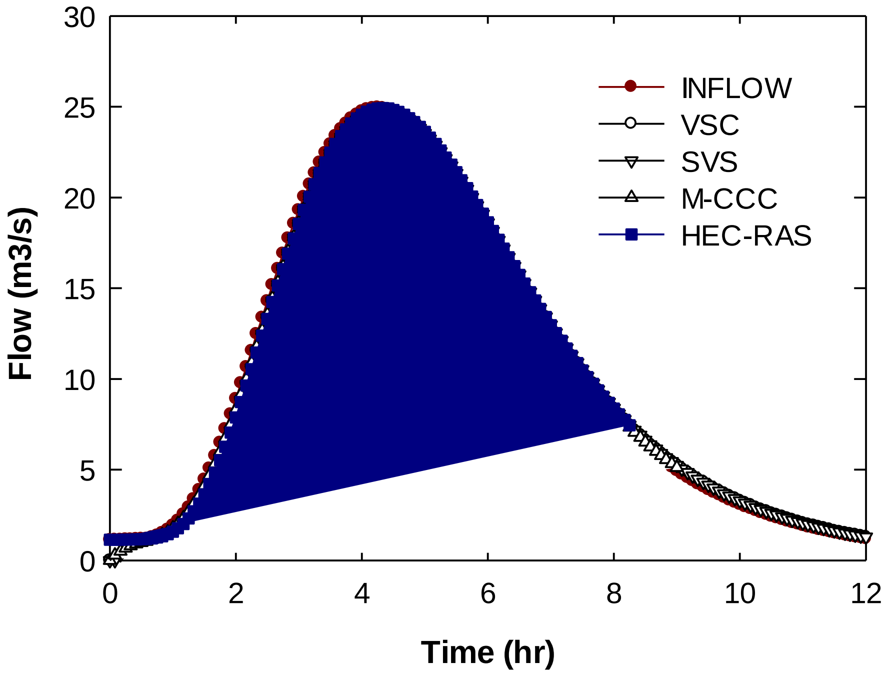
Routing Result: Test 1



	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)

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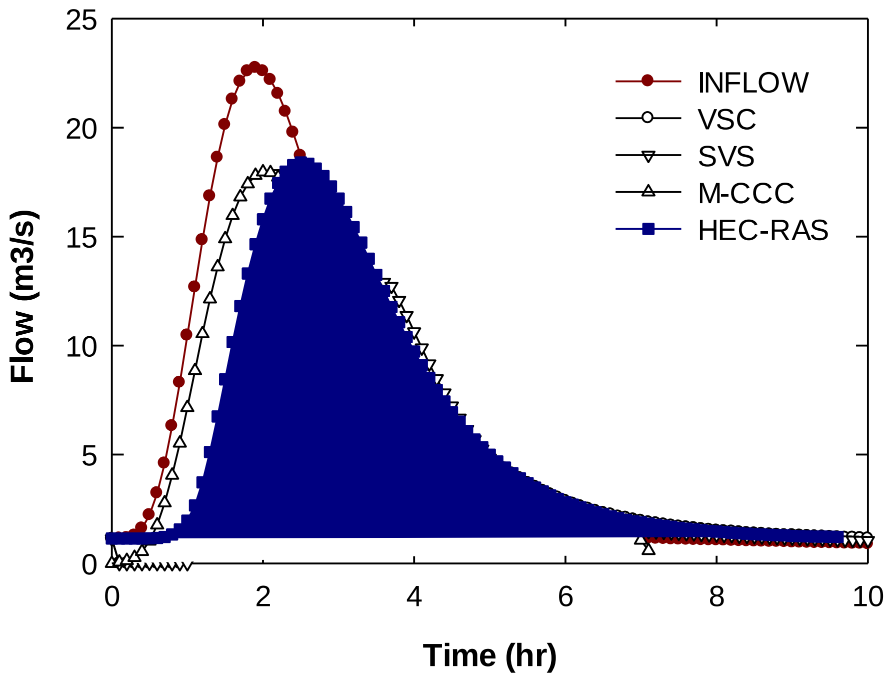
Routing Result: Test 3



