

A hydrogeomorphic perspective on emergent topographic properties at landscape equilibrium

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Co-authors:



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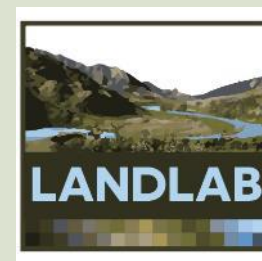


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Funding and Support:

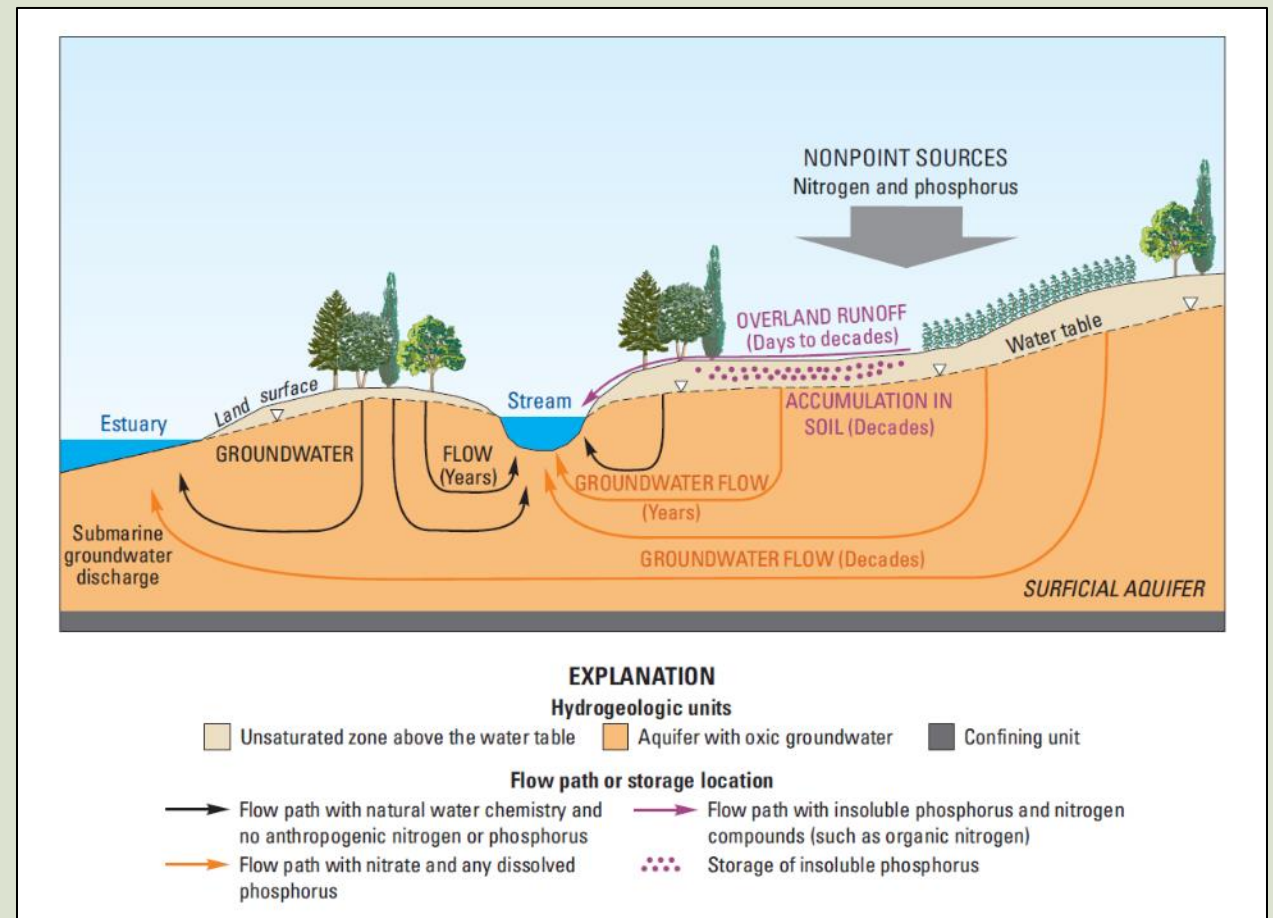


The pathways of water through catchments determine the potential for transport of material downstream

Nutrients, contaminants, carbon, rock-derived compounds, sediment



USGS



USGS

Landscape and climate control runoff generation pathways

Expected runoff generation:

Subsurface storm flow



Surface variable source areas



Infiltration excess overland flow



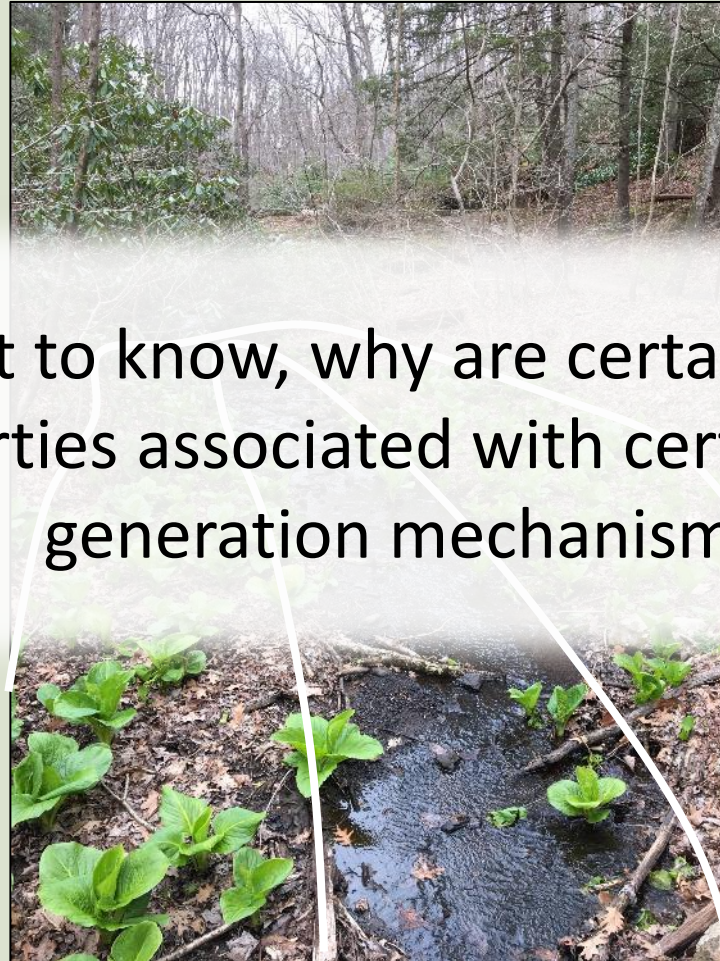
Landscape and climate control runoff generation pathways

Expected runoff generation:

Subsurface storm flow



Surface variable source areas



Infiltration excess overland flow



We want to know, why are certain landscape properties associated with certain runoff generation mechanisms?

