Application of a non-steady runoff method in Landlab: implications for modeling landscape change

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April 13, 2016

LANDLAB

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CSDMS
COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

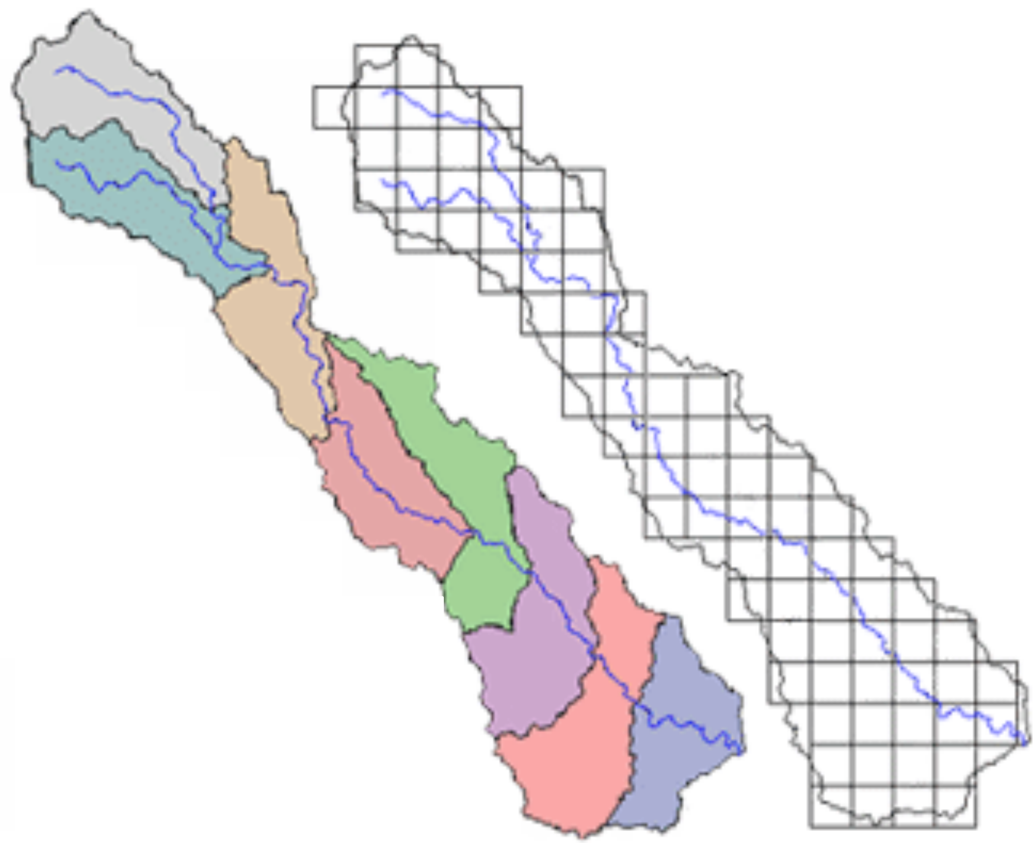
J. Adams supported by NSF grants ACI-1147519 and ACI-1450338

What is a landscape evolution model?

A model of topographic change through time

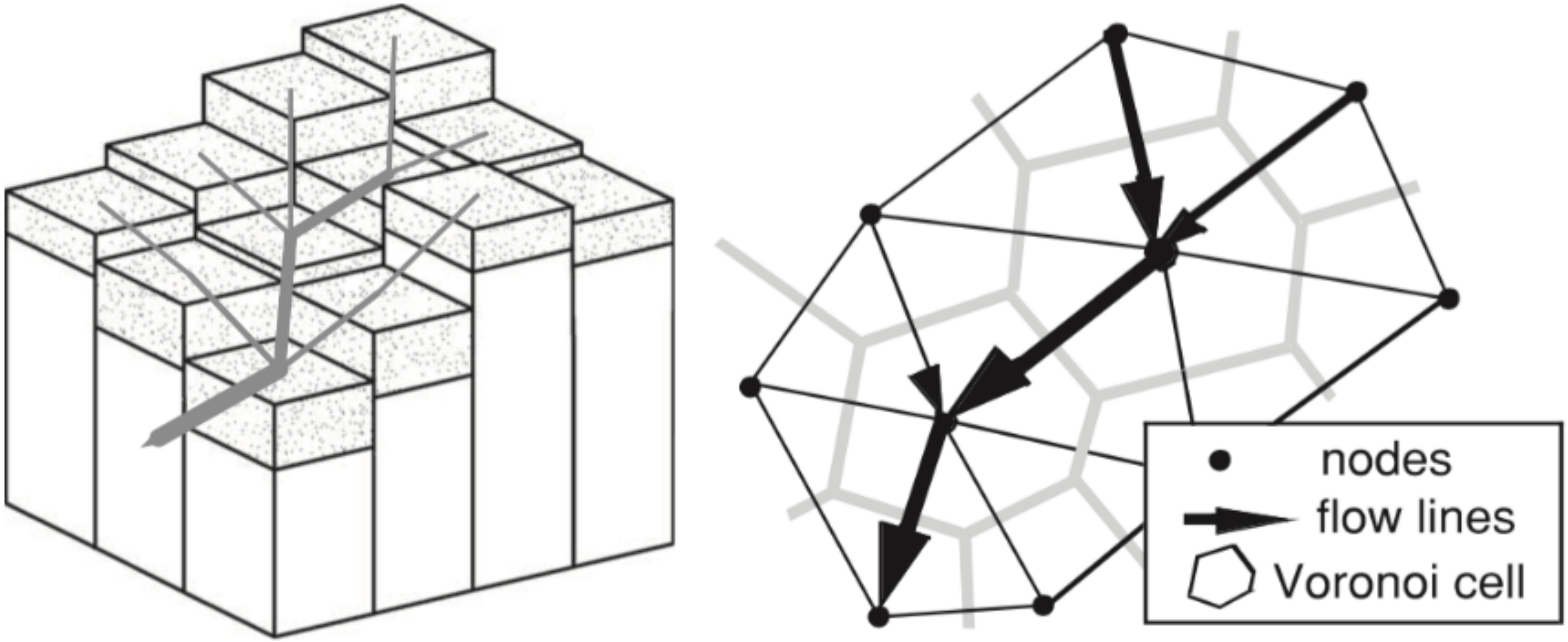
Sample watershed

Lumped ⟶ **Distributed**



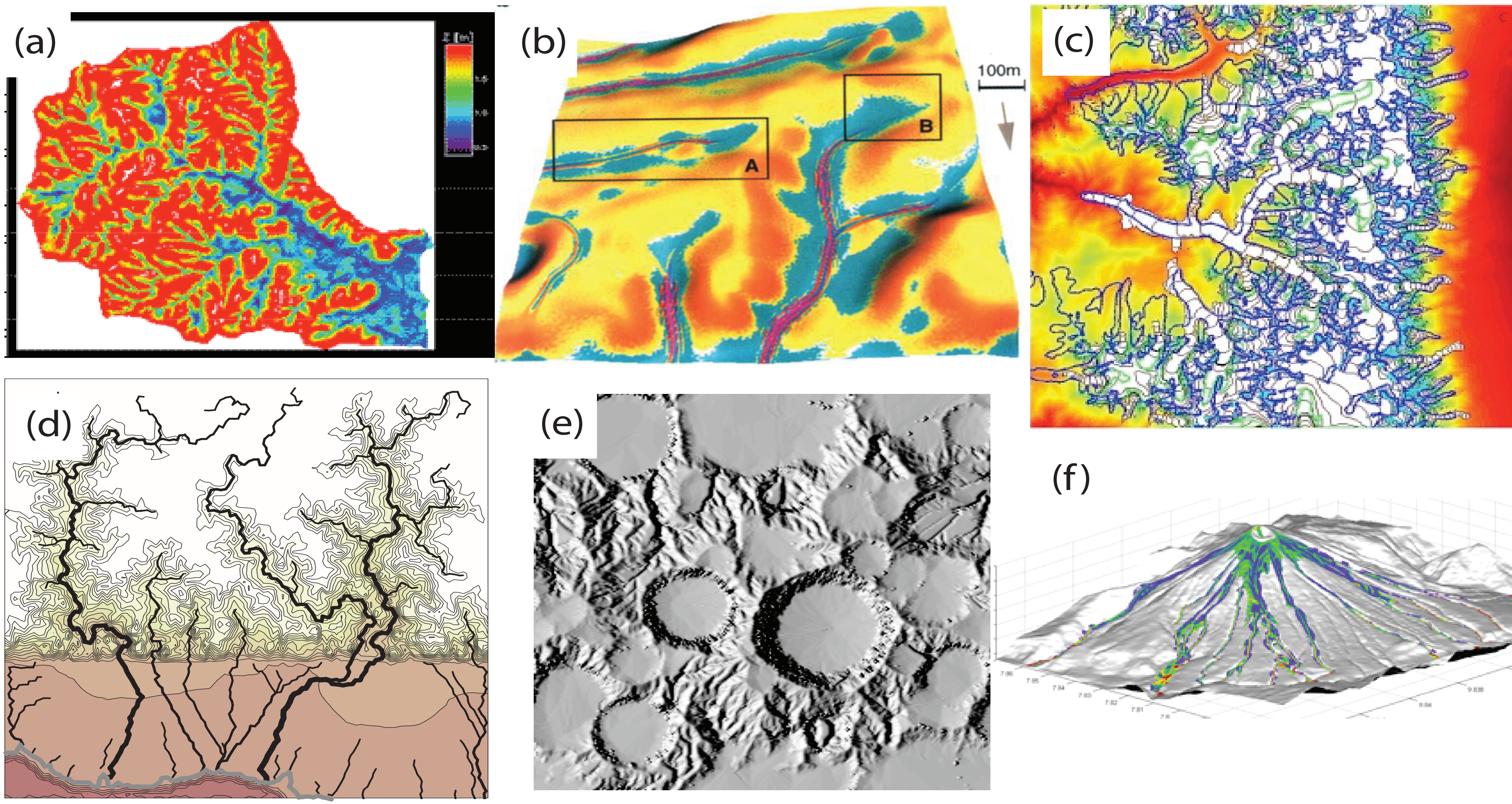
NOAA / NWS / The COMET Program

What is a landscape evolution model?



Tucker and Hancock, 2010

What is a landscape evolution model?



(a) Ivanov et al., 2004; (b) Mitas and Mitasova, 1998; (c) Kessler et al., 2006; (d) Tucker and Hancock, 2010; (e) Howard, 2007; (f) Kelfoun et al., 2009

Limitations in landscape evolution modeling

- Open-source versus proprietary
- Existing models: read-only, high level for entry, highly specific
- Lack of documentation

Efforts to share models and modeling tools:

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OpenTopography

Landlab: *A Python toolkit for modeling Earth surface processes*

- Eliminate redundancies
- Emphasize flexibility, fundamentals
- ‘Black box’ to developer level
- Training: workshops, one-on-one

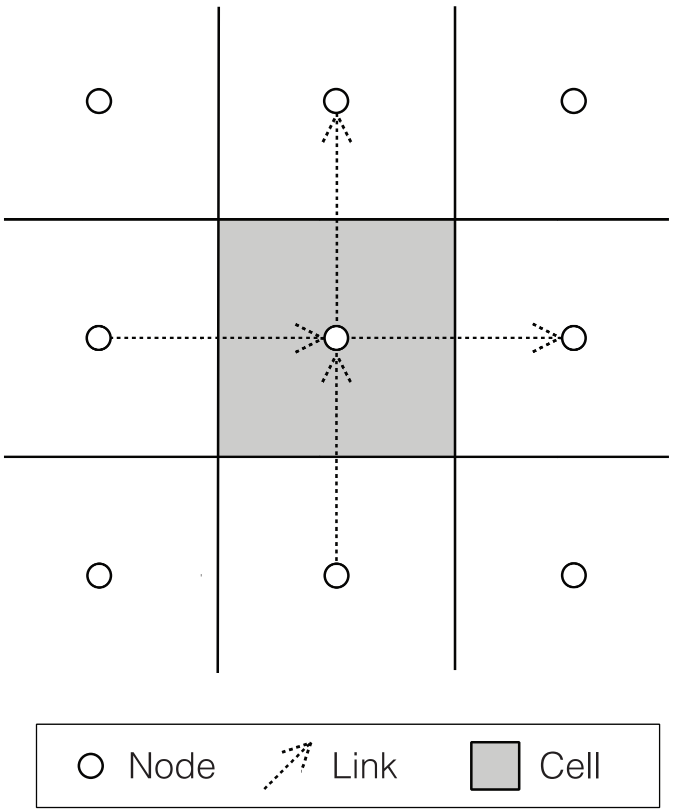
Hopefully accelerate scientific progress!

Landlab: *A Python toolkit for modeling Earth surface processes*

Contains:

- Gridding library
  - (**structured**, Voronoi, hexagonal, radial…)
- Process components
  - (**overland flow**, hillslope diffusion, soil moisture…)
- Data sharing and handling
- Input / Output utilities
  - (NetCDF, **ESRI ASCII**)
- Plotting utilities

Raster grid



Landlab: *A Python toolkit for modeling Earth surface processes*

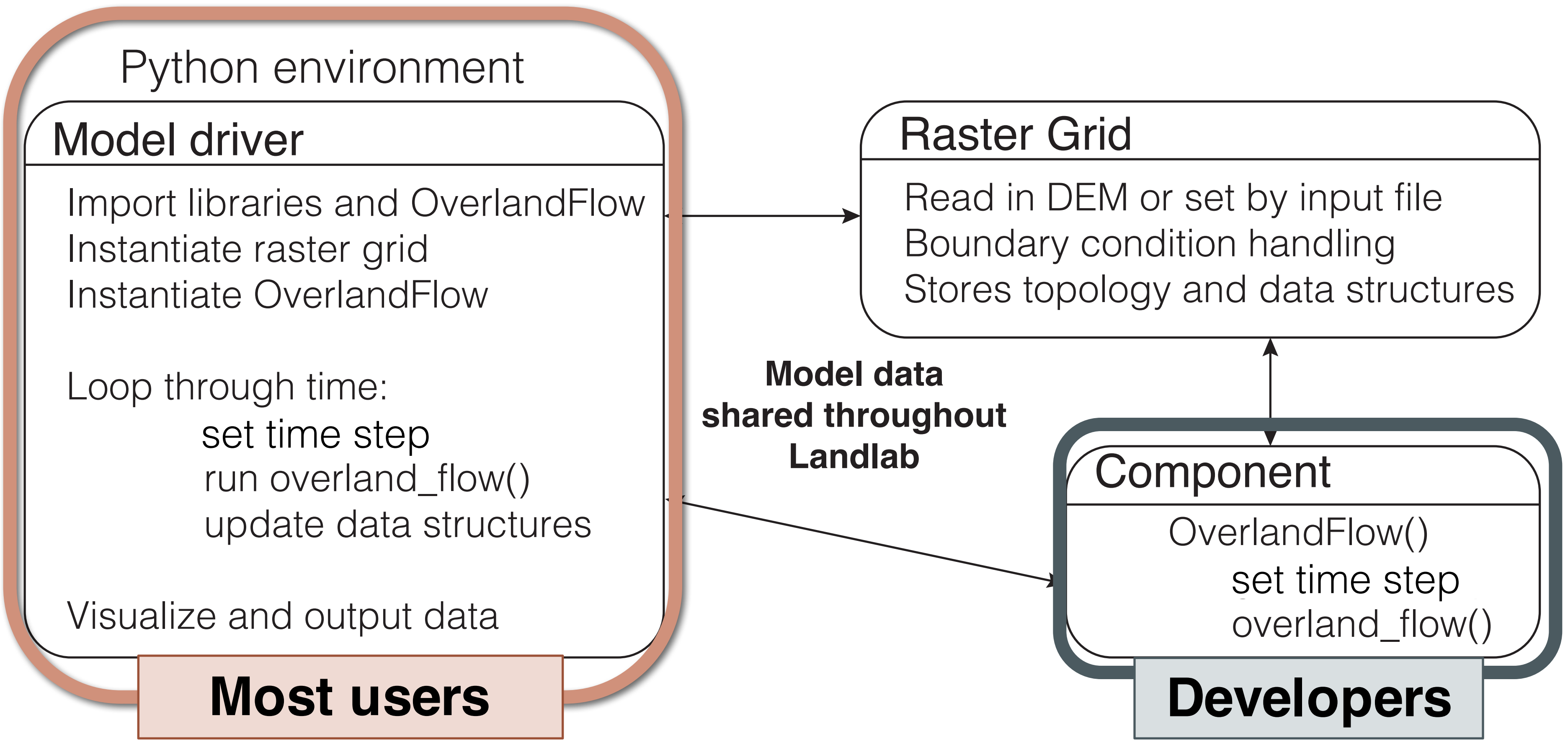
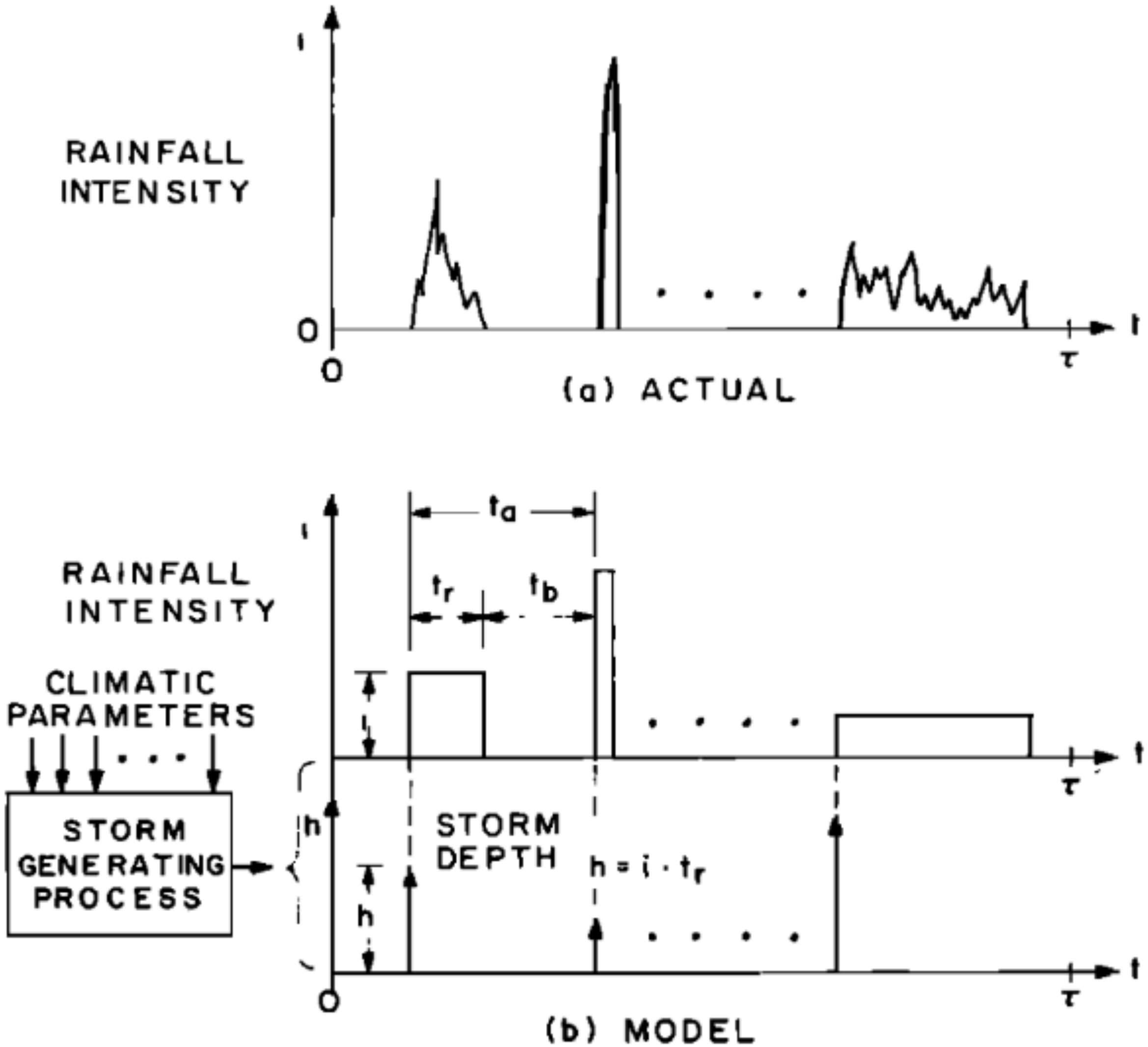