	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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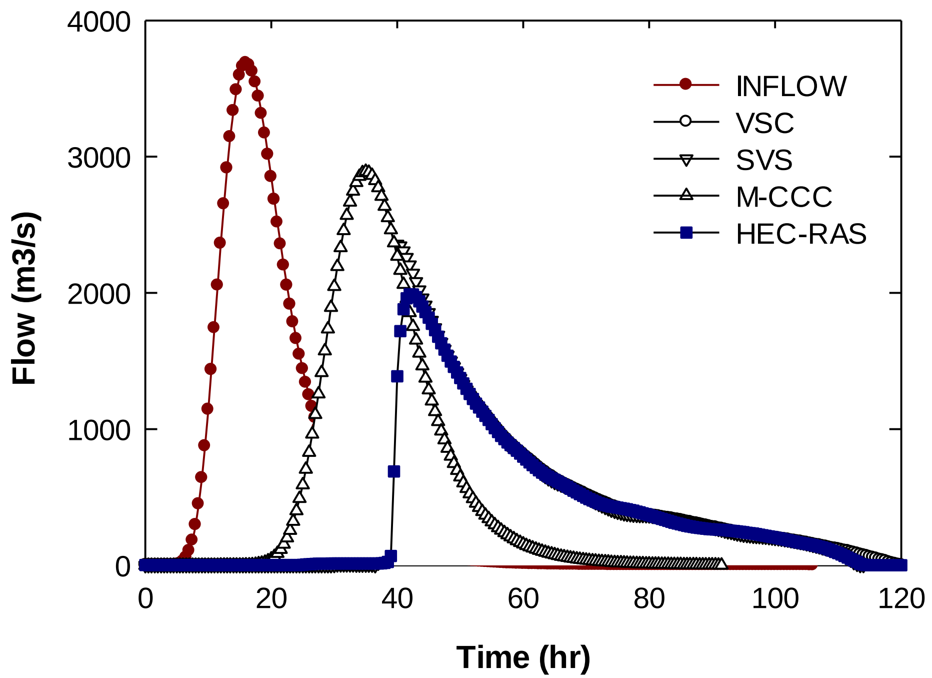
Routing Result: Test 5



	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)

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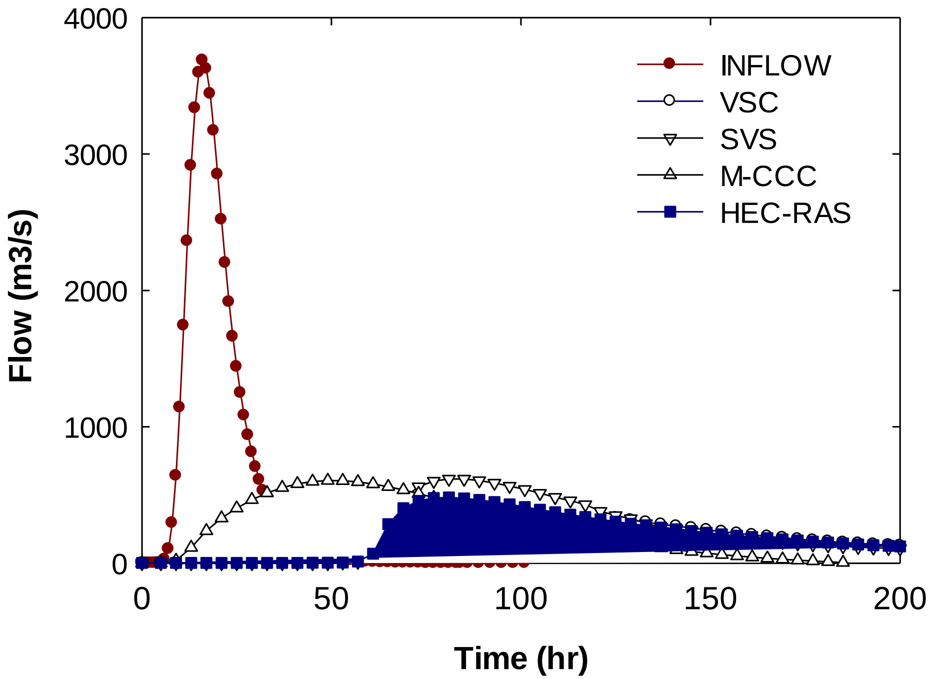
Routing Result: Test 6