At the same time, runoff generation also contributes to landscape organization



Incised channel head in northern CO



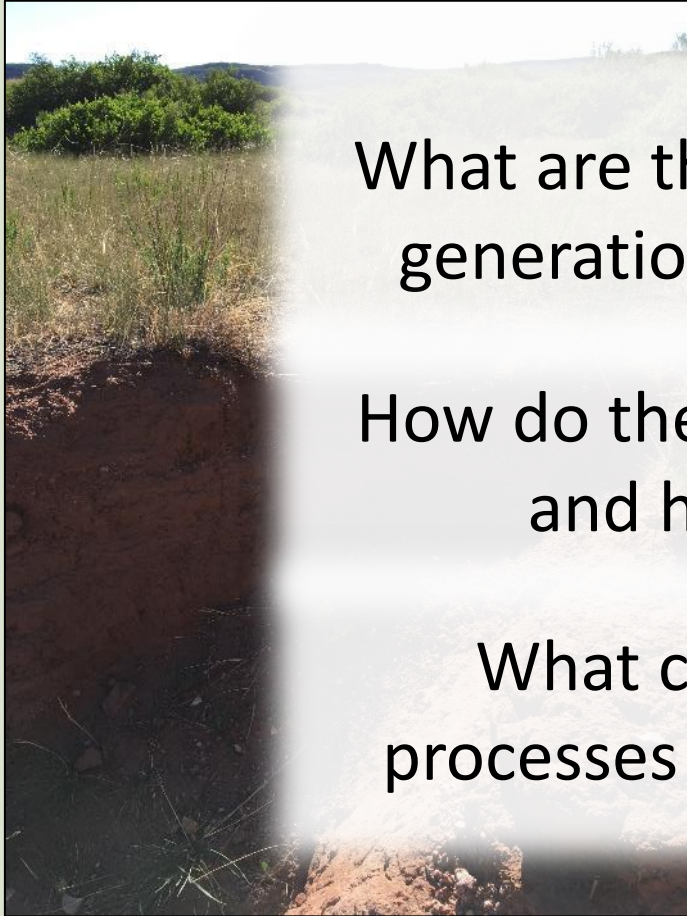
Drainage network with tree-lined riparian areas at Konza Prairie, KS

Here we will explore the following questions:

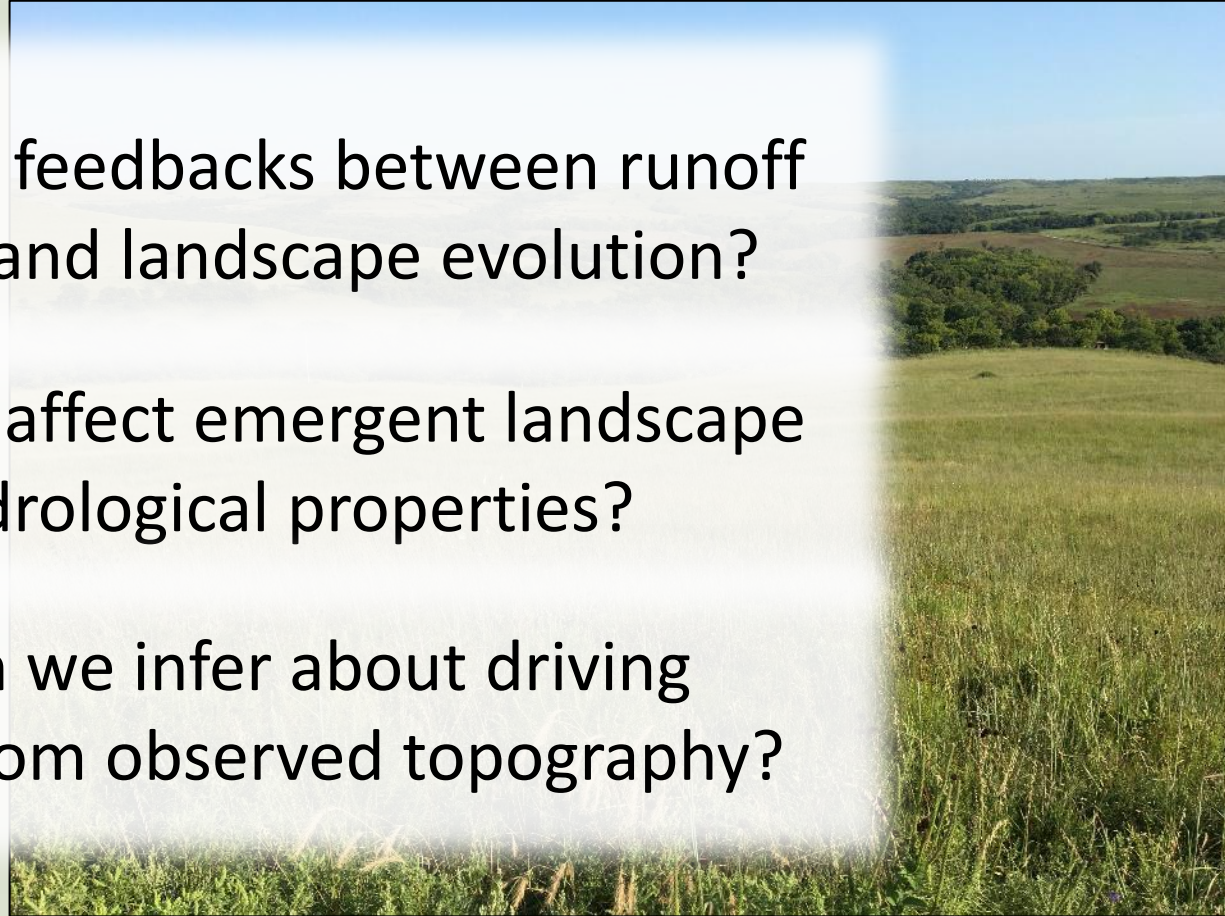
What are the feedbacks between runoff generation and landscape evolution?

How do they affect emergent landscape and hydrological properties?

What can we infer about driving processes from observed topography?