Photo: National Park Service

Photo: National Park Service

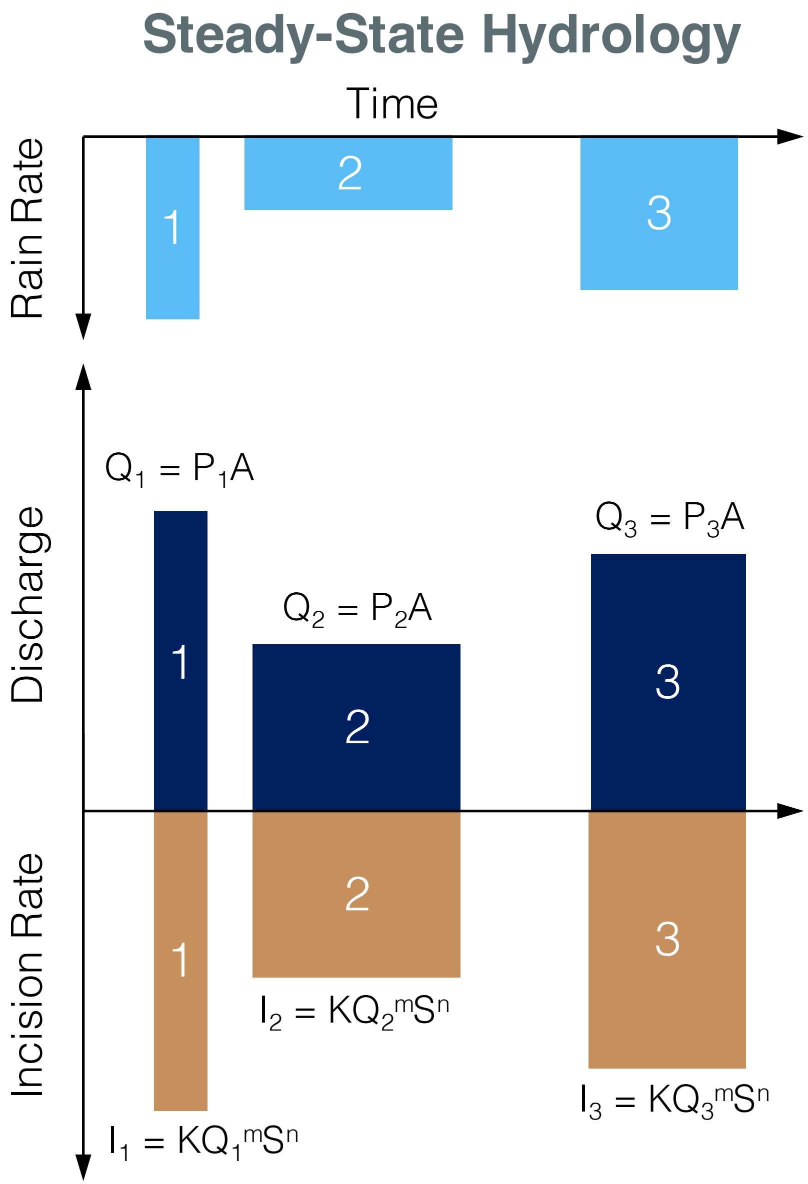
Wednesday, April 13, 2016

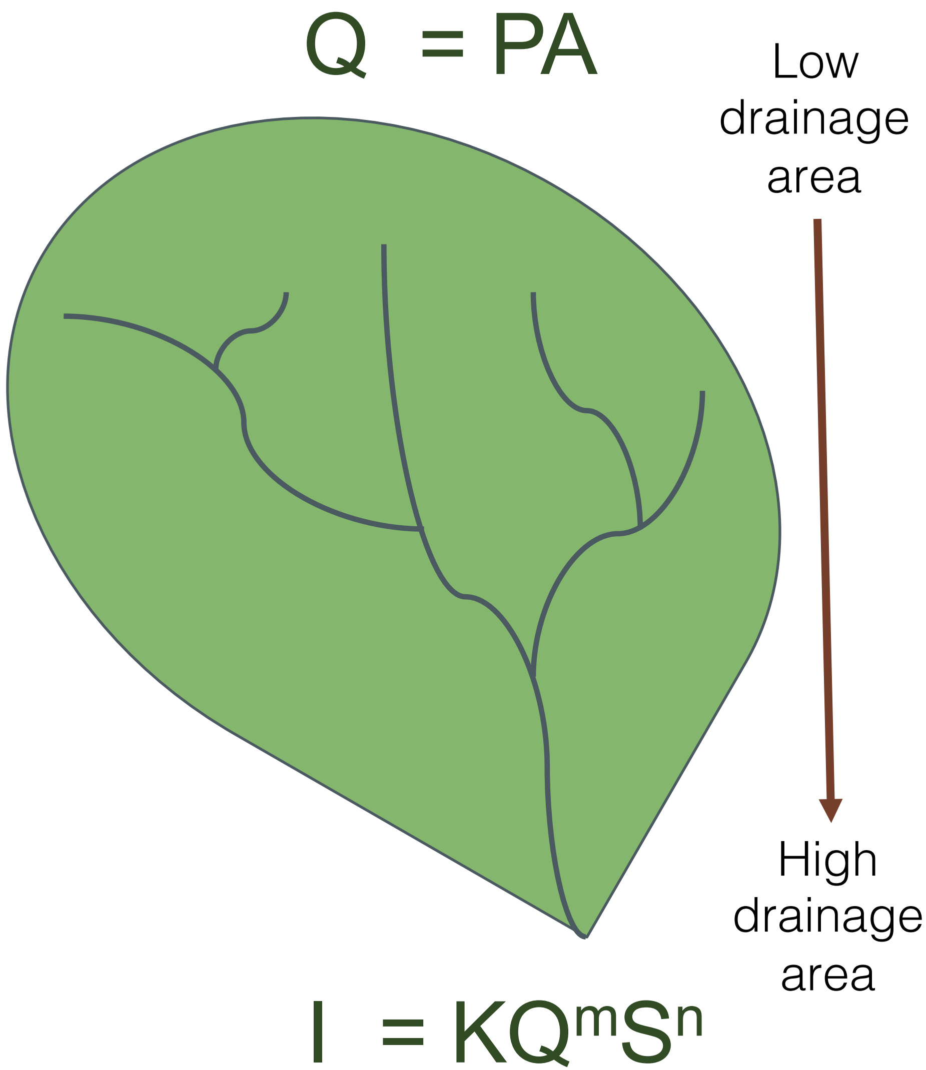
Steady-state hydrology: **Precipitation**



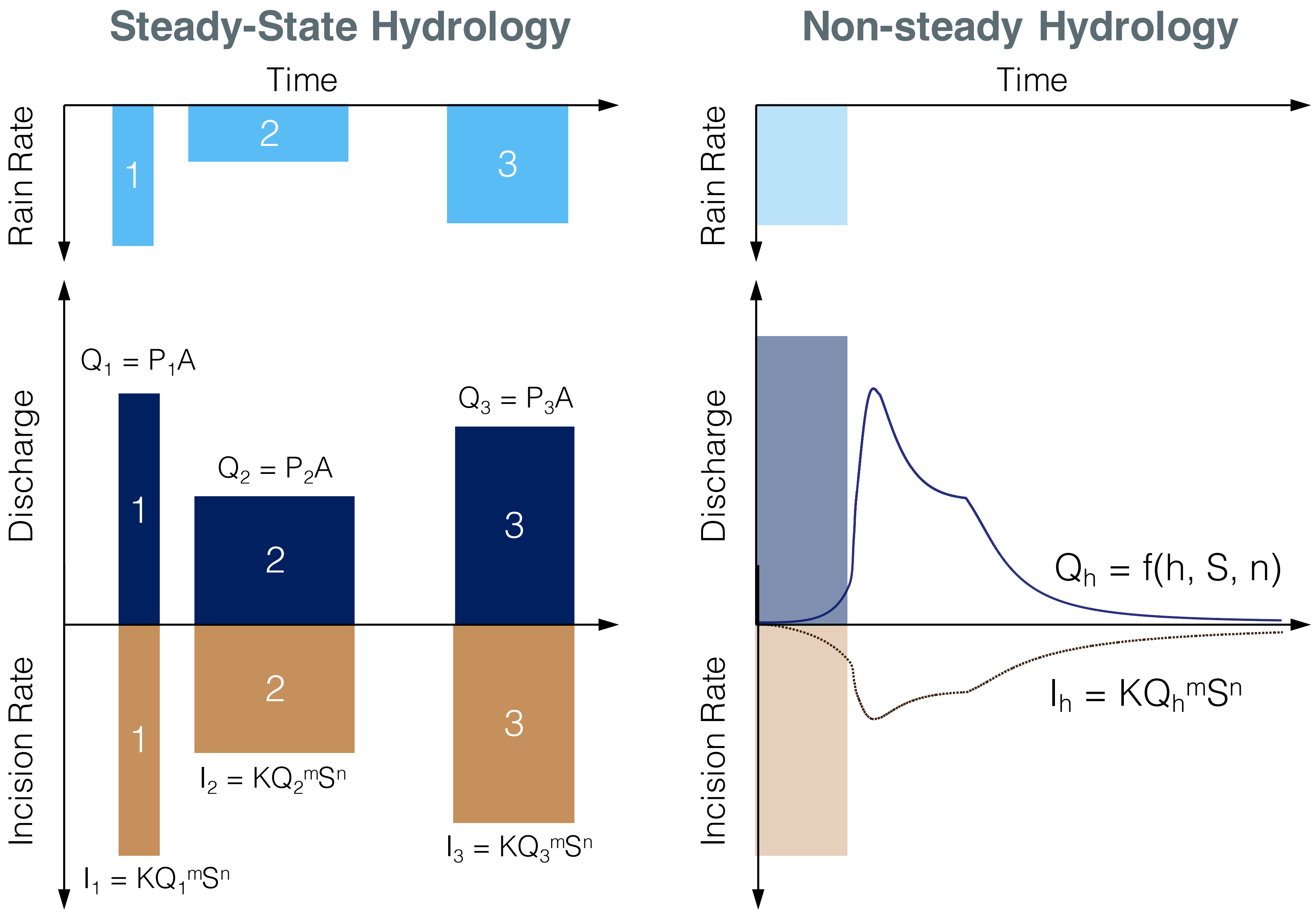
Eagleson, 1978 *WRR*

Steady-state hydrology: **Discharge** and **channel incision**





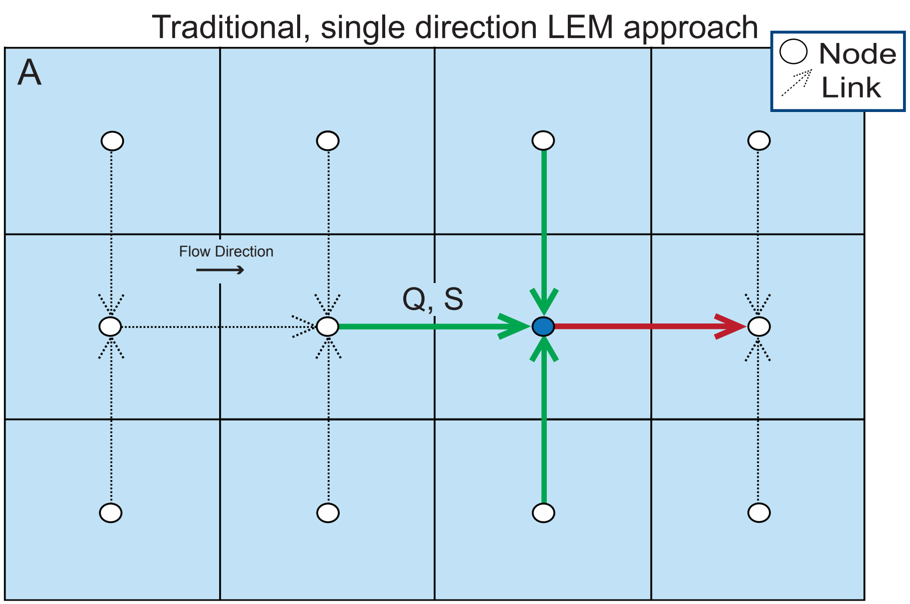
Steady-state hydrology: **Discharge** and **channel incision**