	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)

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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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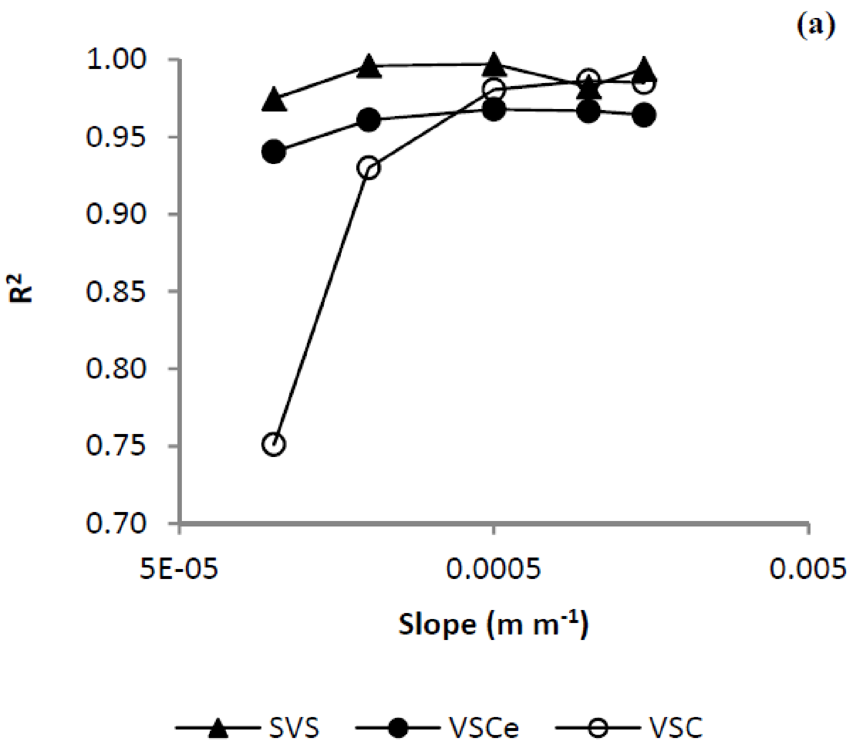
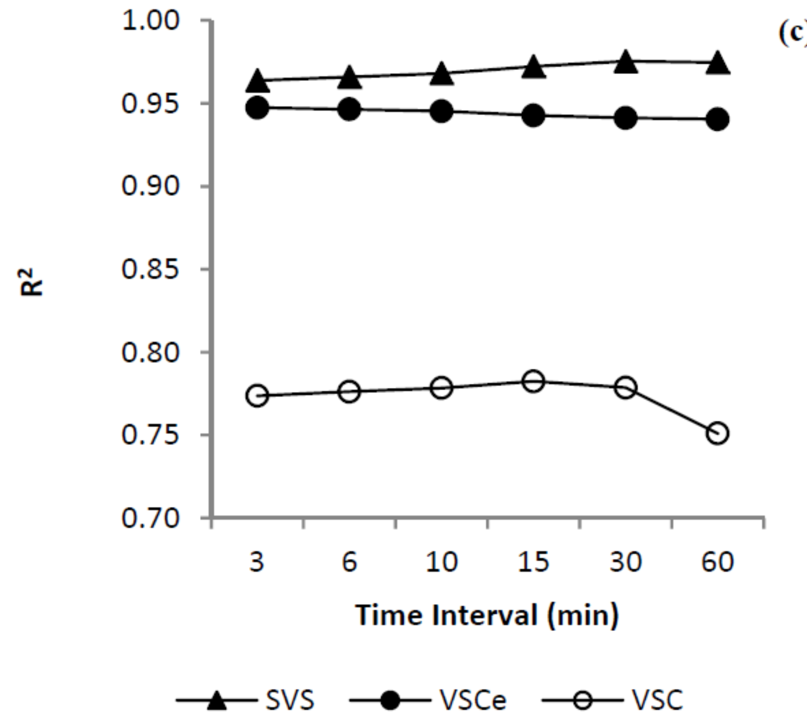
Reliability test