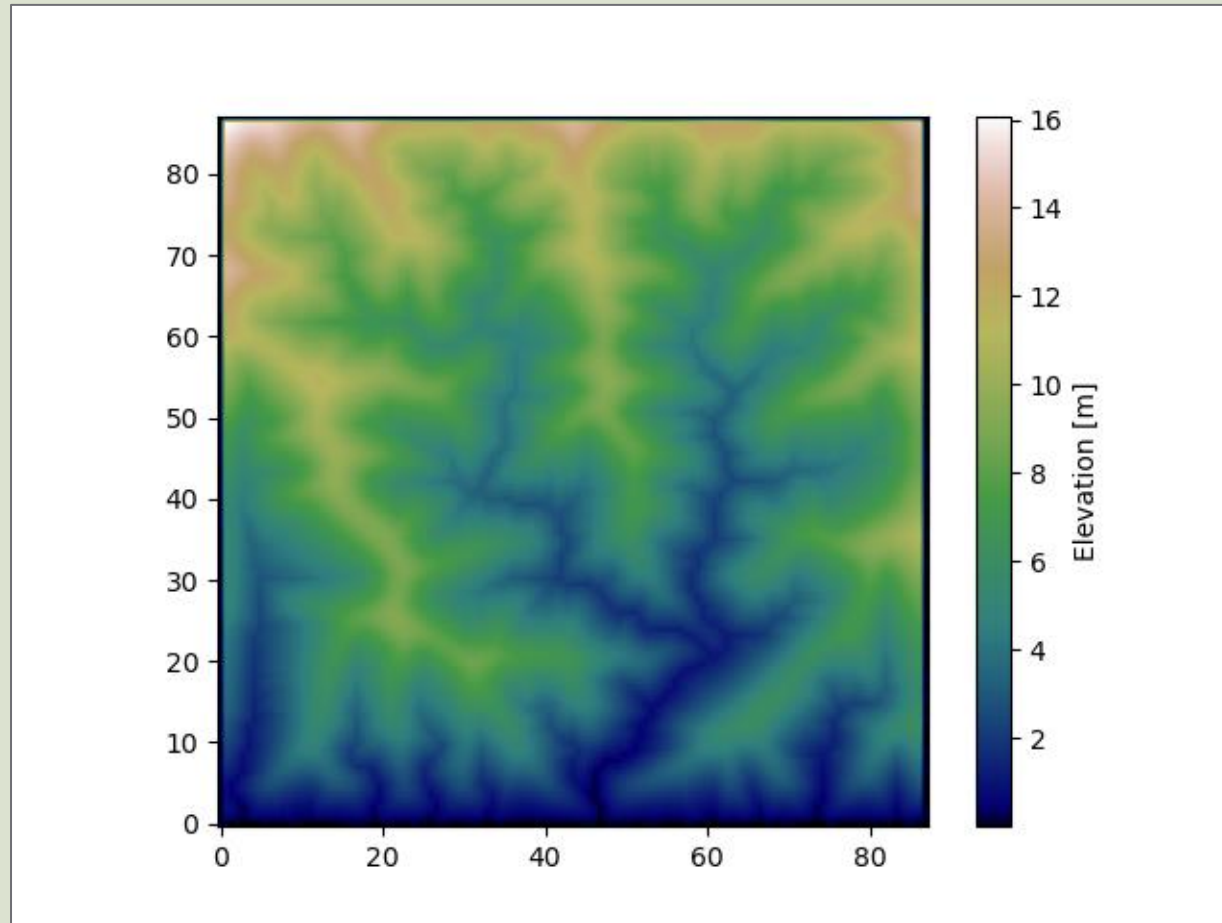


Incised channel head in northern CO



Drainage network with tree-lined riparian areas at Konza Prairie, KS

Landscape evolution models (LEMs) are tools for investigating coevolution



Fluvial and hillslope processes drive the erosional evolution of landscapes

Rate of change of
topographic elevation

$$\frac{\partial z}{\partial t} = -E_f - E_h + U$$

Uplift/Baselevel fall

Fluvial erosion

Hillslope erosion

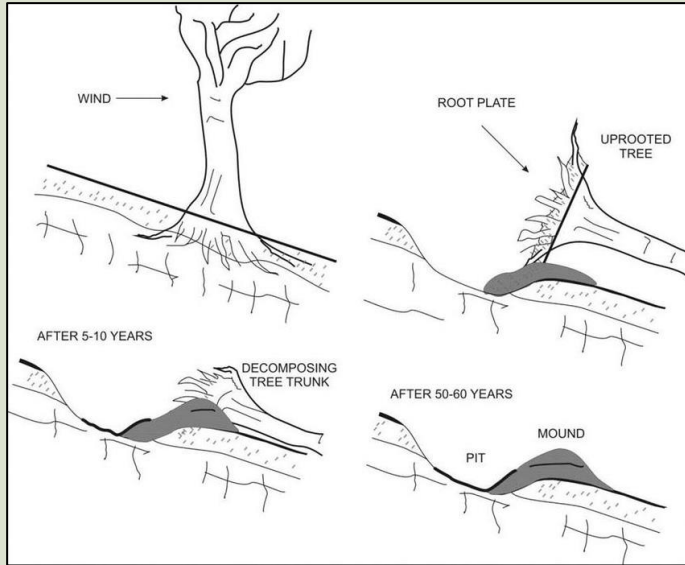


USGS

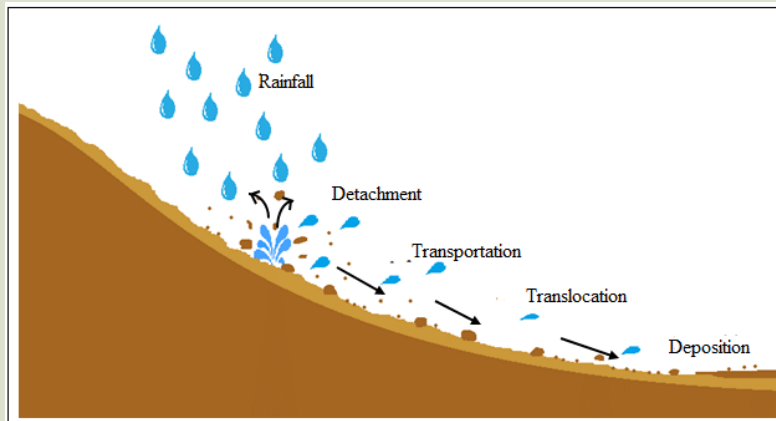


Britannica

Hillslope erosion processes vary with setting, but are often assumed proportional to slope



Erosion by treethrow. Pawlik 2013 Earth Sci. Reviews



Erosion by rainsplash. Zulkifli 2017

Hillslope sediment flux is proportional to slope:

$$q_h = -D \nabla z$$

$$E_h = \nabla \cdot q_h = -D \nabla^2 z$$

$z(x,y,t)$ = elevation

q_h = hillslope sediment flux

D = hillslope diffusivity

E_h = hillslope erosion rate

Streampower erosion law is the most common form in LEMs

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. B8, PAGES 17,661–17,674, AUGUST 10, 1999

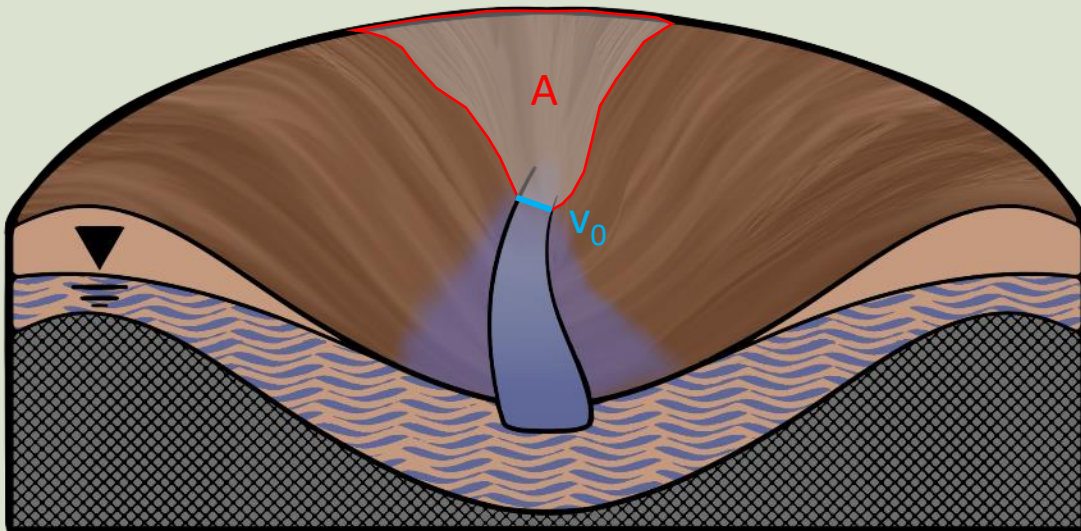
Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs

Kelin X. Whipple

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge

Gregory E. Tucker

Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge



Canonical streampower erosion law:

$$E_f = K A^m |\nabla z|^n$$
$$= K \sqrt{A} |\nabla z|$$

A = upslope area

$|\nabla z|$ = slope

K = streampower coefficient

m, n = power law parameters

*Infers discharge : $Q=f(A)$
We want to calculate Q
explicitly*

Upslope area: the area that drains to a particular point**

$$-\nabla \cdot \left(\frac{A}{v_0} \frac{\nabla z}{|\nabla z|} \right) = 1$$

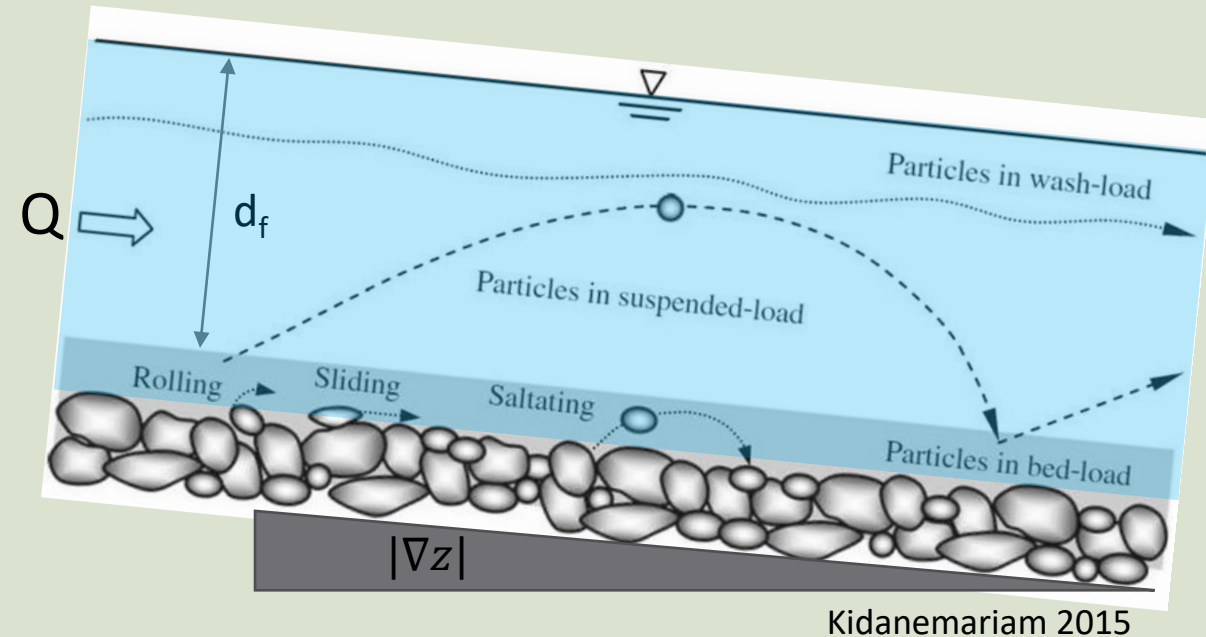
v_0 = unit contour width

Here on we will often use *area per contour width*:

$$a = \frac{A}{v_0}$$

** see Bonetti et al 2020 PNAS

Fluvial erosion derived from bed shear stress



Kidanemariam 2015

$$E_f = k_e (\tau - \tau_c)^\beta$$

Fluvial erosion function of
bed shear stress

$$\tau = \rho_w g d_f |\nabla z|$$

$$d_f = \left(\frac{Q}{C w \sqrt{|\nabla z|}} \right)^{2/3}$$

Flow depth from
constitutive flow equation
(Chezy)

$$w = k_w \sqrt{v_0 a}$$

Channel width function of
area per unit contour width

$$E_f = K \sqrt{v_0} Q^* \sqrt{a} |\nabla z|$$

Fluvial erosion with
dimensionless runoff rate
 $Q^* = Q/(pA)$

τ = shear stress

τ_c = critical shear stress

ρ_w = density of water

g = gravitational acceleration

d_f = flow depth

Q = discharge

w = channel width

v_0 = unit contour width

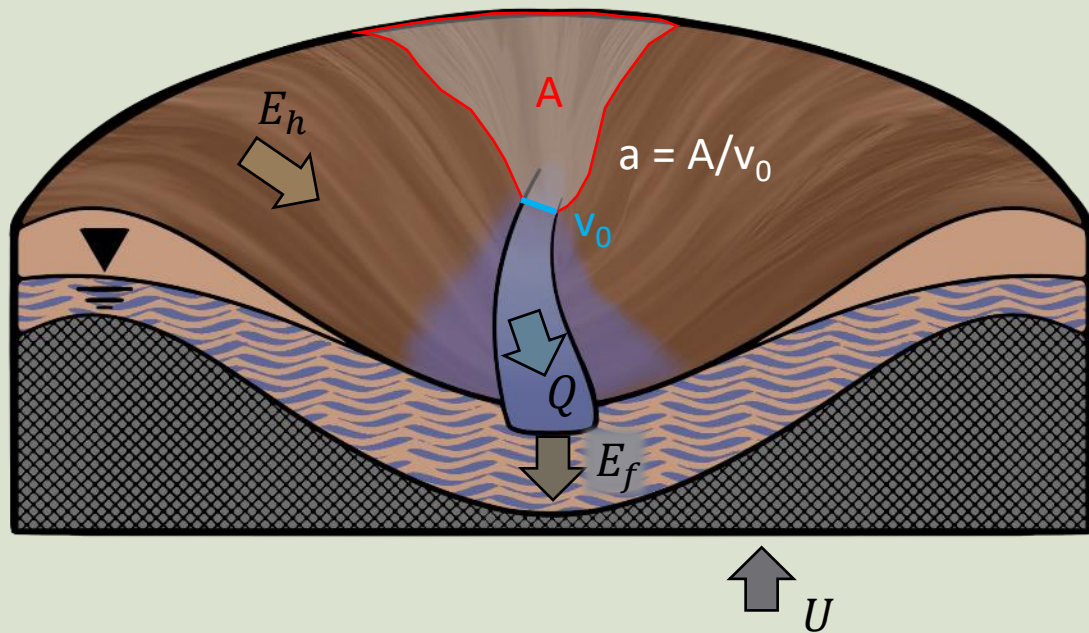
a = area per unit contour width

A = upslope area

p = average precipitation rate

k_e k_w C = erosion, width, and Chezy
coefficients

Modified derivation of the streampower law yields a simple form with explicit runoff



Landscape evolution model

$$\frac{\partial z}{\partial t} = \underbrace{-K \sqrt{v_0} Q^* \sqrt{a} |\nabla z|}_{E_f: \text{Fluvial erosion}} + \underbrace{D \nabla^2 z}_{E_h: \text{Hillslope erosion}} + \underbrace{U}_{\text{Uplift}}$$

$$-\nabla \cdot \left(a \frac{\nabla z}{|\nabla z|} \right) = 1 \quad \text{Area per contour width condition}$$

z = topographic elevation [L]

K = streampower incision coefficient [1/T]

v_0 = unit contour width [L]

Q^* = dimensionless runoff rate [-]

a = area per unit contour width [L]

D = hillslope diffusion coefficient [L²/T]

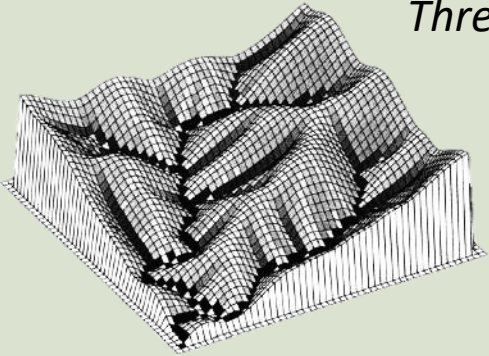
U = Uplift rate [L/T]

How do we find the runoff rate (Q^*)?

Infiltration excess, **steady state**

Threshold rain intensity i_c

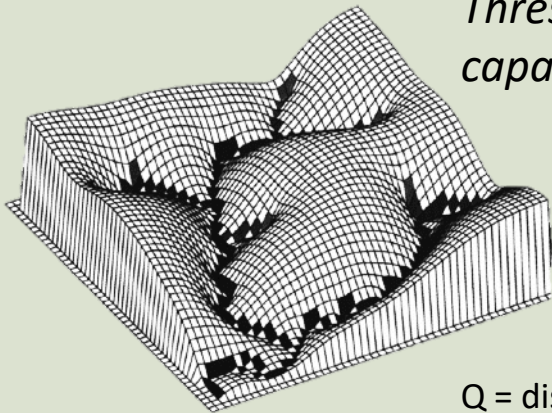
$$Q = (i - i_c)A$$



Saturation excess, **steady state**

Threshold subsurface capacity $k_s b w$

$$Q = iA - k_s b v_0 |\nabla z|$$



Q = discharge

A = catchment area

i = rainfall intensity

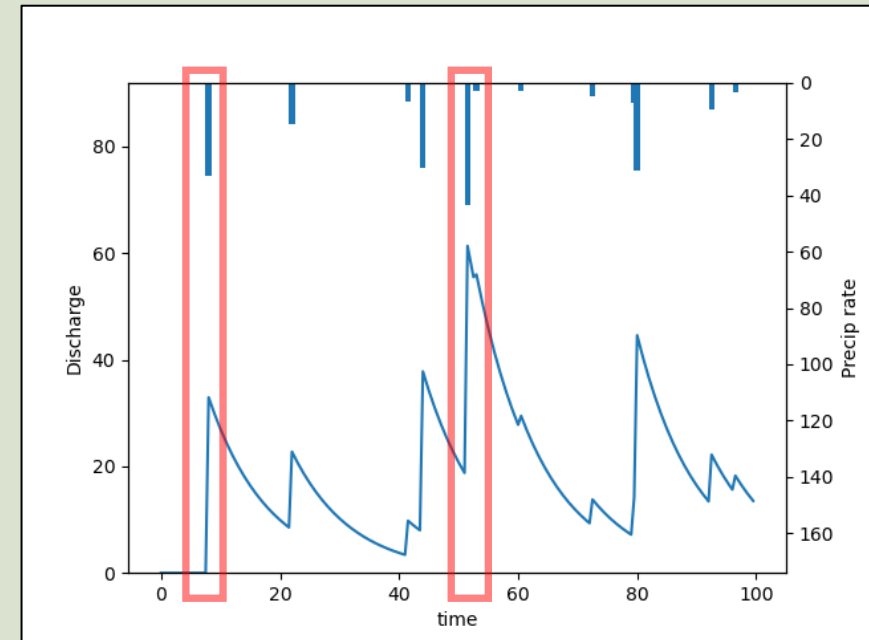
i_c = critical intensity

k_s = hydraulic conductivity

b = permeable thickness

v_0 = unit contour width

... But runoff generation **varies in space and in time** as landscape responds to dynamic weather forcing



Antecedence matters!