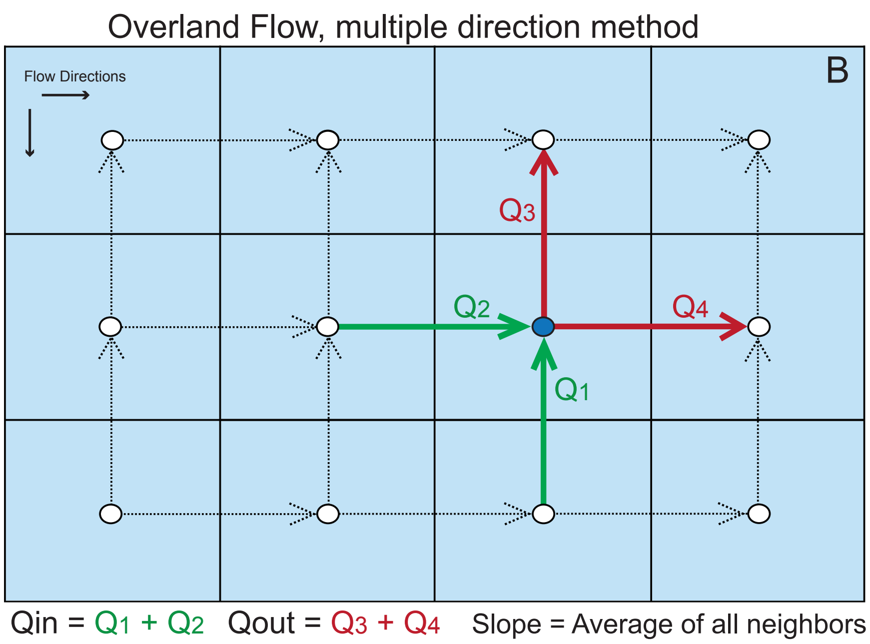


Steady-state hydrology: **flow routing**

$$Q = PA$$
$$I = KQ^mS^n$$

$$Q_h = f(h, S, n)$$
$$I = KQ_h^mS^n$$





Flow along ***one*** path of steepest descent

Single peak discharge and incision rate

Flow in ***all*** directions out of a given node

Changing discharge and incision rate

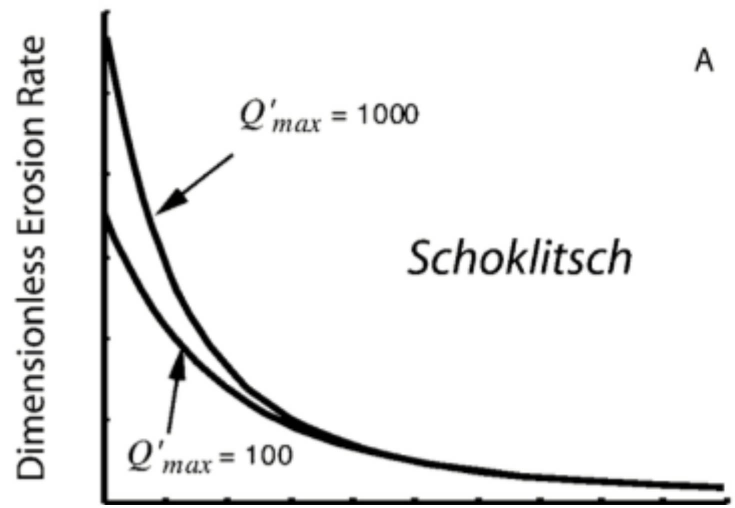
Molnar, 2001, *Geology*

Less rainfall = larger flood impact

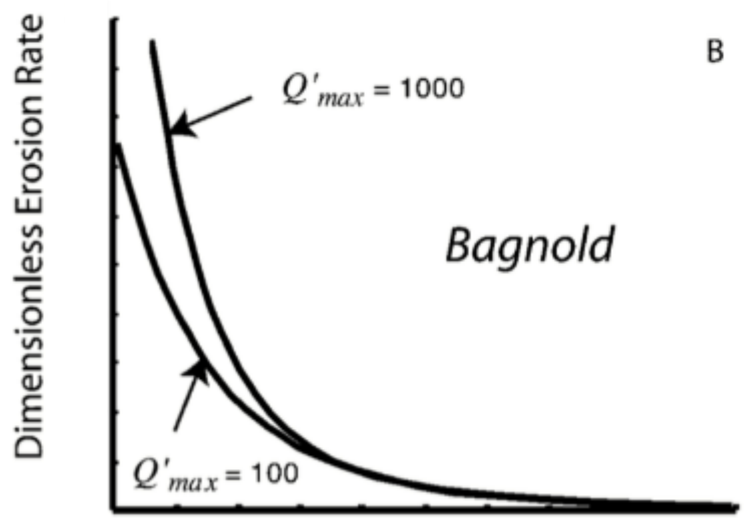
Larger floods = larger discharges

Larger discharges = more incision

Global climate change linked to aridity: **more erosion**

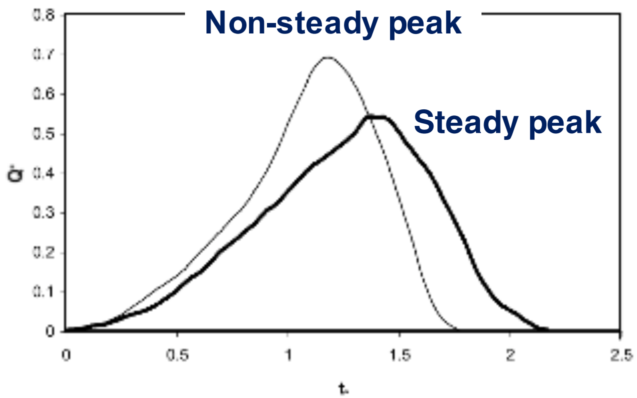


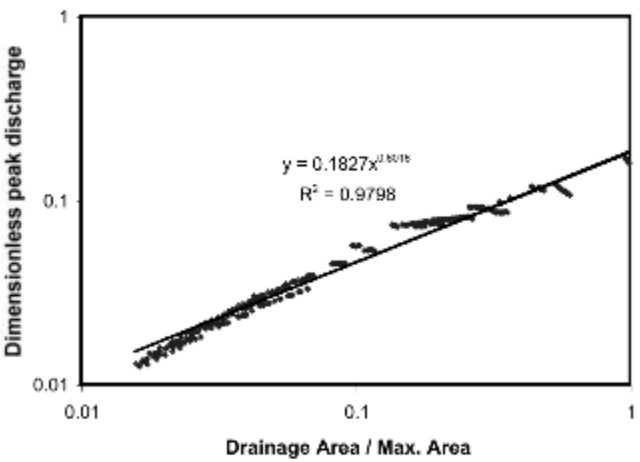
More arid → less arid
Extreme events — Frequent events



More arid → less arid
Extreme events — Frequent events

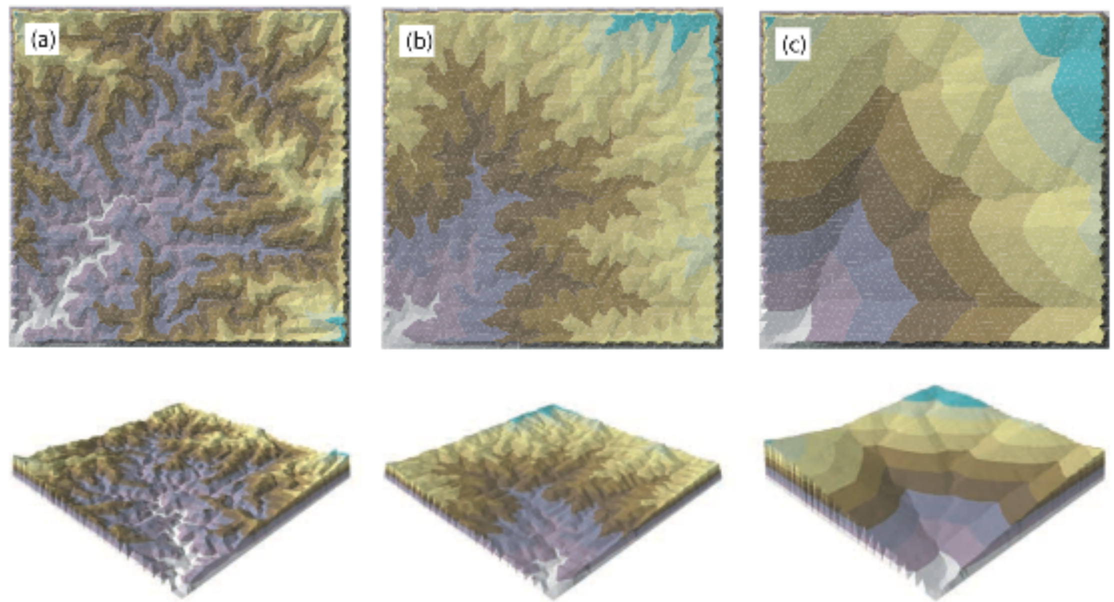
Sólyom and Tucker, 2004, *JGR*





$$Q_p = \frac{(R-I)A}{F_{hs}} \frac{T_r}{T_r + L/U_f}$$

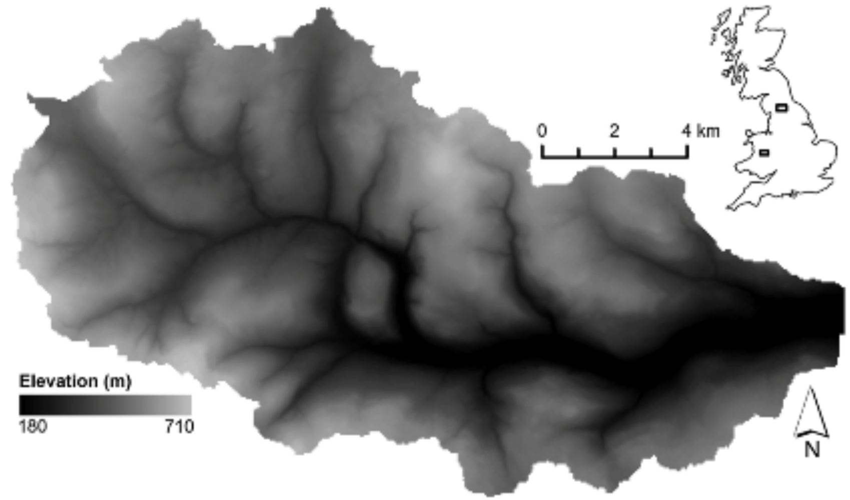
Steady-state → Non-steady state



Non-steady discharge:

- Higher peak than steady-state
- Lower valley density
- Convex channel profiles

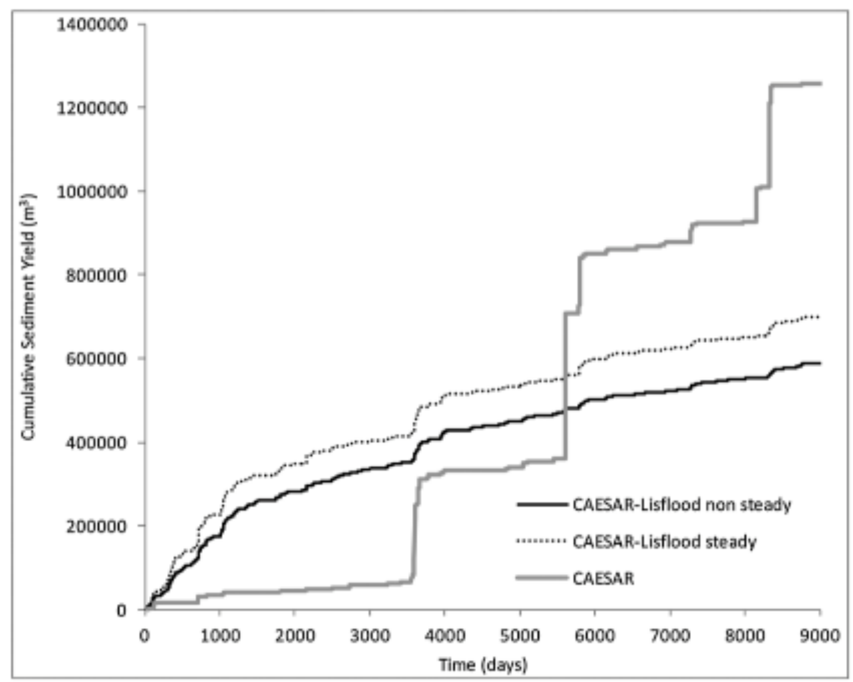
Coulthard et al., 2012, *ESPL*



Model behavior dependent on hydrodynamic method

Note:

- "Steady" cases calculated using Manning's equation
- CAESAR model allows divergent flow



Non-steady flow routing in Landlab

$$q_{t+1} = \frac{[\theta q_t + \frac{1-\theta}{2}(q_{t,\ left} + q_{t,\ right})] - gh\Delta t S_w}{1 + g\Delta t n^2 |q_t| / h^{7/3}}$$

de Almeida et al., 2012, WRR

Adaptive time step

$$\Delta t = \alpha \frac{\Delta x}{\sqrt{gh_f}}$$

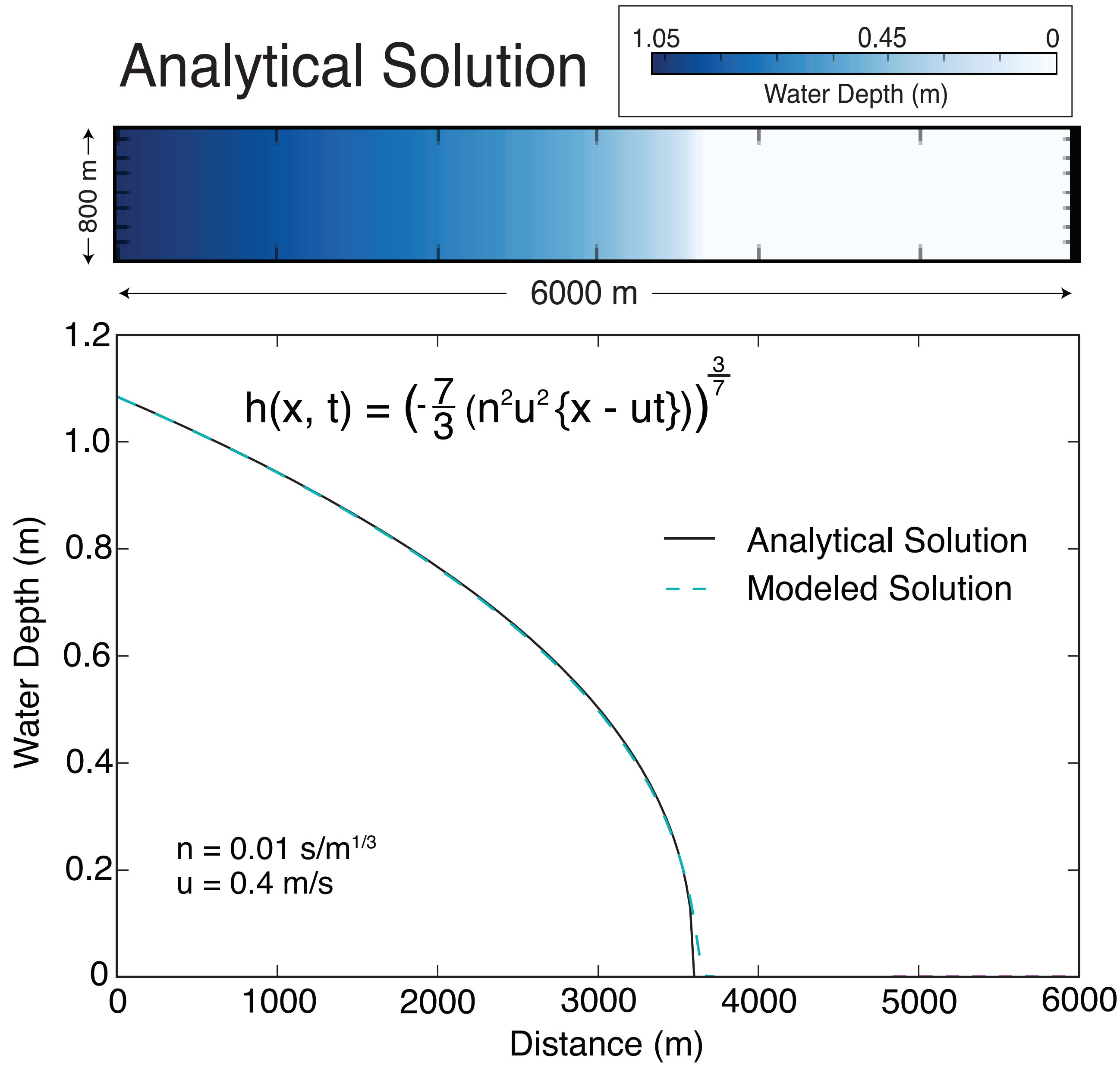
Hunter et al., 2005,
Advances in Water Resources