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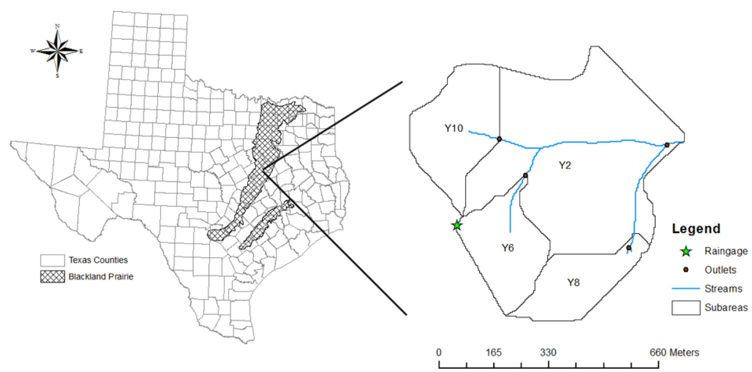
Case Study



USDA-ARS Riesel Experimental Station, Y2 Watershed

- Area: 44ha
- Soil: Houston Black (50% clay)
- Crops: Corn, Wheat, Sorghum, Oats, Fallow
- Slope: 2.0 %
- Rainfall: 1,100 mm
- Period: 2003-2004
- Time step: 6 min
- Historical land managements incorporated

6	1	30	266	0	2	53	66.1	.00	0.00	0.0	0.0000	0.00	0.000	fertilizer (Nitrogen)
6	1	30	160	21	2	0	0.00	0.00	0.00	0.0	0.0000	0.00	0.000	tillage (field caltivator)
6	3	17	160	12	2									tillage (field caltivator)
6	3	19	136	21	2	0	2000.	4.	0.00	0.0	4.0	0.00	0.000	plant corn
6	8	25	292	0	2	0	0.00	0.00	0.00	0.0	0.0000	0.00	1.150	harvest
6	8	25	451	0	2	0	0.00	0.00	0.00	0.0	0.0000	0.00	0.000	kill
6	8	25	329	0	2	0	0.00	0.00	0.00	0.0	0.0000	0.00	0.000	shred
6	9	26	261	15	2	3	9238.00	.00	0.00	0.0	0.0000	0.00	0.000	fertilizer (poultry litter)
6	9	29	160	21	2	0	0.00	0.00	0.00	0.0	0.0000	0.00	0.000	tillage (field caltivator)
6	9	30	247	12	2									tillage (tuffline)
6	10	22	160	21	2									tillage (field caltivator)
6	10	23	146	21	10	0	1500.	4.0	0.00	0.0	140.	0.00	0.000	plant wwht
7	6	7	292	0	10									harvest
7	6	7	451	0	10									kill
7	8	5	211	12	10									tillage (chisel)
7	8	31	261	15	10	4	8715.00	.00	0.00	0.0	0.0000	0.00	0.000	fertilizer (poultry litter)
7	9	2	247	12	10									tillage (tuffline)