Steady state form does not account for nonlinearity of groundwater flow

Couple a dynamic shallow aquifer model

Quasi-3D Boussinesq aquifer model:

$$\frac{\partial h}{\partial t} = \frac{1}{n} \left(i - \nabla \cdot q - q_s \right)$$

Conservation of mass

$$q = -h \cos \theta k_s (\nabla z + \nabla h) \cos \theta$$

Groundwater flux

$$q_s = \mathcal{G} \left(\frac{h}{b} \right) \mathcal{R} \left(i - \nabla \cdot q \right)$$

Local surface runoff

$$Q = \int_A q_s dA$$

Surface water discharge

$h(x, y, t)$ = aquifer thickness [L]

$i(t)$ = recharge/precipitation rate [L/T]

$\theta(x, y)$ = aquifer base angle [rad]

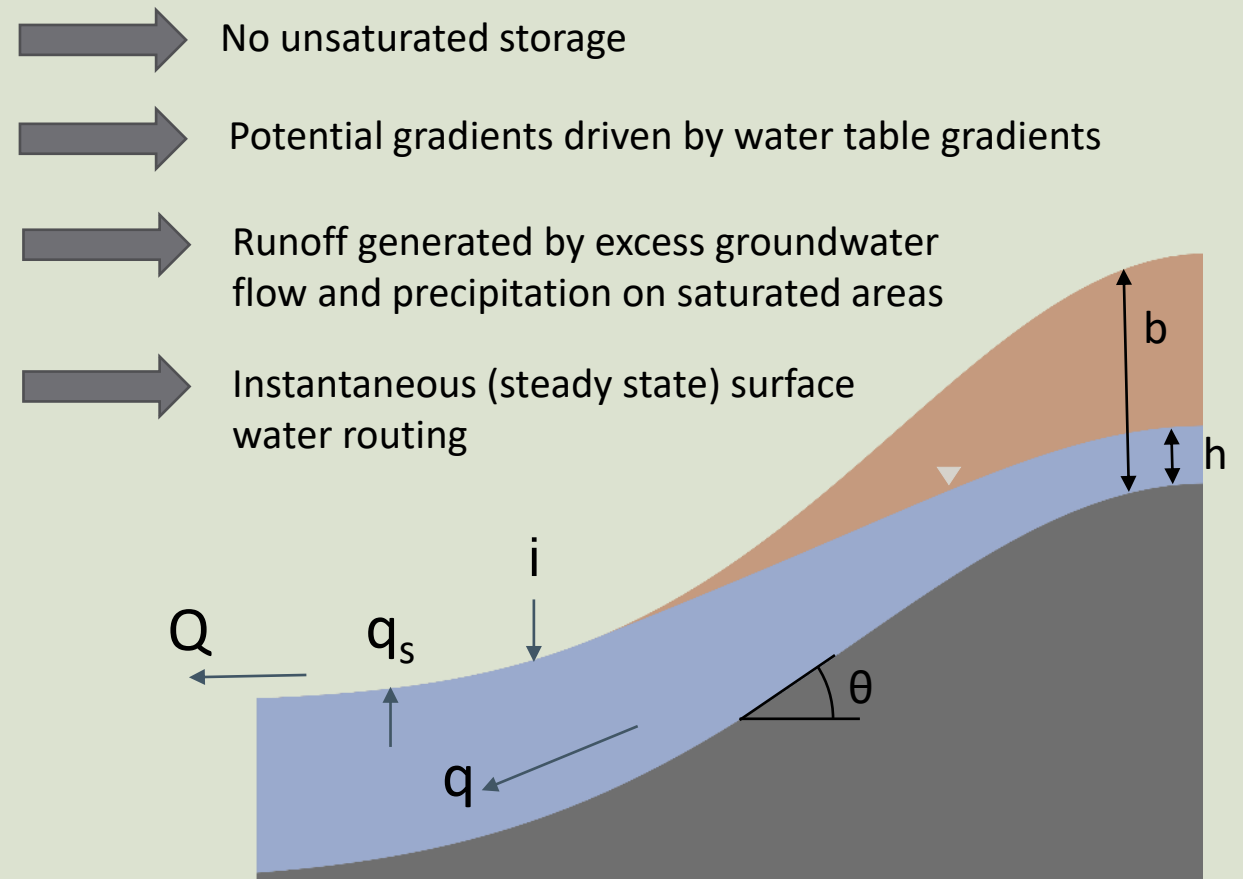
n = porosity [-]

k_s = hydraulic conductivity [L/T]

b = permeable thickness [L]

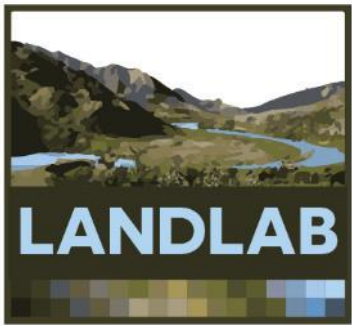
$\mathcal{G}$ = step function

$\mathcal{R}$ = ramp function



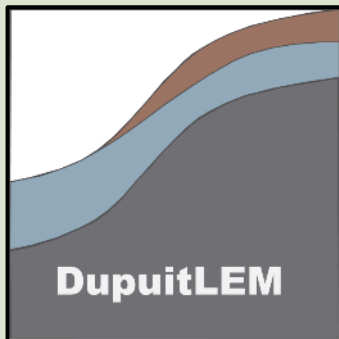
Numerical solution

Grid, solving governing equations, IO



<https://github.com/landlab/landlab>

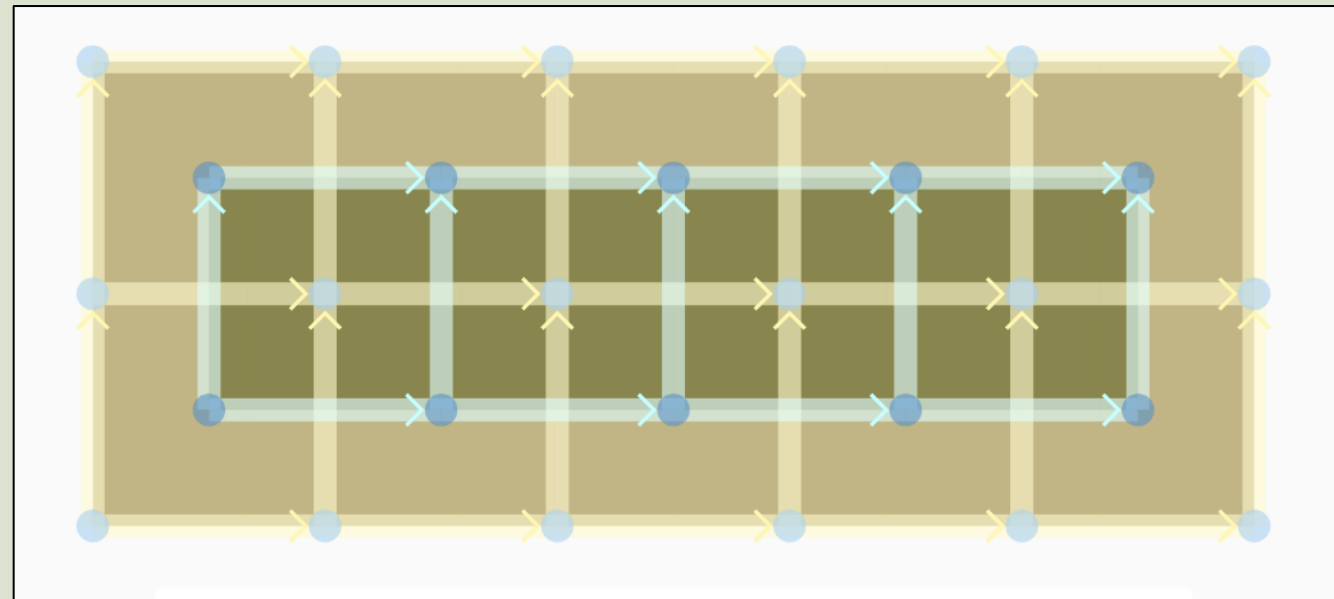
Coupling Landlab components
Handling timescale differences