Steady-state hydrology

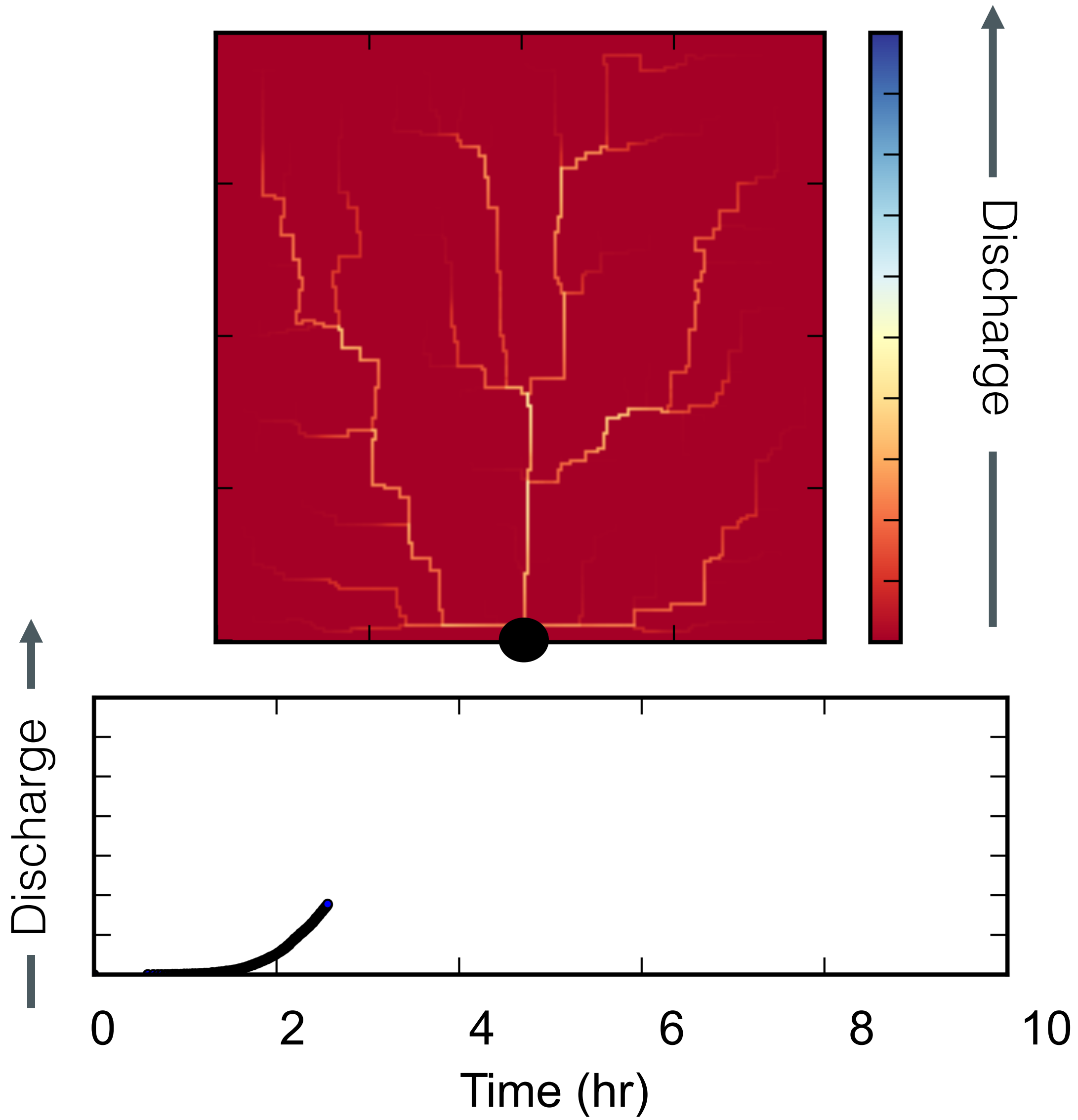
$$q = P\frac{A}{W}$$

Model validation

Non-breaking wave propagation over a horizontal plane



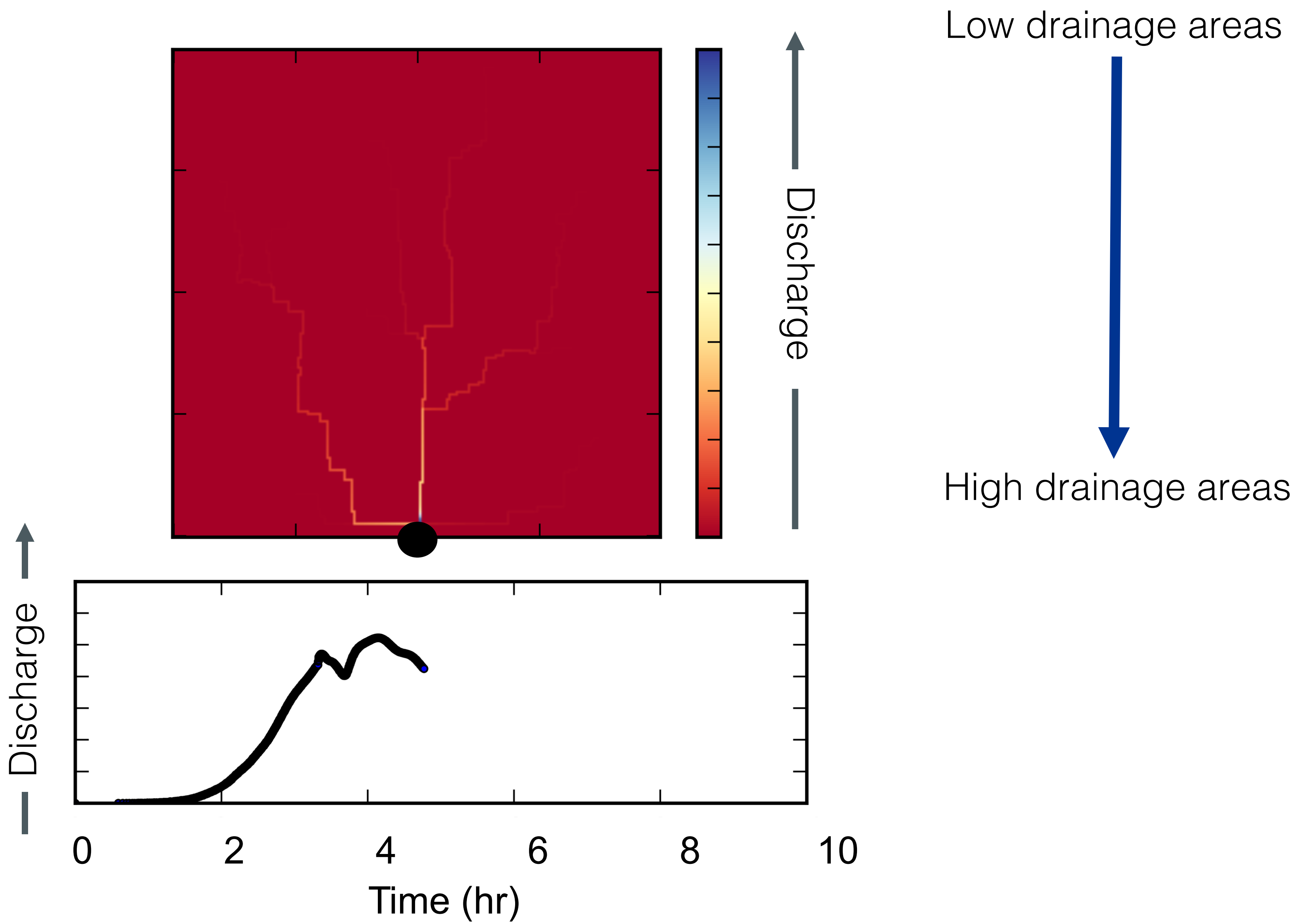
Video: https://www.youtube.com/watch?v=4Ltr6HRUrQI



Low drainage areas

High drainage areas

Video: https://www.youtube.com/watch?v=4Ltr6HRUrQI



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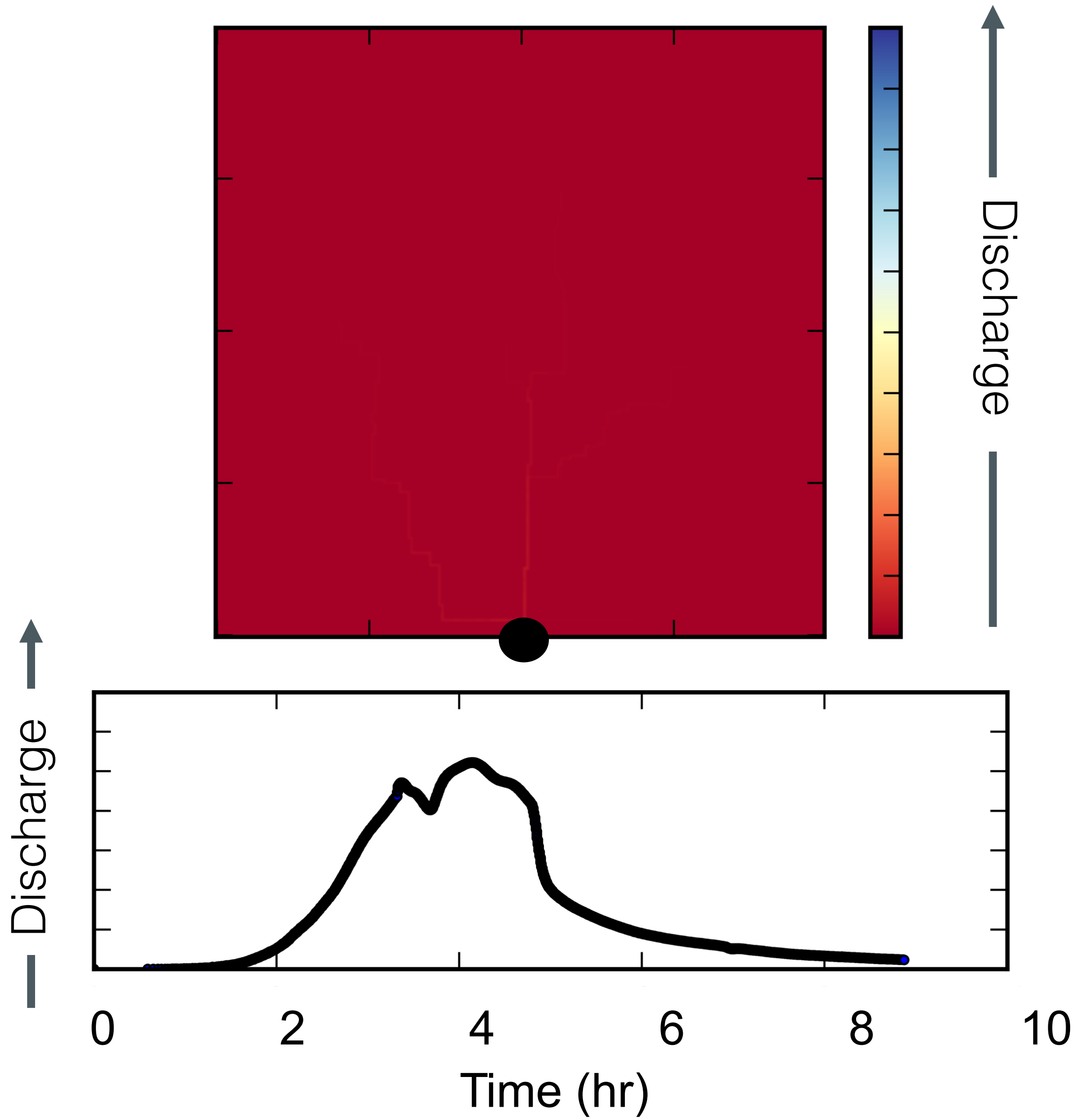

Low drainage areas

High drainage areas

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

How does the model behave across different basin shapes?

How do non-steady methods scale across changing rainfall duration?

…changing rainfall intensities?

Potential real world application of the non-steady hydrologic model.

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

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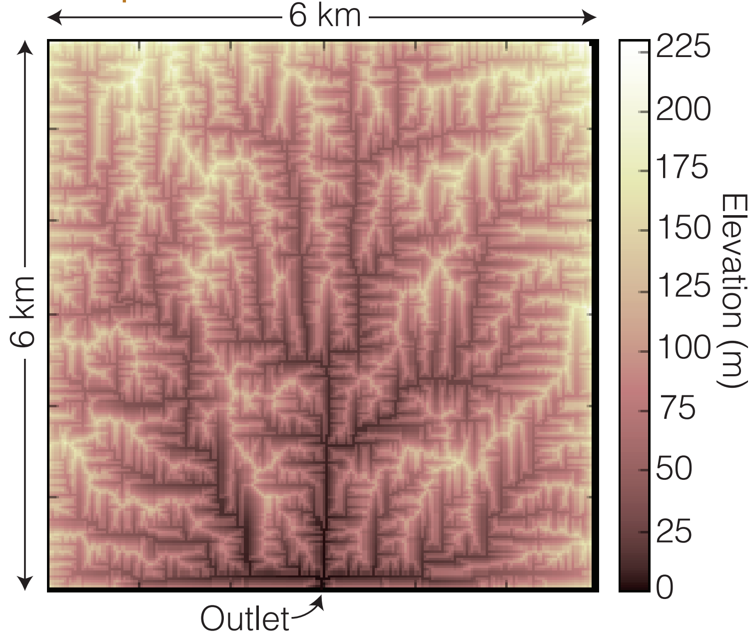
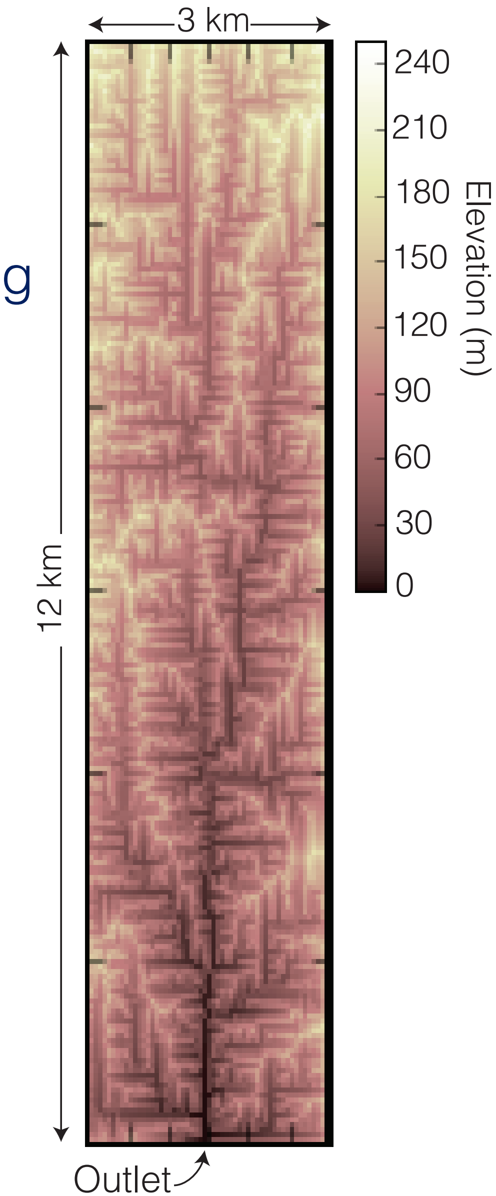
Potential real world applications of the non-steady hydrologic model.

Square



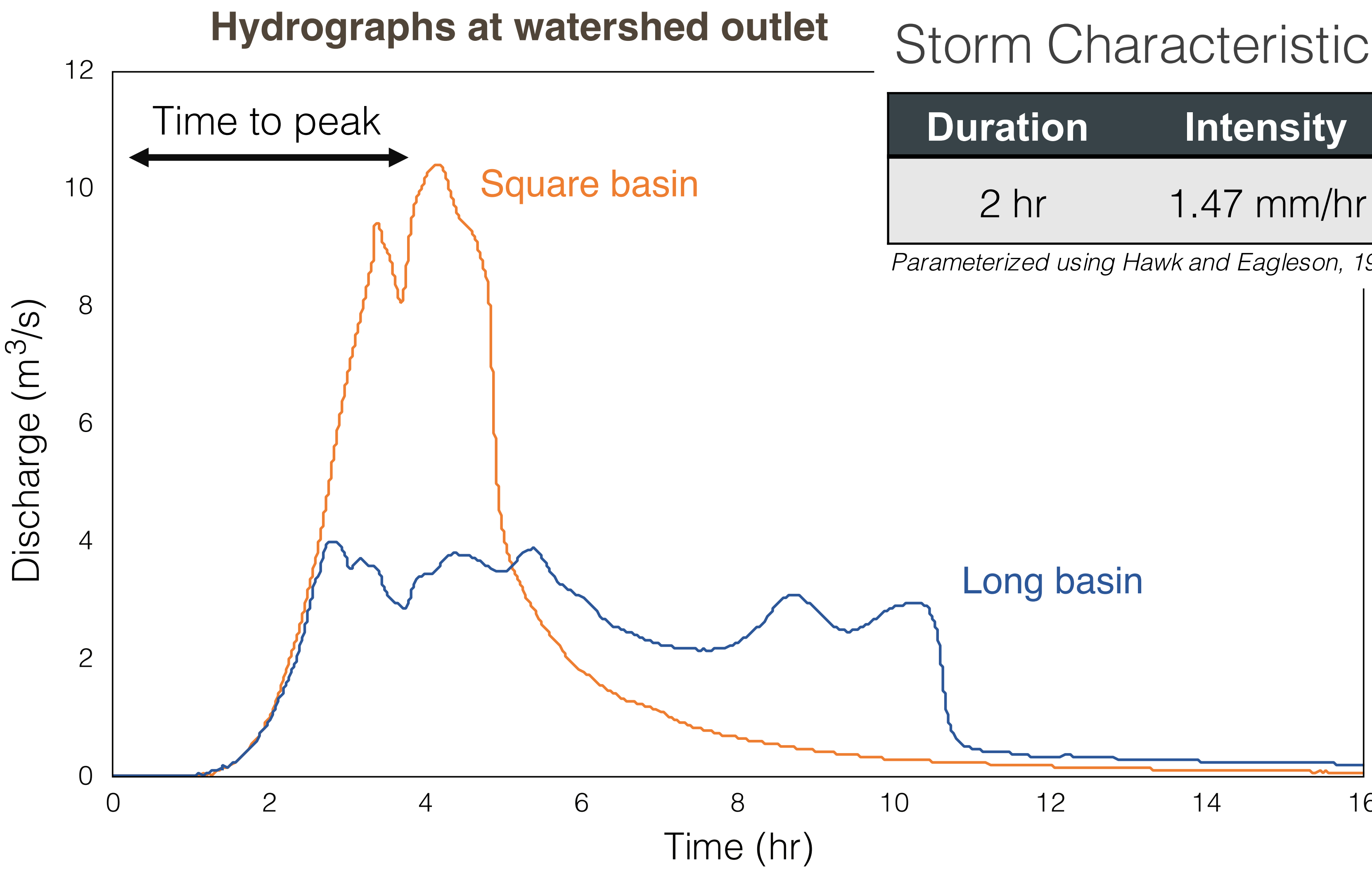
(a) Square basin topography

Long



(b) Long basin topography

- Same drainage area
- Steady-state topography
- 30 m grid resolution
- Steep slopes (10^{-1} to 10^{-2})