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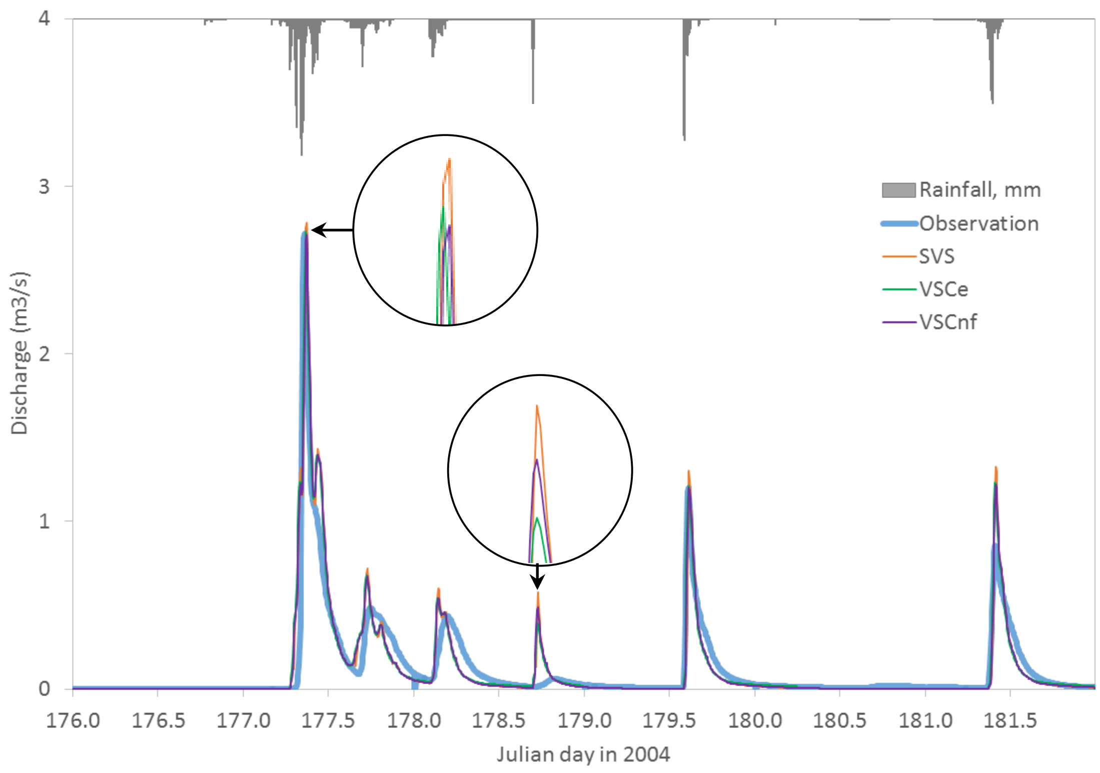
Y2 Flow Calibration