<https://github.com/DavidLitwin/DupuitLEM>

GroundwaterDupuitPercolator: A Landlab component for groundwater flow

David G. Litwin¹, Gregory E. Tucker^{2, 3, 4}, Katherine R. Barnhart^{2, 3}, and Ciaran J. Harman^{1, 5}



Patches

Links

Nodes

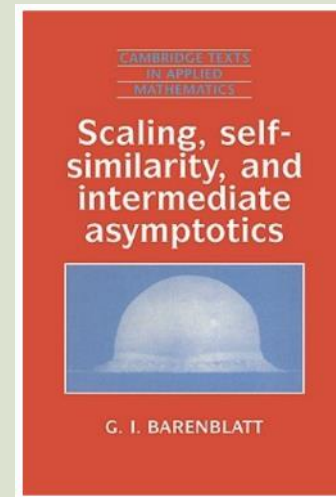
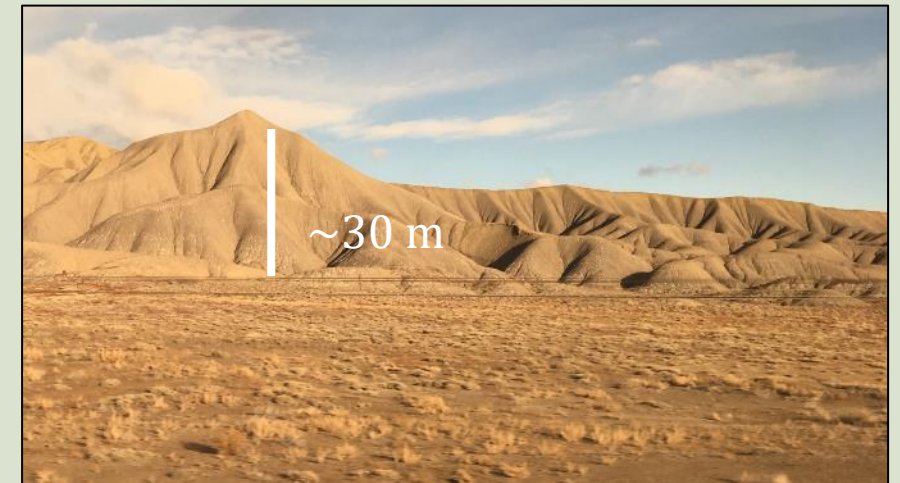
Cells

Faces

Corners

Insight through nondimensionalization

- Ad-hoc approaches to nondimensionalization left many possibilities and lacked clarity
- We use an alternative approach:
 - Re-express parameters in terms of **characteristic scales**
 - Find **symmetry groups**: sets of transformations under which equations are unchanged
 - Use symmetries to **eliminate parameters** and identify dimensionless groups



Derivations ahead! If you would like to see results, skip to slide 26

Characteristic scales: geomorphology

Three characteristic scales: horizontal, vertical, time:

$$h_g, \ell_g, t_g$$

*vertical and horizontal
dimensions scale independently*

Without redefining state variables, we can rewrite in terms of characteristic scales:

$$\frac{\partial z}{\partial t} = -K\sqrt{v_0}Q^*\sqrt{a}|\nabla z| + D\nabla^2 z + U$$



$$\frac{\partial z}{\partial t} = -\frac{\sqrt{\ell_g}}{t_g}Q^*\sqrt{a}|\nabla z| + \frac{\ell_g^2}{t_g}\nabla^2 z + \frac{h_g}{t_g}$$

Solving for the three scales:

$$h_g = \left(\frac{DU^3}{v_0^2 K^4}\right)^{1/3}, \ell_g = \left(\frac{D^2}{v_0 K^2}\right)^{1/3}, t_g = \left(\frac{D}{v_0^2 K^4}\right)^{1/3}$$

Earth Surf. Dynam., 6, 779–808, 2018
https://doi.org/10.5194/esurf-6-779-2018
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the Creative Commons Attribution 4.0 License.



Earth Surface
Dynamics 

Scaling and similarity of a stream-power incision and linear diffusion landscape evolution model

Nikos Theodoratos¹, Hansjörg Seybold¹, and James W. Kirchner^{1,2}

$$-\nabla \cdot \left(a \frac{\nabla z}{|\nabla z|} \right) = 1$$

Characteristic scales: hydrology

Add scales particular to hydrological model:

$$h_c = \frac{p \ell_g}{k_s h_g / \ell_g} \quad \text{Characteristic aquifer thickness}$$

$$t_d = \frac{\ell_g n}{k_s h_g / \ell_g} \quad \text{Characteristic aquifer drainage time}$$

$$p \quad \text{Average recharge rate}$$

WATER RESOURCES RESEARCH, VOL. 45, W01417, doi:10.1029/2008WR007067, 2009

A similarity framework to assess controls on shallow subsurface flow dynamics in hillslopes

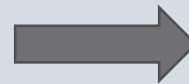
Ciaran Harman¹ and Murugesu Sivapalan^{1,2}

$$\frac{\partial h}{\partial t} = \frac{1}{n} \left(i - \nabla \cdot q - q_s \right)$$

$$q = -h \cos \theta k_s (\nabla z + \nabla h) \cos \theta$$

$$q_s = \mathcal{G} \left(\frac{h}{b} \right) \mathcal{R} \left(i - \nabla \cdot q \right)$$

$$Q = \int_A q_s dA$$



$$\frac{\partial h}{\partial t} = \frac{h_c}{t_d} \left(\frac{i}{p} - \frac{\nabla \cdot q}{p} - \frac{q_s}{p} \right)$$

$$\frac{q}{p} = -h \cos^2(\arctan |\nabla z|) \frac{\ell_g^2}{h_g h_c} (\nabla h + \nabla z)$$

$$\frac{q_s}{p} = \mathcal{G} \left(\frac{h}{b} \right) \mathcal{R} \left(\frac{i}{p} - \frac{\nabla \cdot q}{p} \right)$$

$$Q^* = \frac{1}{A p} \int_A q_s dA_c$$

Identifying symmetries: NoHyd model ($Q^*=1$)

Example: vertical scaling symmetry group

$$\frac{\partial z}{\partial t} = -\frac{\sqrt{\ell_g}}{t_g} \sqrt{a} |\nabla z| + \frac{\ell_g^2}{t_g} \nabla^2 z + \frac{h_g}{t_g}$$

$$-\nabla \cdot \left(a \frac{\nabla z}{|\nabla z|} \right) = 1$$

$$\{z \rightarrow cz, h_g \rightarrow ch_g\} \quad ?$$

$$\frac{\partial(cz)}{\partial t} = -\frac{\sqrt{\ell_g}}{t_g} \sqrt{a} |\nabla(cz)| + \frac{\ell_g^2}{t_g} \nabla^2(cz) + \frac{ch_g}{t_g}$$

$$-\nabla \cdot \left(a \frac{\nabla(cz)}{|\nabla(cz)|} \right) = 1$$

Governing equations for the simpler NoHyd model, where $Q^*=1$ for all (x, y)

Can we apply this transformation (symmetry group), leaving equations unchanged?

Apply transformations in group, all c 's cancel – yes, the transformation worked!