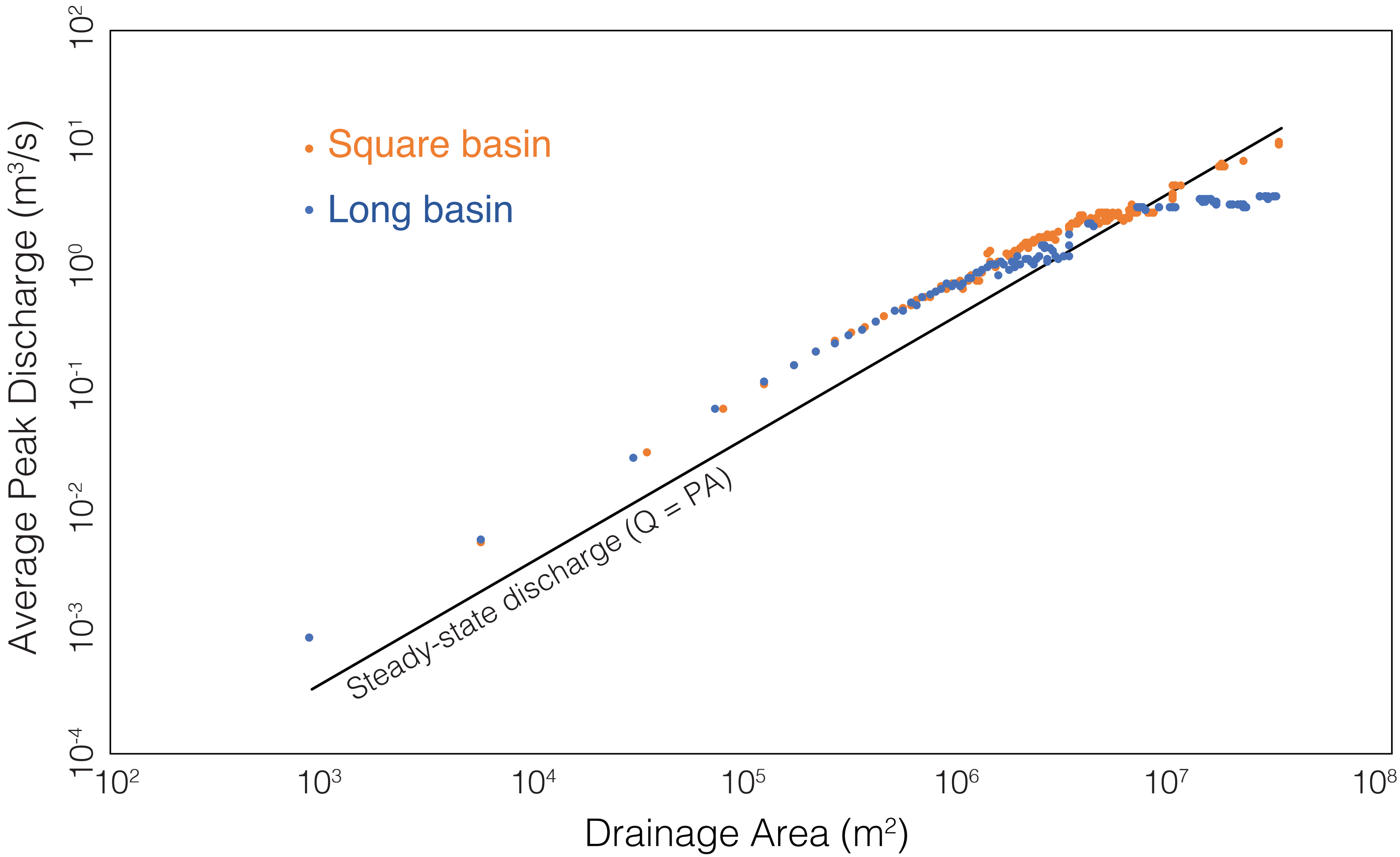


Storm Characteristics

Duration	Intensity
2 hr	1.47 mm/hr

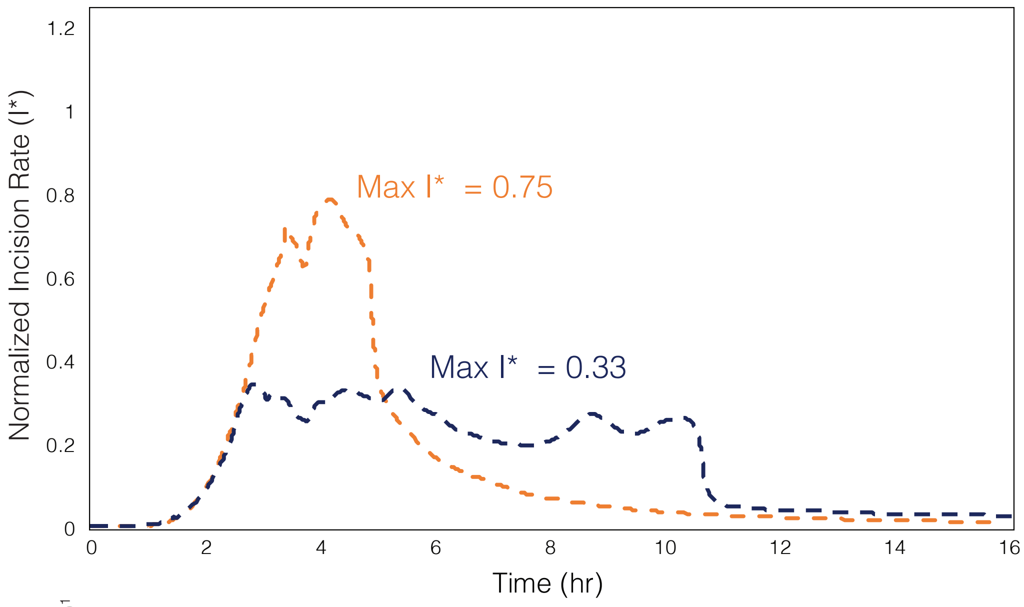
Parameterized using Hawk and Eagleson, 1992

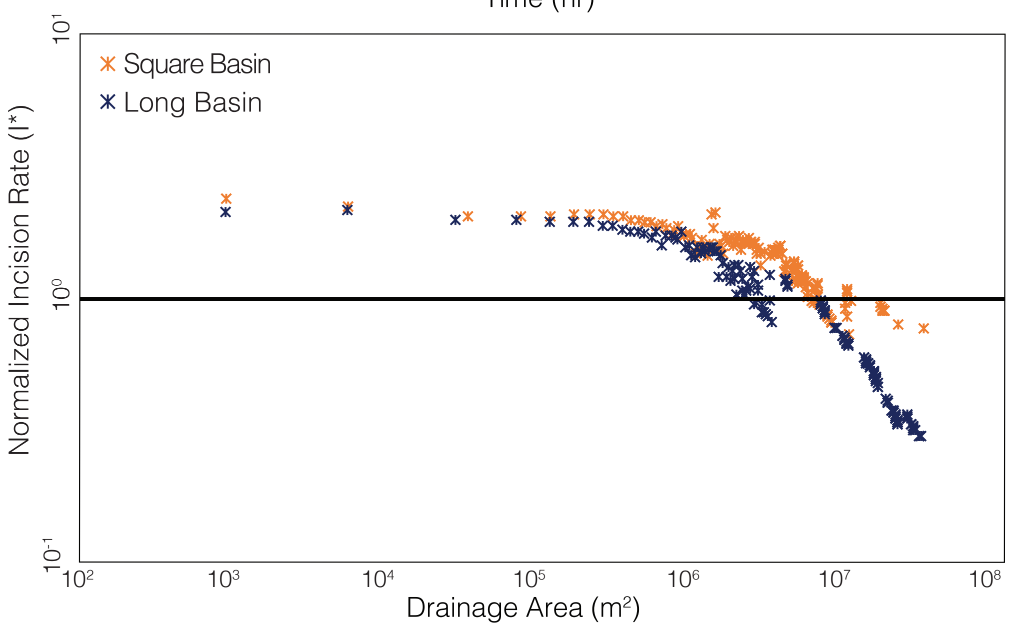
How does this model behave across different basin shapes?



Upstream → **Downstream**

How does this model behave across different basin shapes?





Upstream → **Downstream**

Stream power incision

$$I = k_e \tau^{1.5}$$

$$\tau = \rho g n^{0.6} q^{0.6} S^{0.7}$$

Eq. in form of Tucker, 2004, ESPL

Normalized by steady-state incision rate: neglect erodibility

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

How does the model behave across different basin shapes?

- Outlet hydrographs reflect basin shape
- Low drainage areas in both basins: discharge, incision rates exceed predicted steady-state

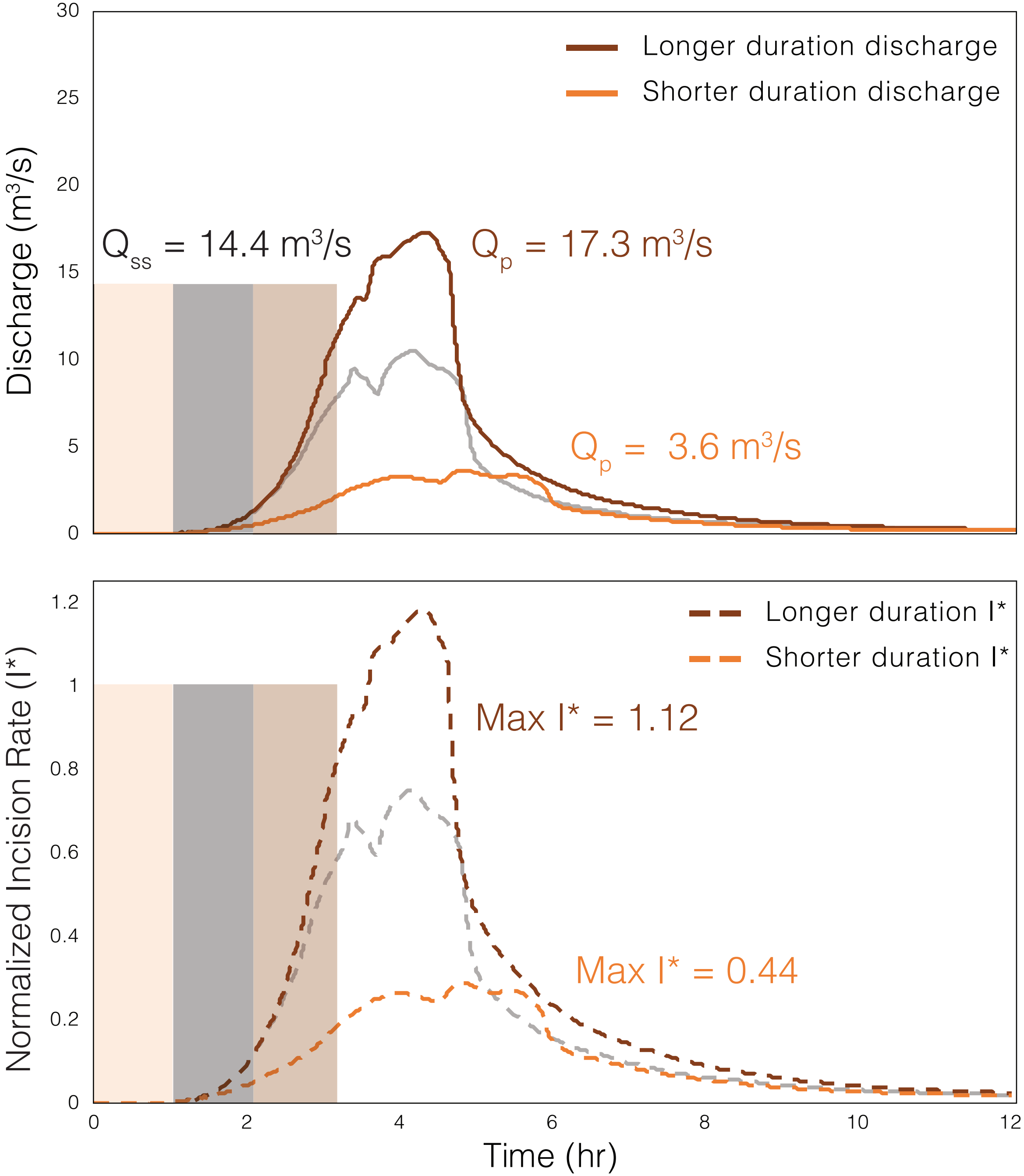
Is steady-state a reasonable assumption for long-term landscape evolution modeling?

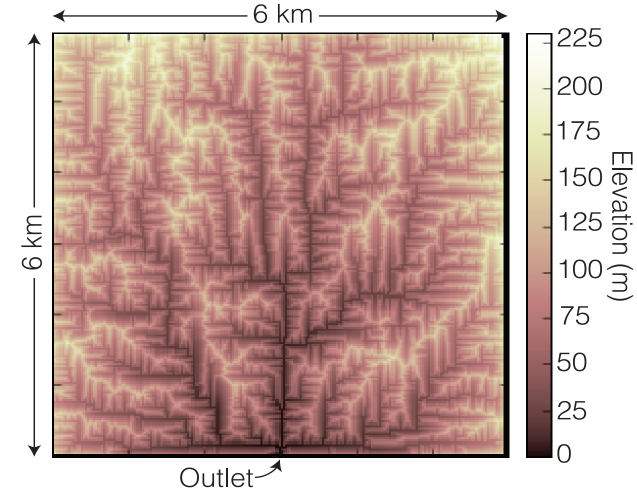
How does the model behave across different basin shapes?

How do non-steady methods scale across changing rainfall duration?

Storm ID	Duration	Intensity
Shorter duration	1 hr	1.47 mm/hr
Average storm	2 hr	1.47 mm/hr
Longer duration	3 hr	1.47 mm/hr

Do these results scale across changing storm duration?



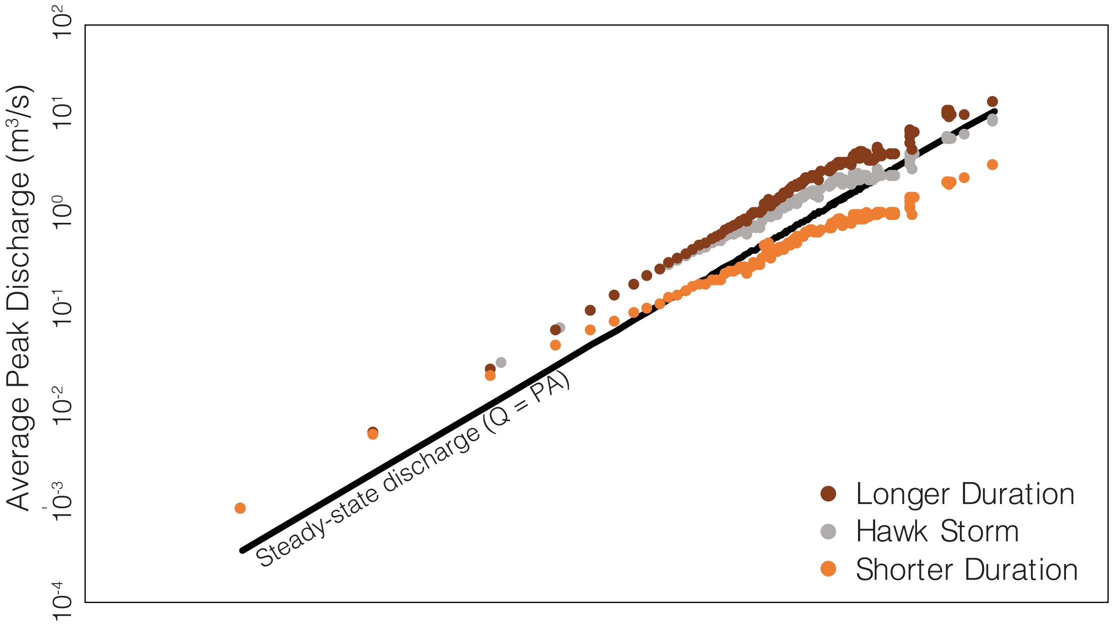


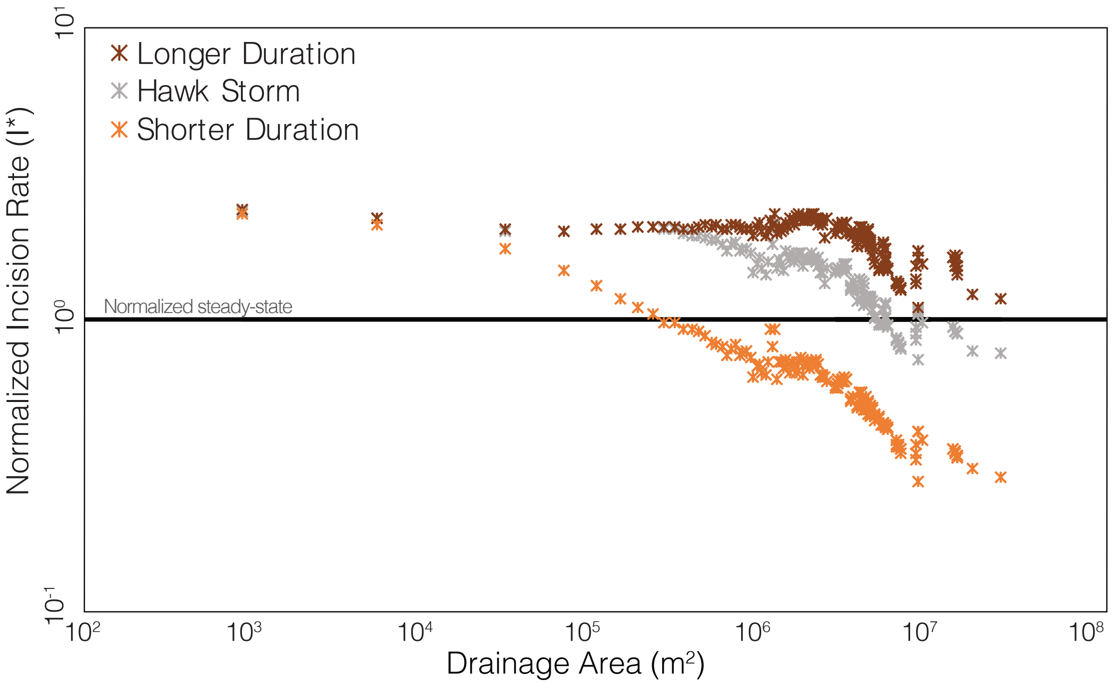
(a) Square basin topography

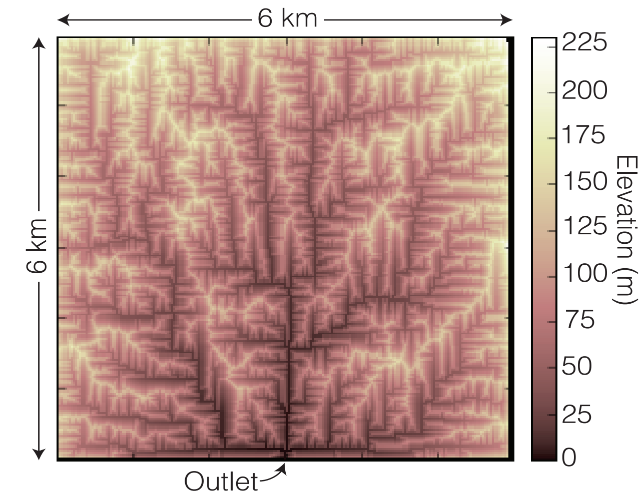
note:

- time to peak
- hydrograph shapes
- peak over steady-state

Do these results scale across changing storm duration?







(a) Square basin topography

note:

- patterns in low drainage area
- longer duration vs. steady-state

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

How do non-steady methods scale across changing rainfall duration?