NSE=0.83 R^2=0.86

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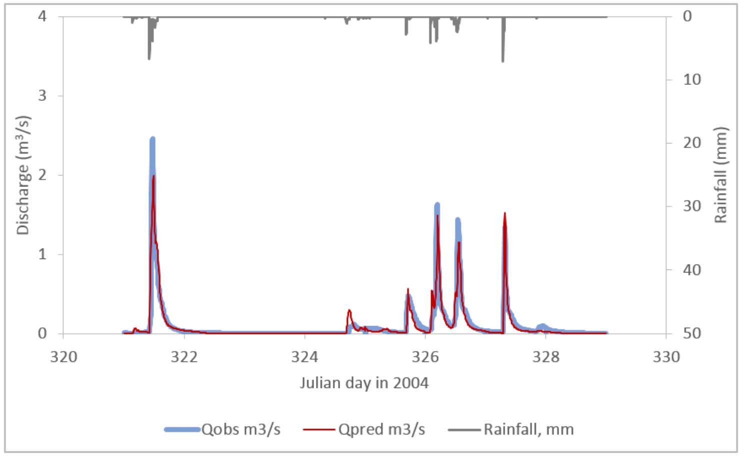
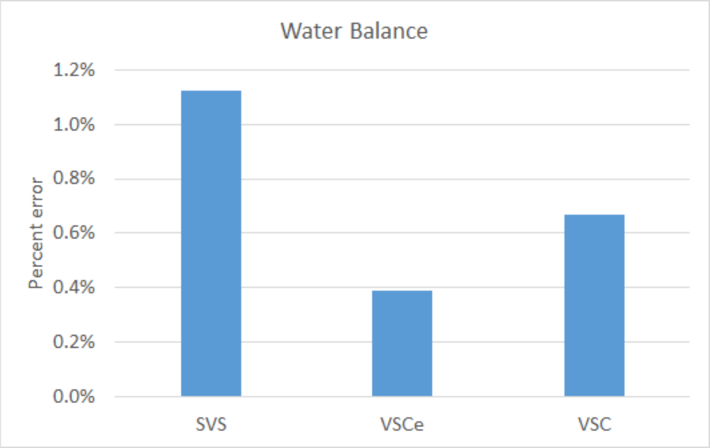
Y2 Flow Evaluation



NSE=0.86 R^2=0.87



The error in **SVS** is attributed to large storms causing flood plain flow

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Summary

- Three enhanced streamflow routing methods (M-C, VSC, and SVS) were tested for stability and accuracy
- Muskingum-Cunge method with constant coefficients as in NRCS TR-20 was inaccurate in response times
- VSCe performed better in single channel-single storm tests over SVS
- SVS exhibited higher peak flows than VSCe or VSC
- VSCe and SVS perform well on the Y2 watershed
- No significant improvement was achieved in discharge estimation with advanced methods on the Y2 watershed (~2% slope)

Improvement of the Variable Storage Coefficient Method with Water Surface Gradient as a Variable

J. Jeong, J. R. Williams, W. H. Merkel, J. G. Arnold, X. Wang, C. G. Rossi

Abstract. *The variable storage coefficient (VSC) method has been used for streamflow routing in continuous hydrological simulation models such as the Agricultural Policy/Environmental eXtender (APEX) and the Soil Water Assessment Tool (SWAT) for more than 30 years. APEX operates on a daily time step and offer options for simulating processes on shorter time steps (e.g., hourly). However, APEX is not adequate for applications such as designing flood control structures or estimating flood damages because of a fundamental assumption in the VSC method: the normal flow condition. The storage with variable slope (SVS) method and an enhanced variable storage coefficient (VSCe) method are proposed as new routing methods for continuous simulation models that will improve flow routing and water quality simulation at subdaily time scales. This study describes the principle of the SVS method and the VSCe method and their performances against HEC-RAS unsteady flow results for various hydraulic and geometric conditions. Results show that the peak flow and the time to peak flow improved by up to 20% with SVS and VSCe on mild slopes (less than 0.0005 $m\ m^{-1}$) and small time steps of less than 1 h when compared to the conventional VSC method, although the difference narrowed as the channel slope and time interval increased. A case study on a small agricultural watershed in Texas indicates that both VSCe and VSC are reliable in watershed applications, but the improvement in streamflow prediction can be marginal in watersheds with steep slopes.*

Keywords. *Continuous simulation, Flood, Streamflow routing, Water surface gradient.*

Traditionally, flood analyses have been performed using a single-event model, which means a model is applied to one or a few storms over a range of frequencies rather than over a range of continuous periods. This was mainly because continuous simulation steady shallow water flow (Jeong and Charbeneau, 2010). However, when simulating streamflow in continuous models, minor terms are often neglected in the formulation, leading to a diffusion wave model or a kinematic wave model. In general, the dynamic wave model is comprised of

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Questions?