Three symmetry groups of the NoHyd model:

$$\{t \rightarrow ct, t_g \rightarrow ct_g\}$$

$$\{z \rightarrow cz, h_g \rightarrow ch_g\}$$

$$\{x \rightarrow cx, y \rightarrow cy, a \rightarrow ca, l_g \rightarrow cl_g\}$$

- Can be applied in any order
- Any number of times applied
- Any value $c > 0$

Next use symmetries to eliminate parameters

Example: vertical scaling symmetry group

$$\{z \rightarrow z/h_g, h_g \rightarrow 1\}$$

Choose a value $c=1/h_g$ such that the characteristic scale h_g goes to 1, define $z'=z/h_g$

$$\frac{\partial z'}{\partial t} = -\frac{\sqrt{\ell_g}}{t_g} \sqrt{a} |\nabla z'| + \frac{\ell_g^2}{t_g} \nabla^2 z' + \frac{1}{t_g}$$

$$-\nabla \cdot \left(a \frac{\nabla z'}{|\nabla z'|} \right) = 1$$

h_g no longer appears

Use symmetries to eliminate parameters

All symmetries of the NoHyd model:

$$\{t \rightarrow t/t_g, t_g \rightarrow 1\}$$

$$\{z \rightarrow z/h_g, h_g \rightarrow 1\}$$

$$\{x \rightarrow x/\ell_g, y \rightarrow y/\ell_g, a \rightarrow a/\ell_g, \ell_g \rightarrow 1\}$$

Choose scales that eliminate
 h_g, ℓ_g, t_g

$$t' = t/t_g, z' = z/h_g, x' = x/\ell_g$$

$$y' = y/\ell_g, \nabla' = \nabla \ell_g, a' = a/\ell_g$$

Define rescaled variables

$$\frac{\partial z'}{\partial t'} = -\sqrt{a'} |\nabla' z'| + \nabla'^2 z' + 1$$

$$-\nabla' \cdot \left(a' \frac{\nabla' z'}{|\nabla' z'|} \right) = 1$$

Apply symmetry groups and
rescaled variable definitions.

No parameters!

*This implies model has one
“typology”: all realizations are
rescaled versions of the same
landscape.*

Application to the DupuitLEM model

DupuitLEM equations with characteristic scales:

$$\frac{\partial z}{\partial t} = -\frac{\sqrt{\ell_g}}{t_g} Q^* \sqrt{a} |\nabla z| + \frac{\ell_g^2}{t_g} \nabla^2 z + \frac{h_g}{t_g}$$

$$-\nabla \cdot \left(a \frac{\nabla z}{|\nabla z|} \right) = 1$$

$$\frac{\partial h}{\partial t} = \frac{h_c}{t_d} \left(\frac{i}{p} - \frac{\nabla \cdot q}{p} - \frac{q_s}{p} \right)$$

$$\frac{q}{p} = -h \cos^2(\arctan |\nabla z|) \frac{\ell_g^2}{h_g h_c} (\nabla h + \nabla z)$$

$$\frac{q_s}{p} = \mathcal{G} \left(\frac{h}{b} \right) \mathcal{R} \left(\frac{i}{p} - \frac{\nabla \cdot q}{p} \right)$$

$$Q^* = \frac{1}{Ap} \int_A q_s dA_c$$

All symmetries of the full model:

$$\{t \rightarrow ct, t_g \rightarrow ct_g, t_d \rightarrow ct_d\}$$

$$\{x \rightarrow cx, y \rightarrow cy, a \rightarrow ca,$$

$$A \rightarrow c^2 A, l_g \rightarrow cl_g, q \rightarrow cq,$$

$$z \rightarrow cz, h \rightarrow ch, h_g \rightarrow ch_g,$$

$$h_c \rightarrow ch_c, b \rightarrow cb\}$$

$$c = 1/(t_g t_d)$$

$$c = 1/(\ell_g h_g h_c)$$

$$h = h' h_c, i = i' p$$

$$q = q' p \ell_g, q_s = q'_s p$$

This time, only two symmetry groups! **You cannot independently scale vertical and horizontal dimensions in the full coupled model**

Choose c values for the transformations above

Definitions for dimensionless hydrological parameters

Dimensionless equations and parameter groups

Dimensionless DupuitLEM equations

$$\frac{\partial z'}{\partial t'} = -Q^* \sqrt{a'} |\nabla' z'| + \nabla'^2 z' + 1$$

$$- \nabla' \cdot \left(a' \frac{\nabla' z'}{|\nabla' z'|} \right) = 1$$

$$\frac{\partial h'}{\partial t} \frac{t_d}{t_g} = i' - \nabla' \cdot q' - q'_s$$

$$q' = -h' \cos^2(\arctan |\nabla' z' h_g / \ell_g|) \left(\nabla' h' \frac{h_c}{h_g} + \nabla' z' \right)$$

$$q'_s = \mathcal{G} \left(h' \frac{h_c}{b} \right) \mathcal{R} \left(i' - \nabla' \cdot q' \right)$$

$$Q^* = \frac{1}{A'} \int_{A'} q'_s dA'$$

Multiple “typologies”: cannot rescale to get all others

Dimensionless parameter groups that remain

$$\gamma = \frac{b}{h_c} = \frac{b k_s h_g}{p \ell_g^2} = \frac{b k_s U}{p D}$$

Drainage capacity index

$$\text{Hi} = \frac{h_g}{h_c} = \frac{k_s}{p \ell_g^2} = \frac{k_s U^2}{p v_0^{2/3} D^{2/3} K^{4/3}}$$

Hillslope number**

$$\alpha = \frac{h_g}{\ell_g} = \frac{U}{v_0^{1/3} D^{1/3} K^{2/3}}$$

Characteristic gradient

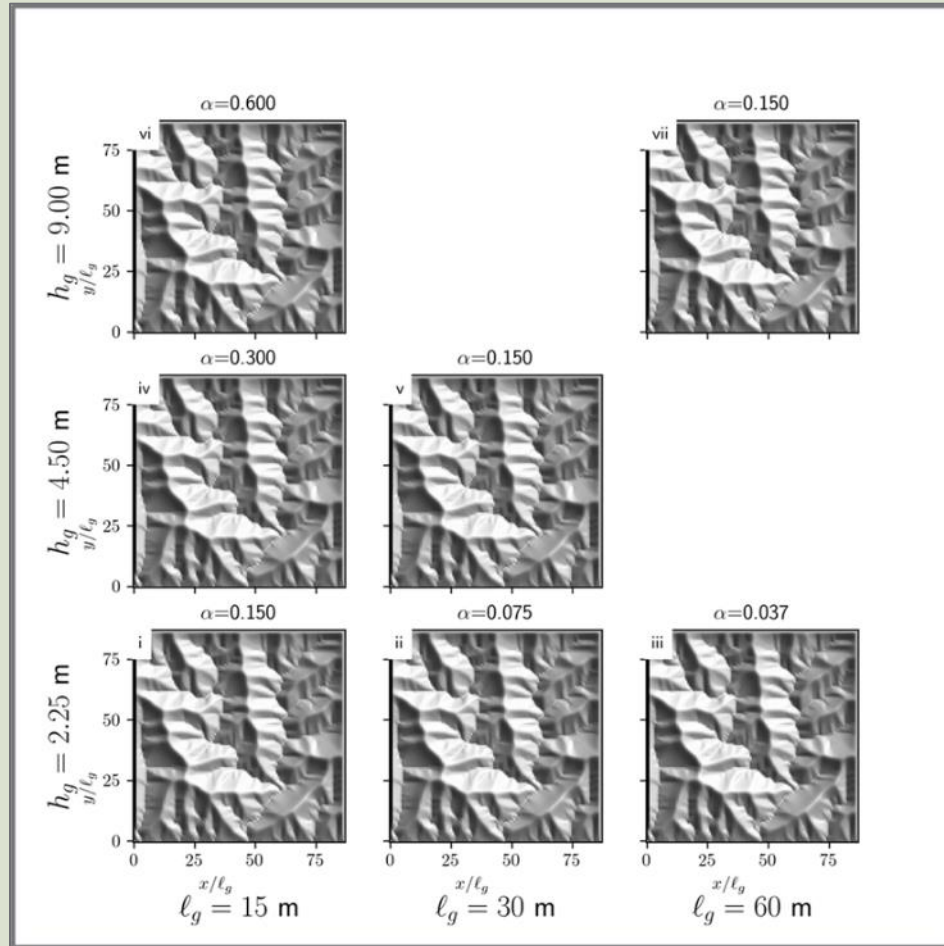
$$\delta = \frac{t_d}{t_g} = \frac{n v_0^{2/3} D^{2/3} K^{4/3}}{k_s U}$$

Timescale index

** Analogous to the hillslope number Hi (see Brutsaert 2005 *Intro to Hydrology*). It is a sort of Peclet number, capturing the relative importance of topographic gradients versus diffusion of the water table in driving groundwater flow.