- Time to peak discharge in the outlet hydrograph inversely related to precipitation duration
- Impacts of changing storm duration: higher drainage areas

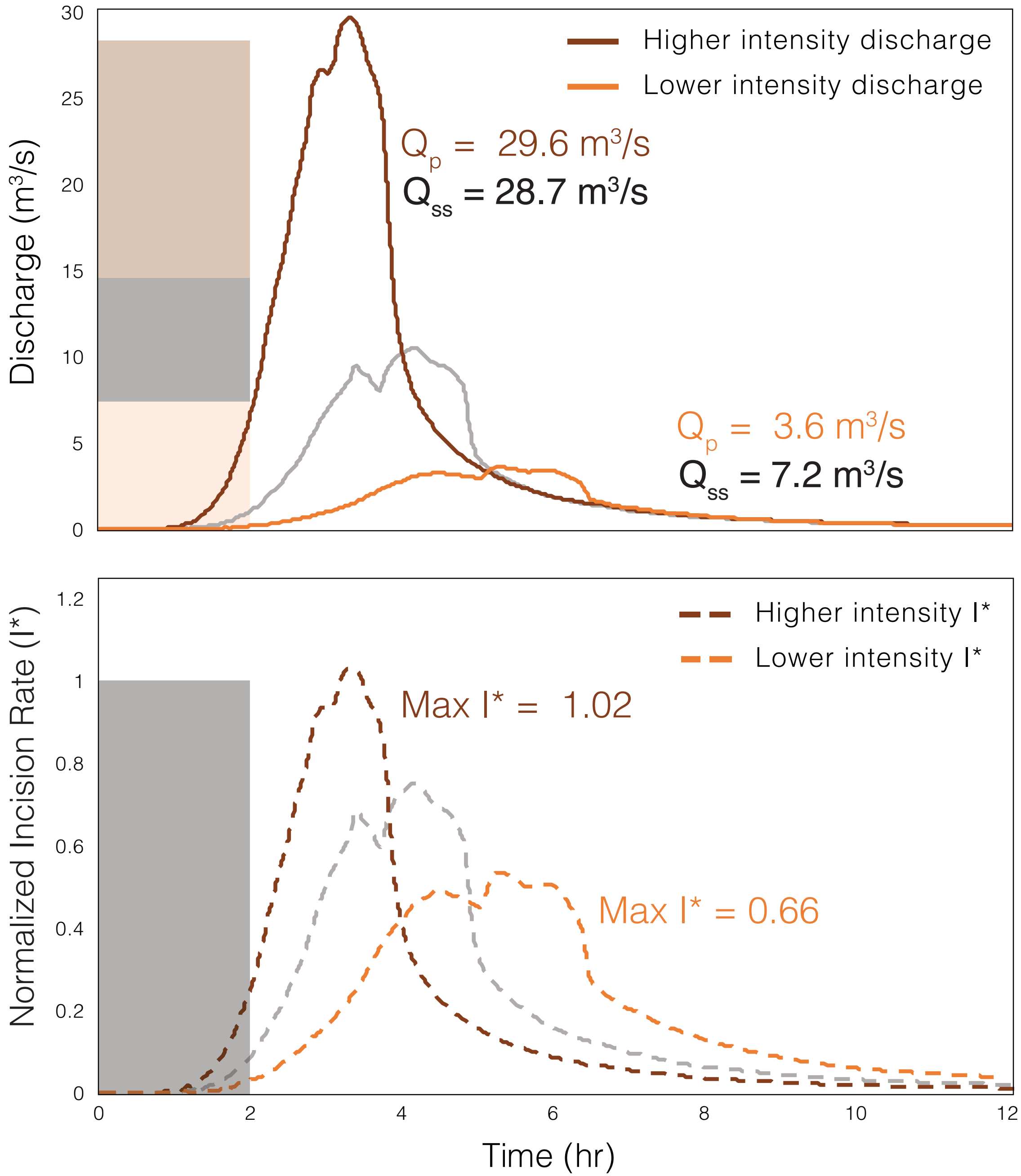
Is steady-state a reasonable assumption for long-term landscape evolution modeling?

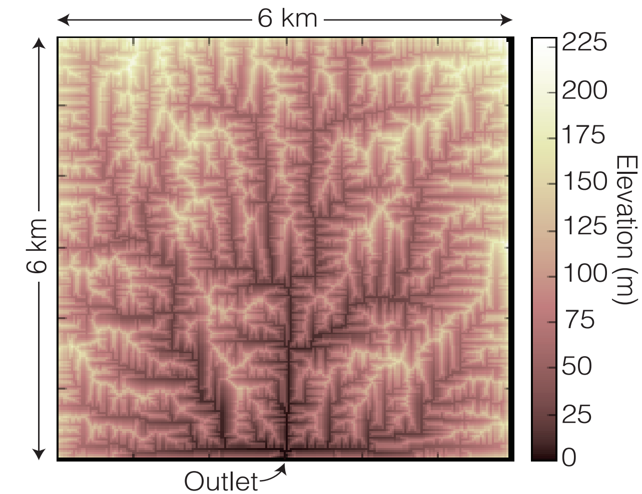
Storm ID	Duration	Intensity
Lower intensity	2 hr	0.74 mm/hr
Average storm	2 hr	1.47 mm/hr
Higher intensity	2 hr	2.94 mm/hr

…changing rainfall intensities?

Potential real world applications of the non-steady hydrologic model.

How does this model behave across different basin shapes?



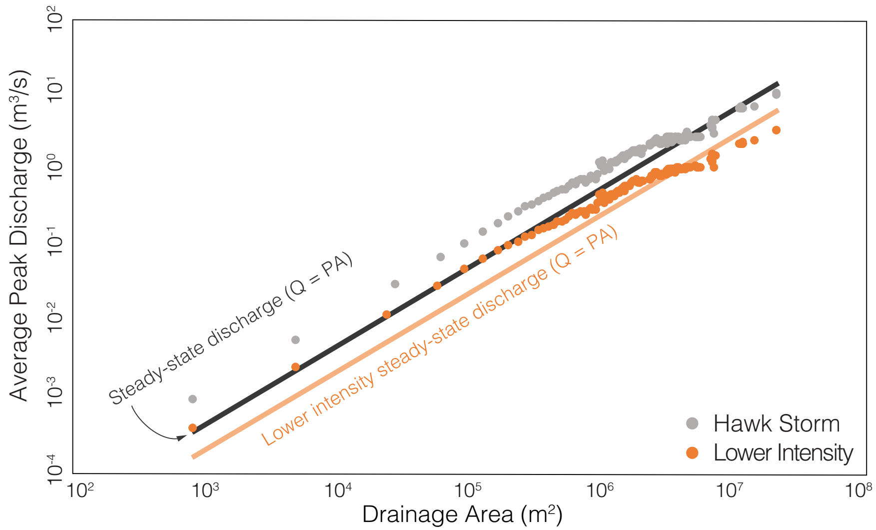


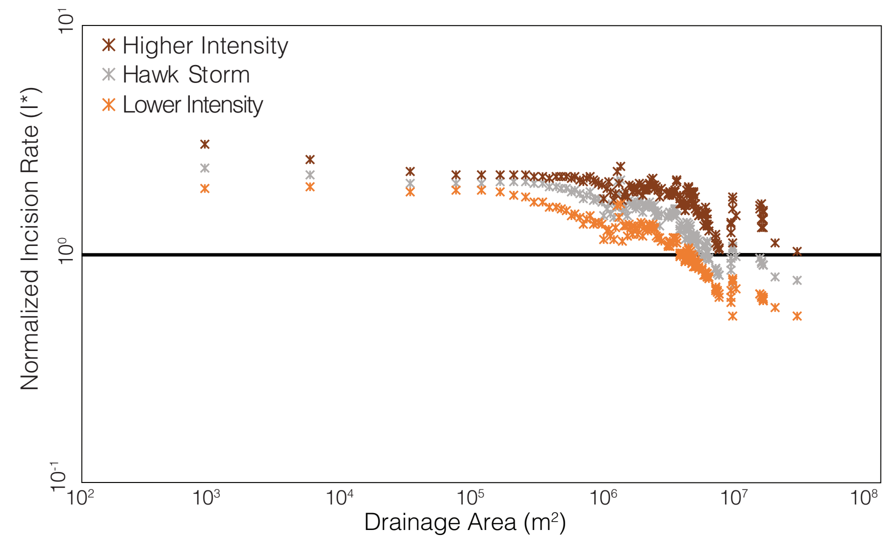
(a) Square basin topography

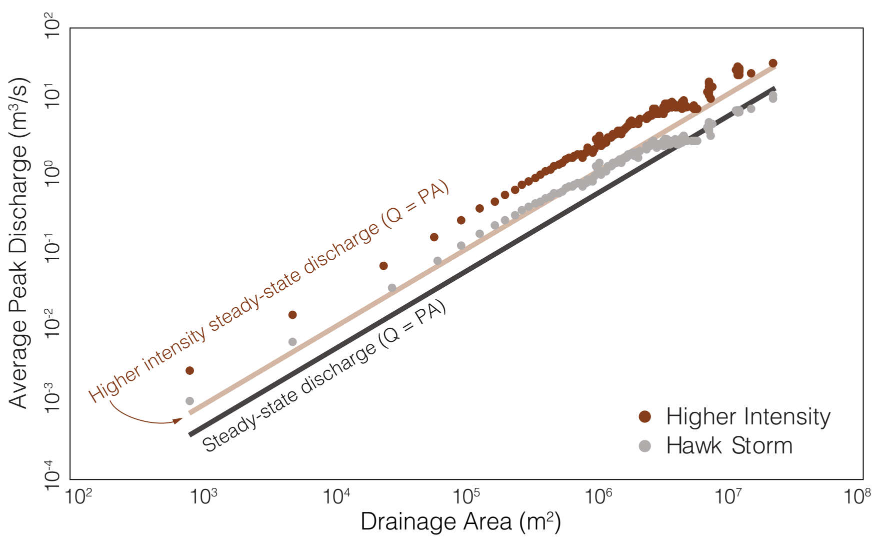
note:

- shift in hydrograph shape
- exceeds steady state in higher intensity case

Do these results scale across changing storm intensity?







note:

- similarities to changing duration runs: shift from low to high drainage areas

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

How do non-steady methods scale across changing rainfall intensity?

- Time to peak discharge inversely related to rainfall intensity
- Higher intensity: exceeds steady-state throughout watershed

Is steady-state a reasonable assumption for long-term landscape evolution modeling?

How does the model behave across different basin shapes?

How do non-steady methods scale across changing rainfall duration?

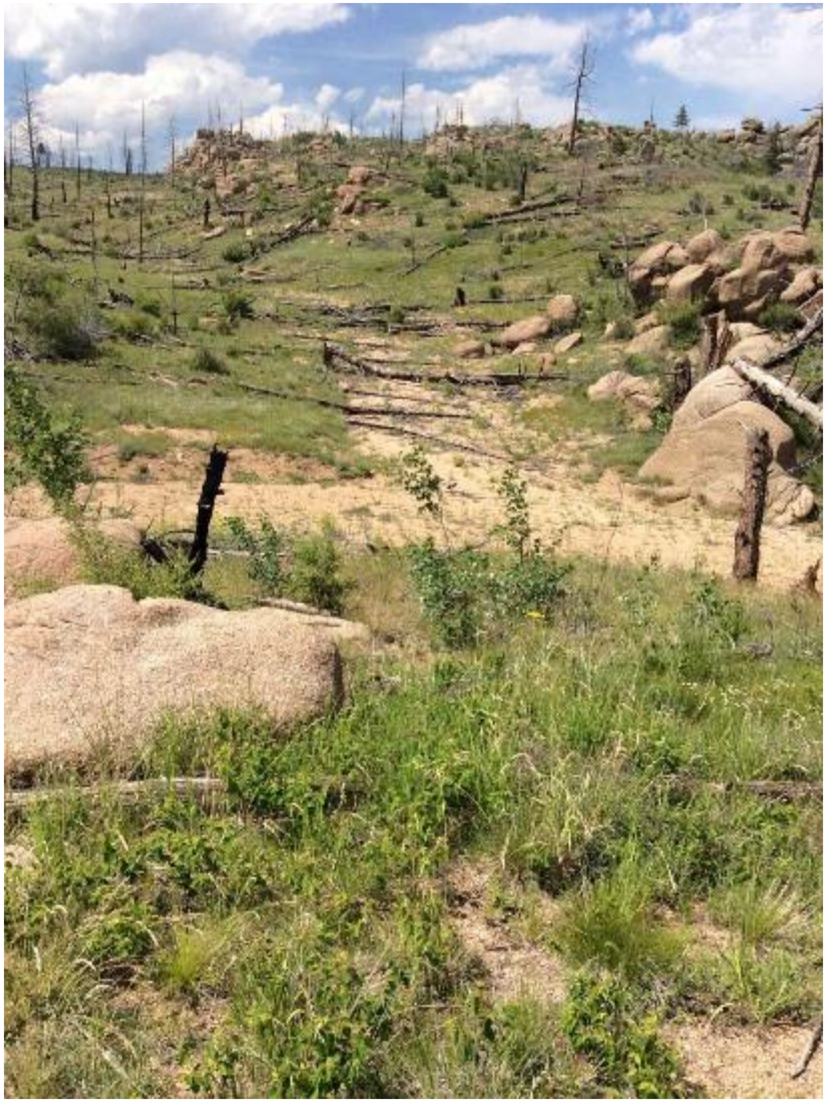
…changing rainfall intensities?

Potential real world applications of the non-steady hydrologic model.

Application in a real world setting: Spring Creek, CO

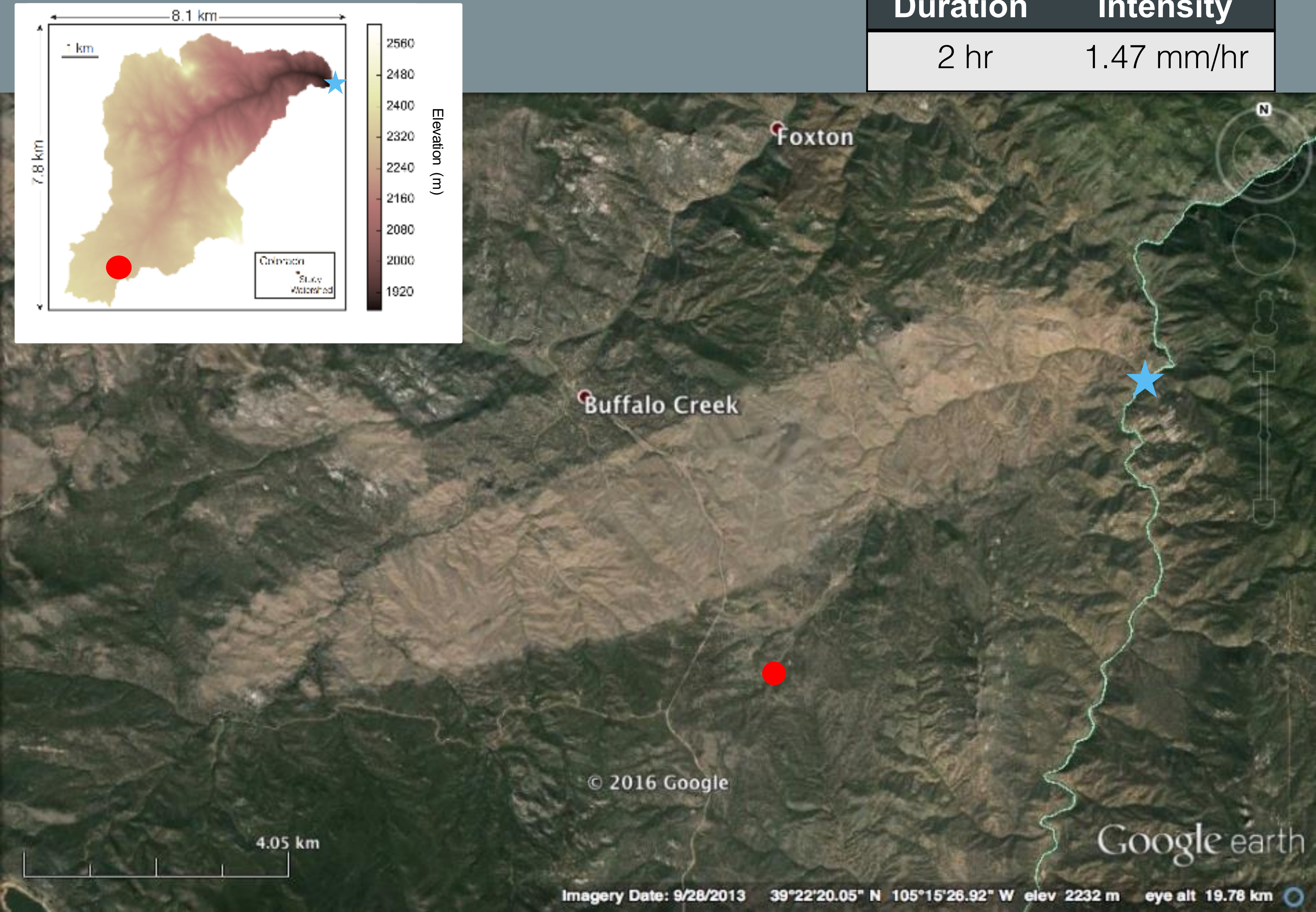
Burned in the 1996 Buffalo Creek Fire

July 12, 1996: 100- to 1000- year recurrence rainfall event



Application in a real world setting: Spring Creek, CO.

Duration	Intensity
2 hr	1.47 mm/hr



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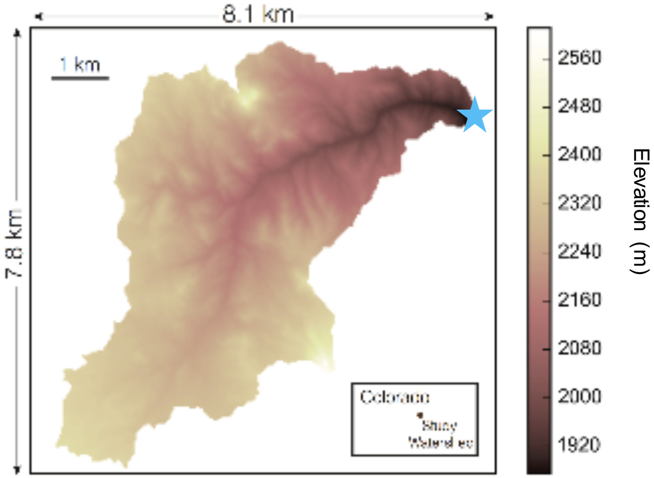

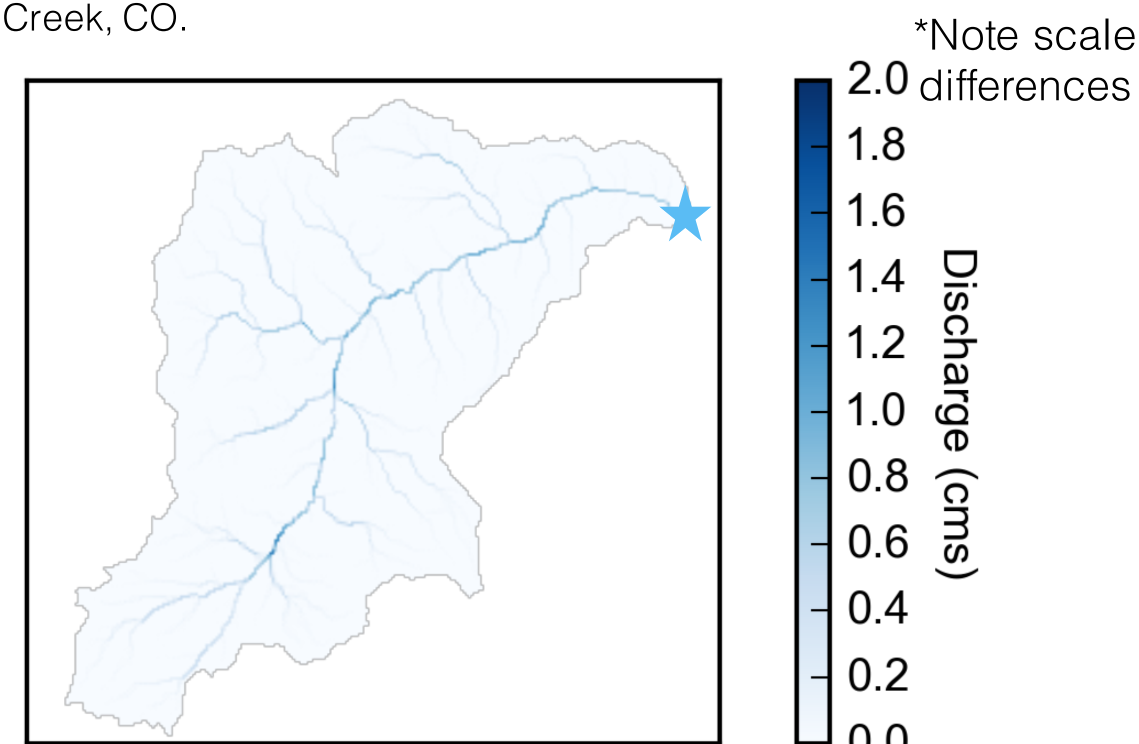

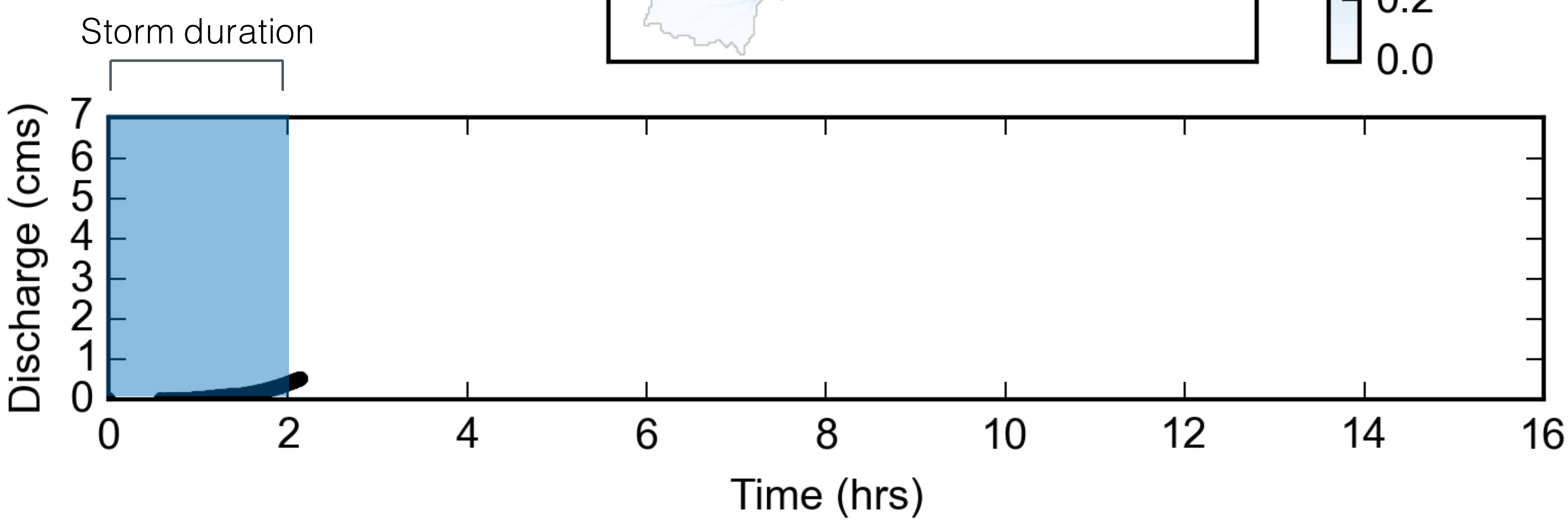

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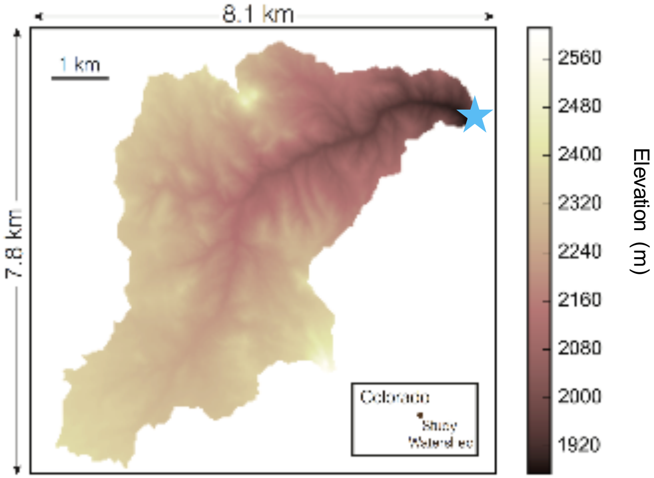
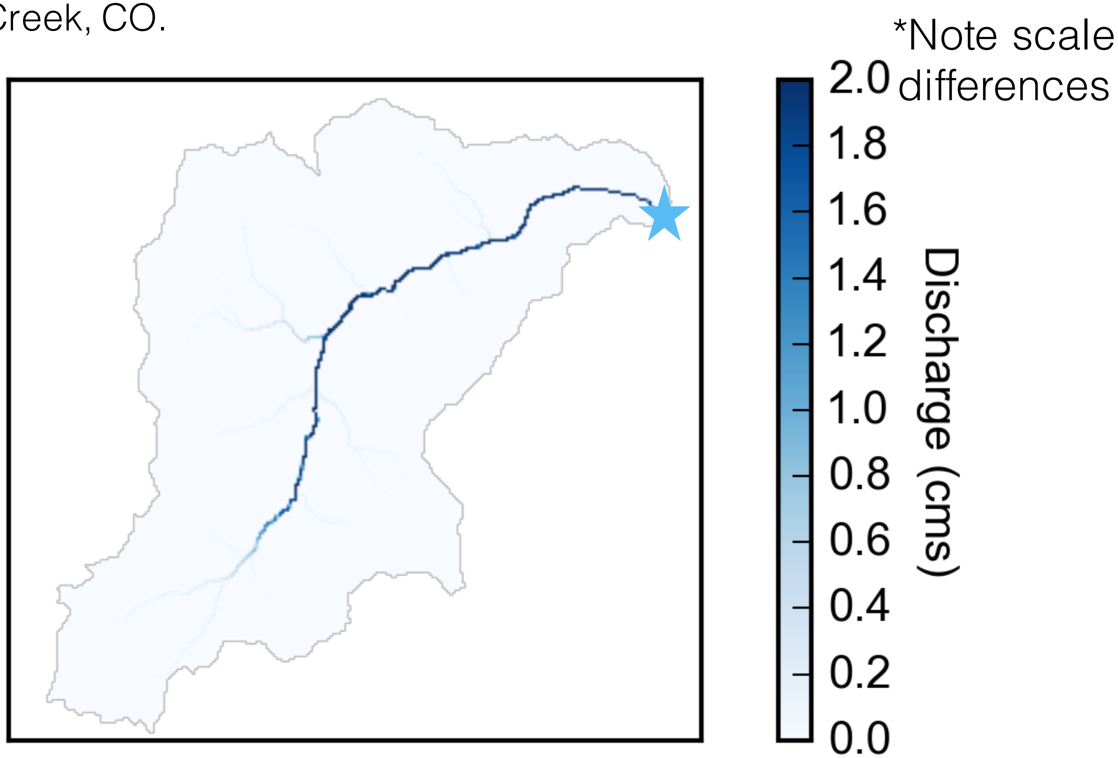
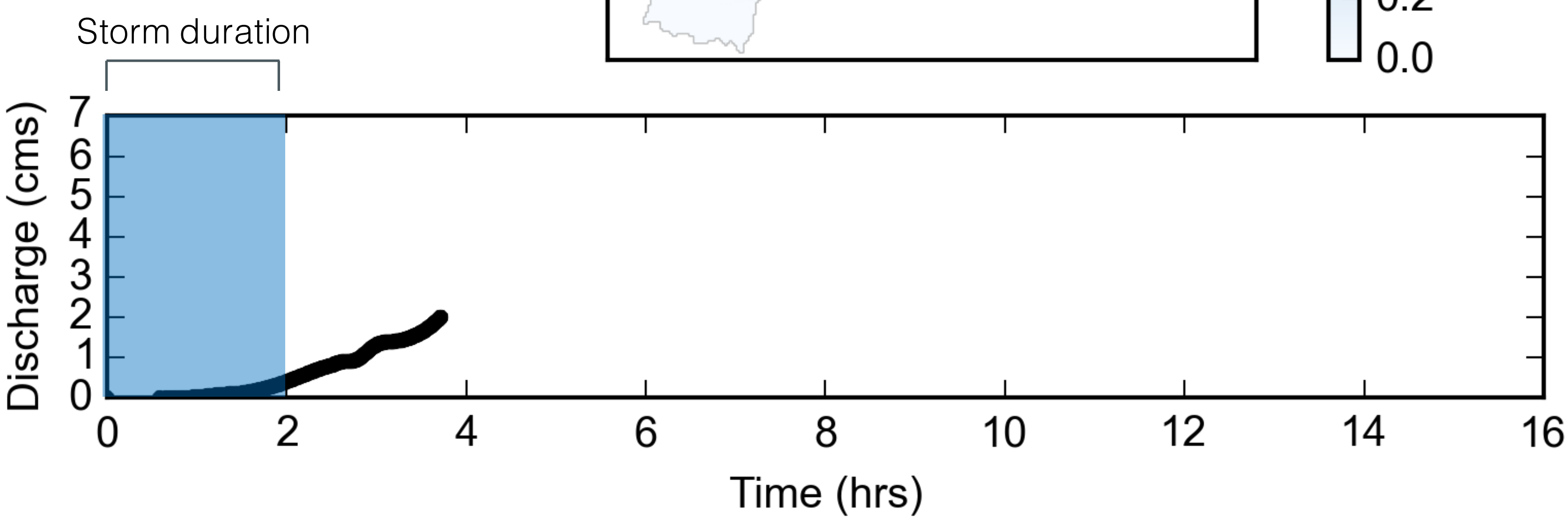
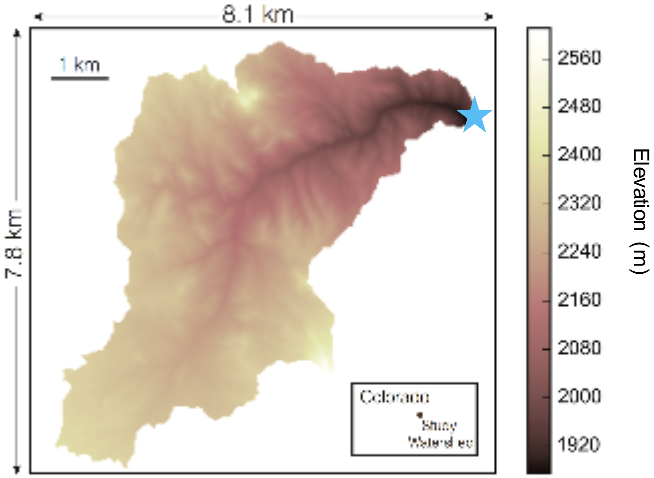


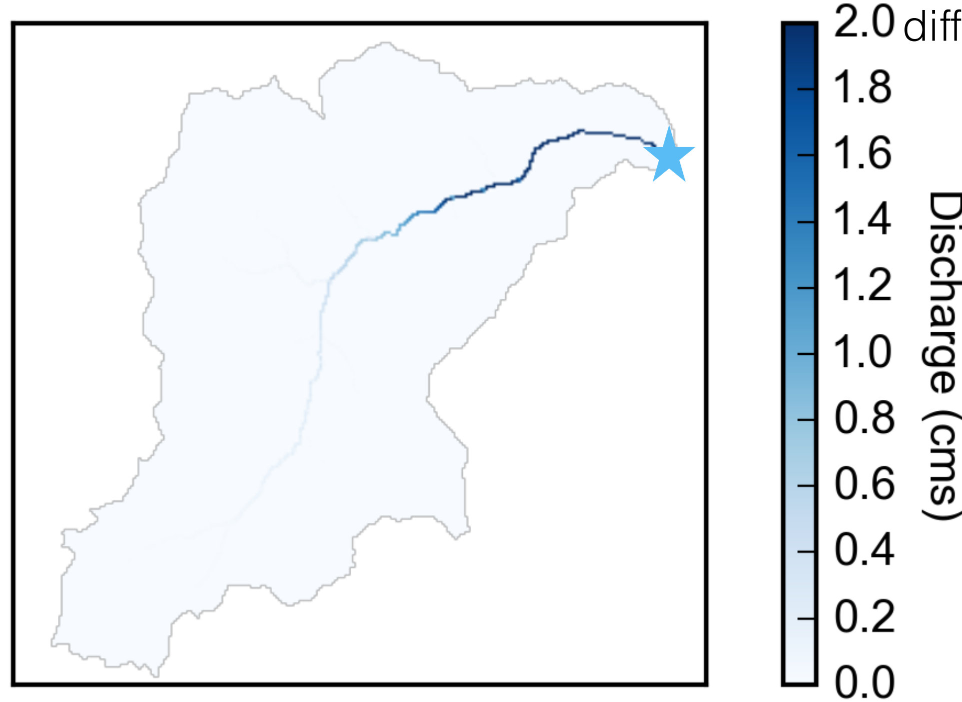


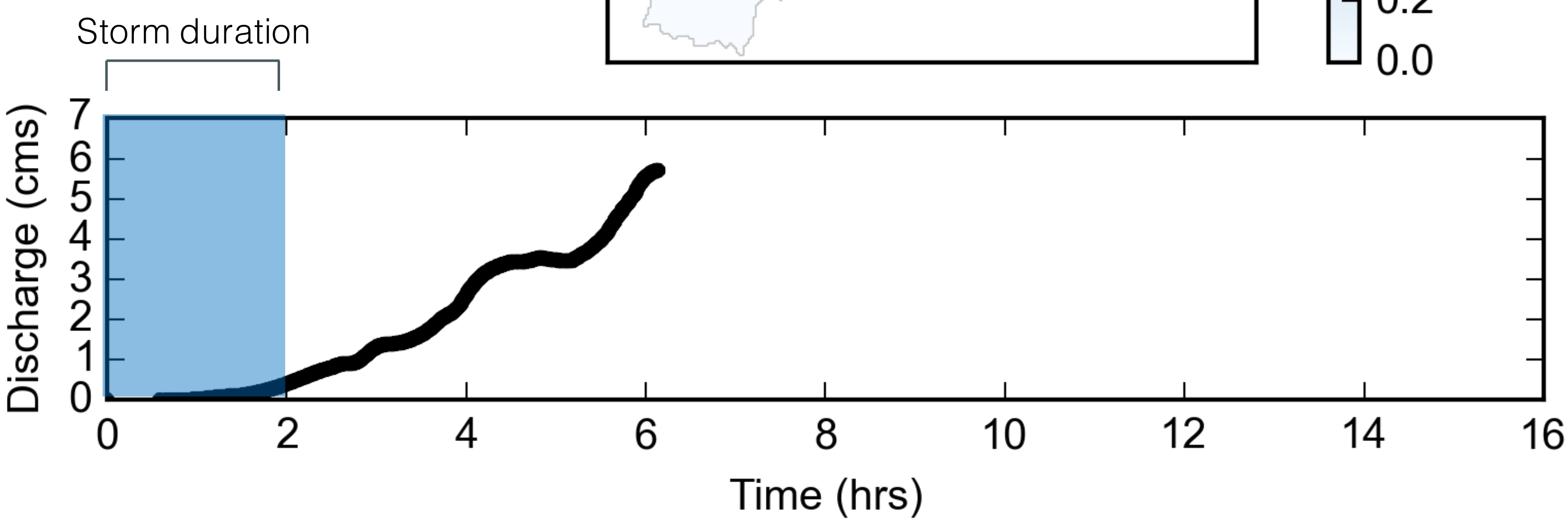


Application in a real world setting: Spring Creek, CO.



*Note scale differences





Application in a real world setting: Spring Creek, CO.

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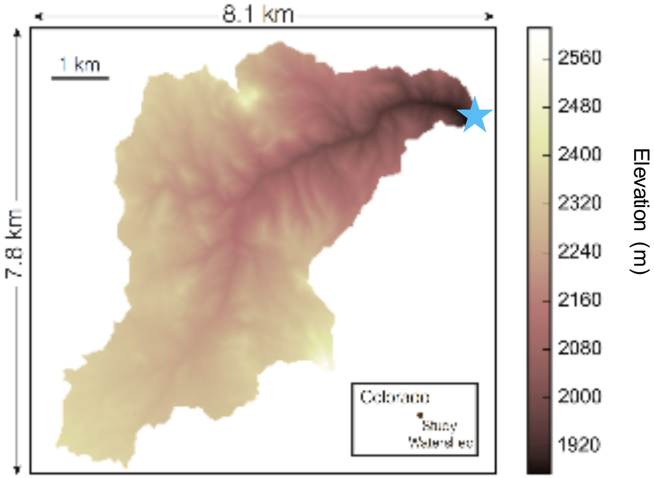

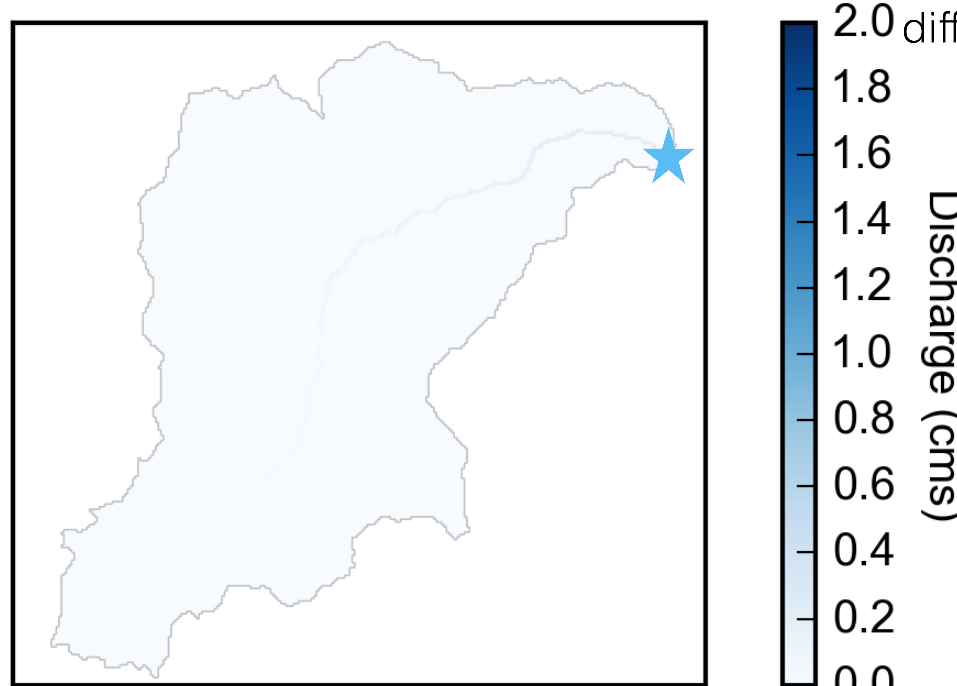

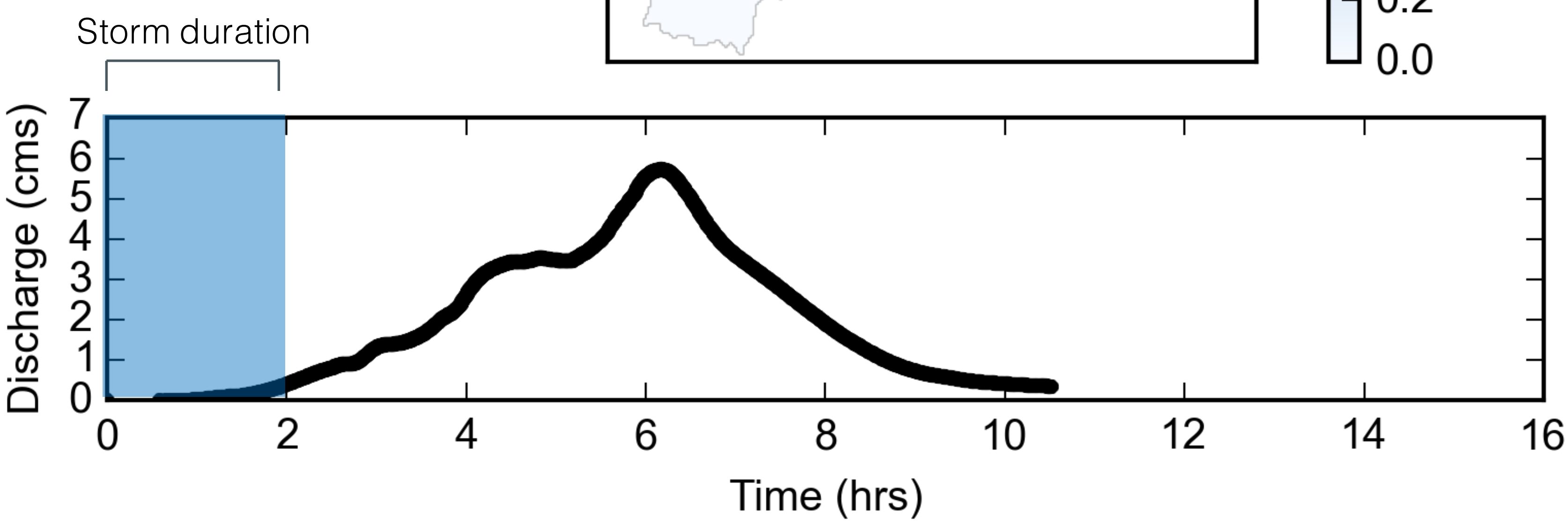

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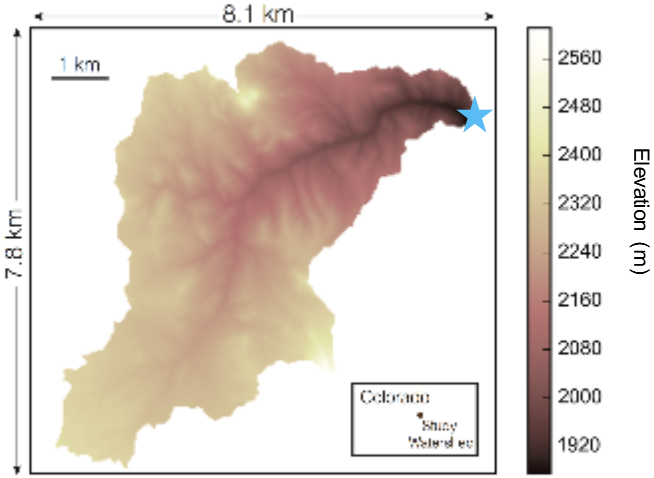

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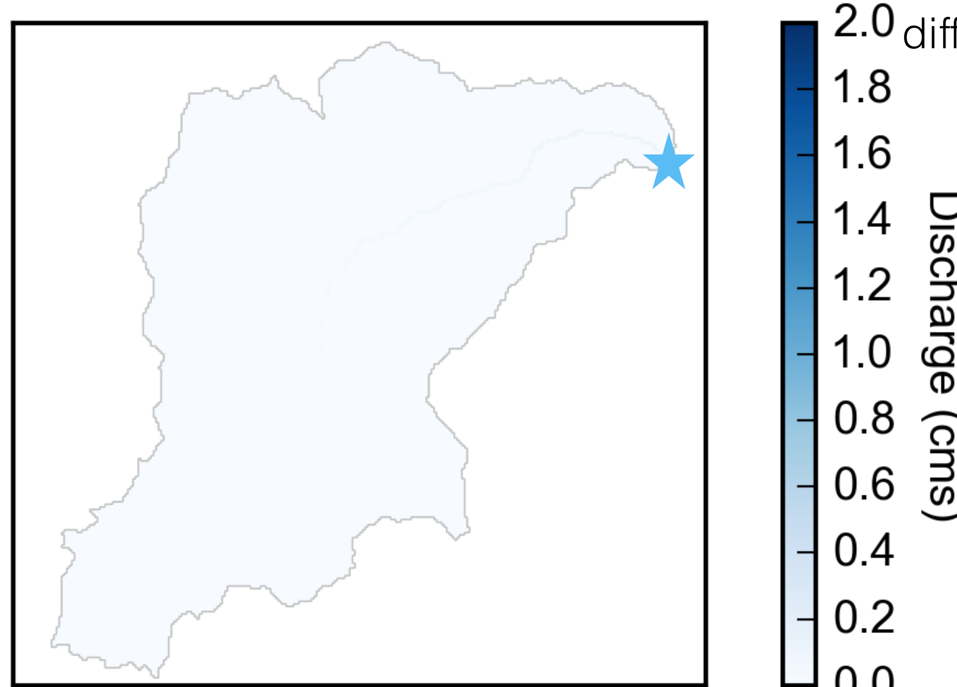

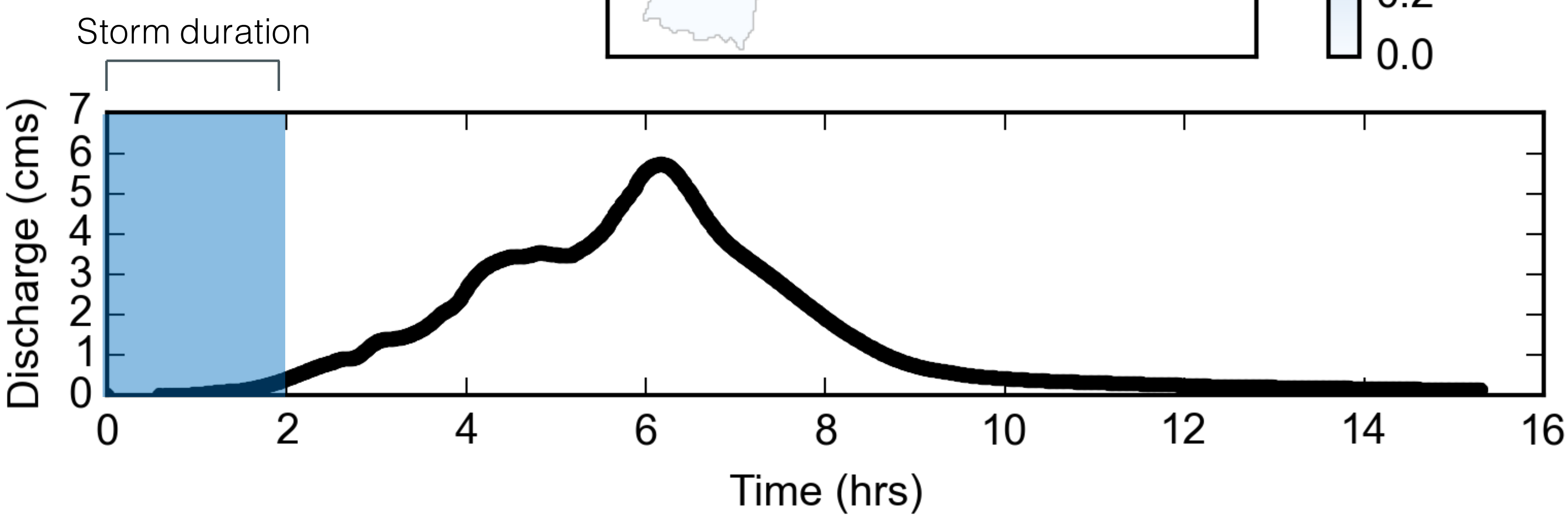

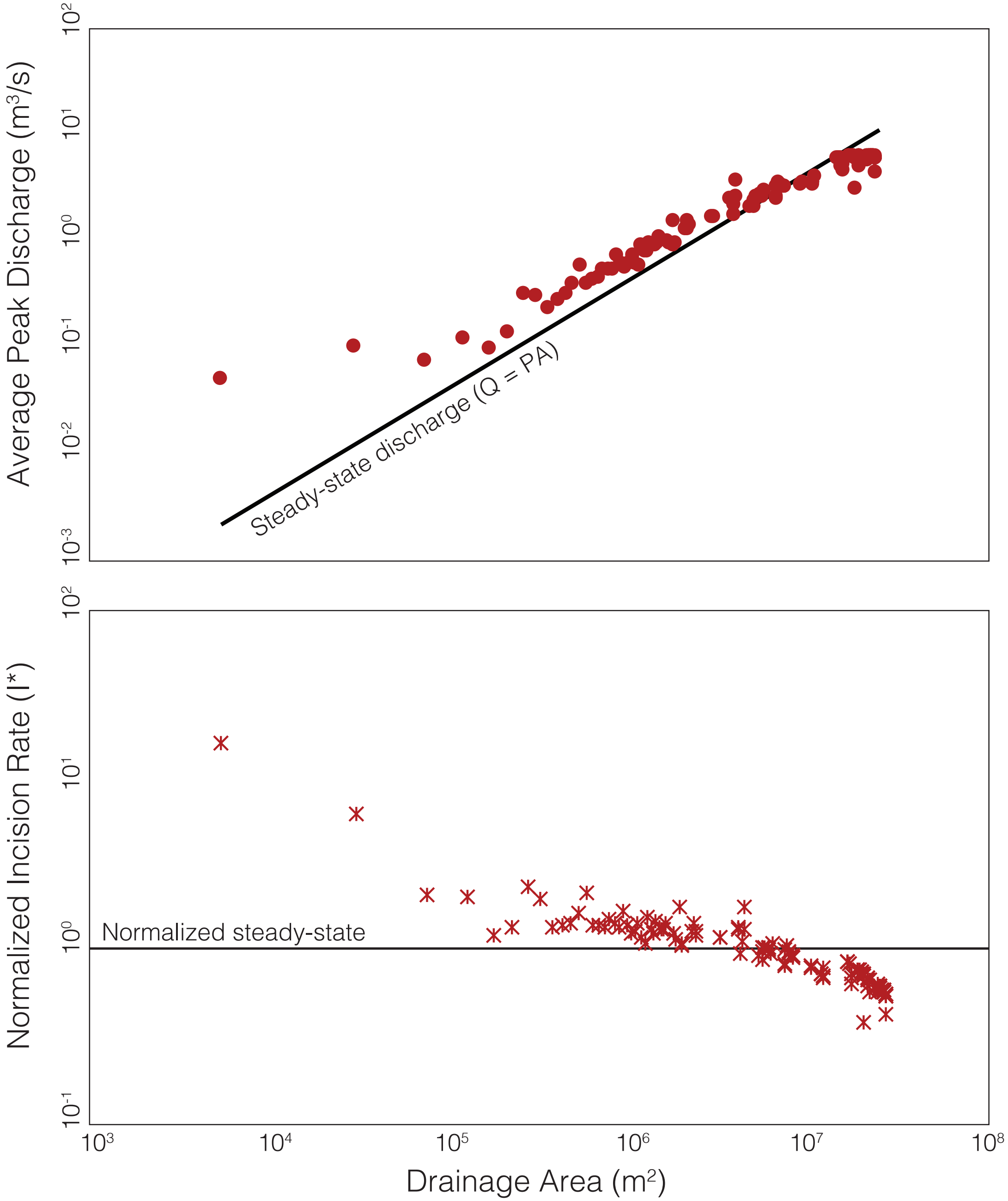

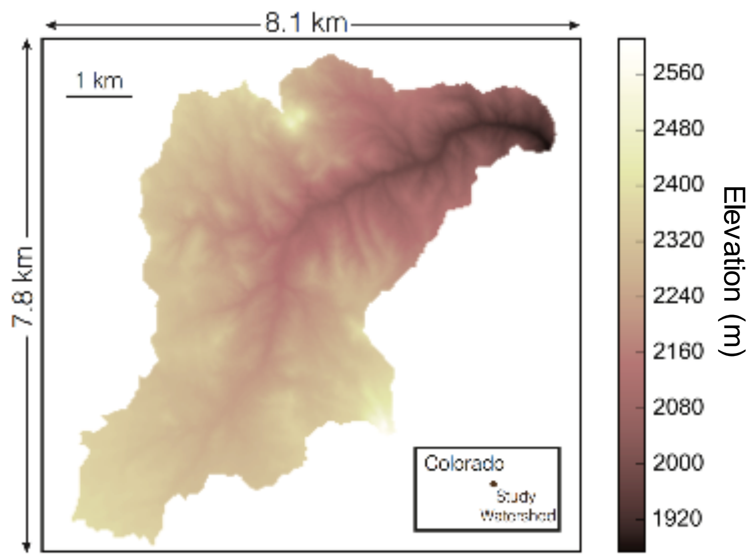

note:

- steep headwaters: imprint on discharge and incision
- ‘small’ test storm – implications for larger flood events?

Conclusions

- Overland flow model is sensitive to differences in basin shape, storm duration and intensity
  - Peak discharge particularly sensitive to rainfall characteristics
- Steady-state hydrology underestimates discharge and incision in steep headwaters in synthetic and natural basins
  - High erosion upstream, lower erosion downstream
- **Choice of hydrologic model in long-term landscape models can have implications for basin evolution**

Questions?

***Landlab disclaimer**: All Landlab functionality described here is in active development. This presentation reflects the Landlab distribution as of Wednesday, April 13, 2016. Please refer to the Landlab documentation for the most up-to-date information.*

[*http://landlab.github.io/#/*](http://landlab.github.io/#/)