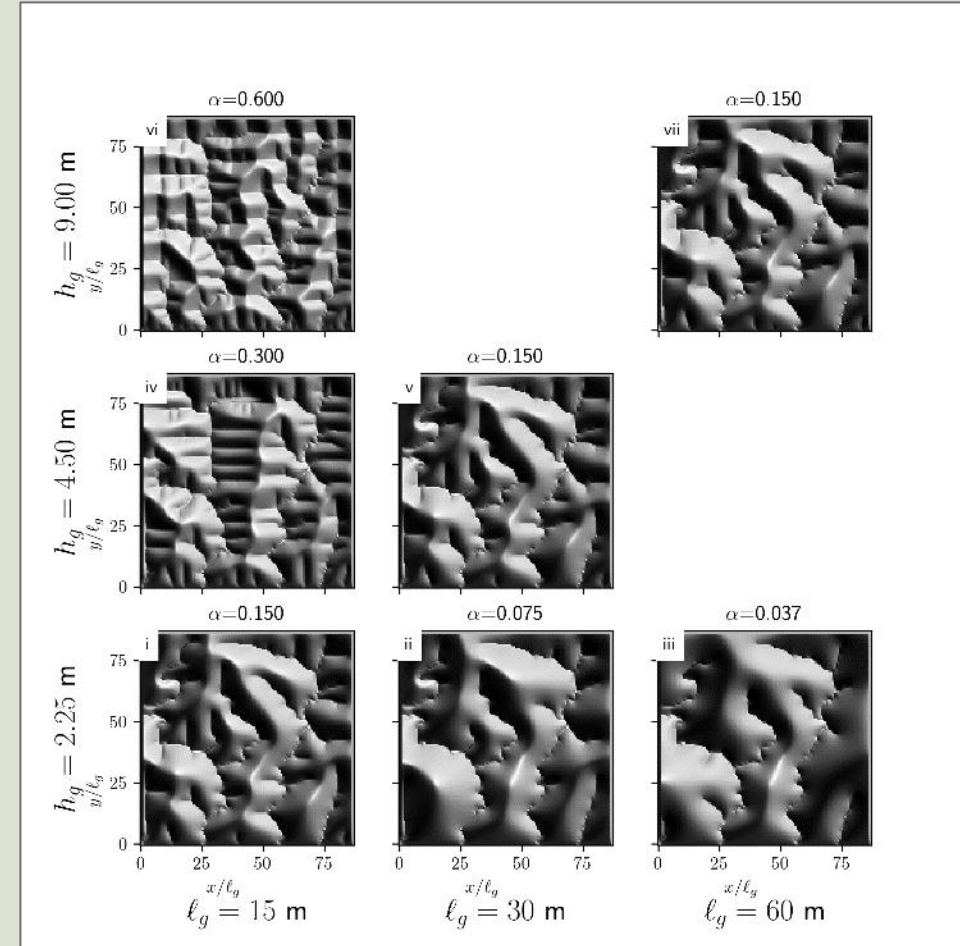
Independence of vertical and horizontal length scales

NoHyd model



Dimensionless topography is all the same!
“One typology”

DupuitLEM model



Dimensionless topography sensitive to
 $\alpha = h_g / \ell_g$

Topographic sensitivity to drainage capacity

Drainage capacity index

$$\gamma = \frac{b}{h_c} = \frac{bk_s h_g}{p\ell_g^2}$$

Hillslope number

$$Hi = \frac{h_g}{h_c} = \frac{k_s}{p\ell_g^2}$$

b = permeable thickness

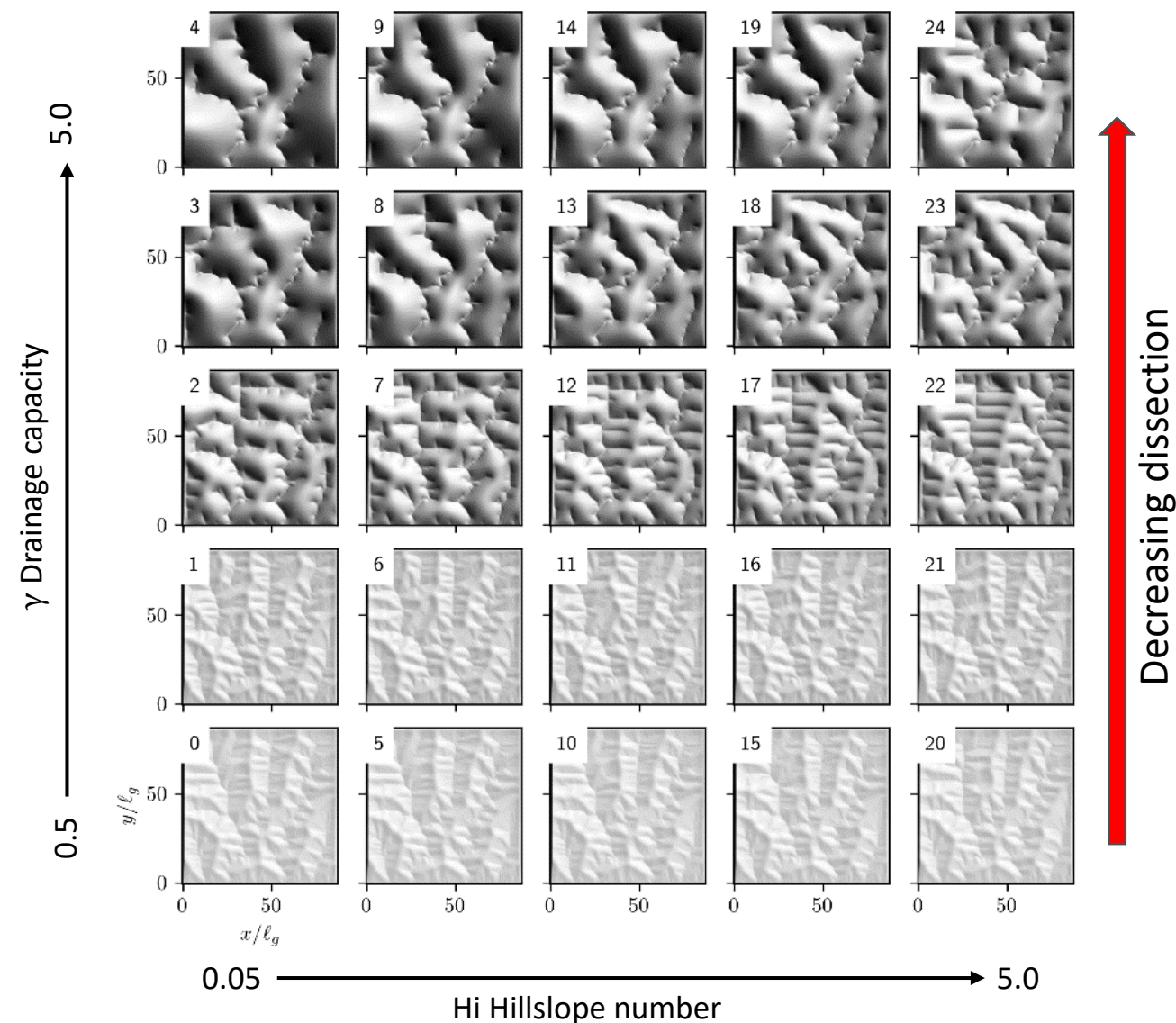
h_c = characteristic aquifer thickness

k_s = hydraulic conductivity

p = average precipitation rate

h_g = characteristic height scale

ℓ_g = characteristic length scale

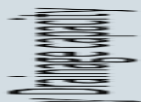


Topographic sensitivity to drainage capacity

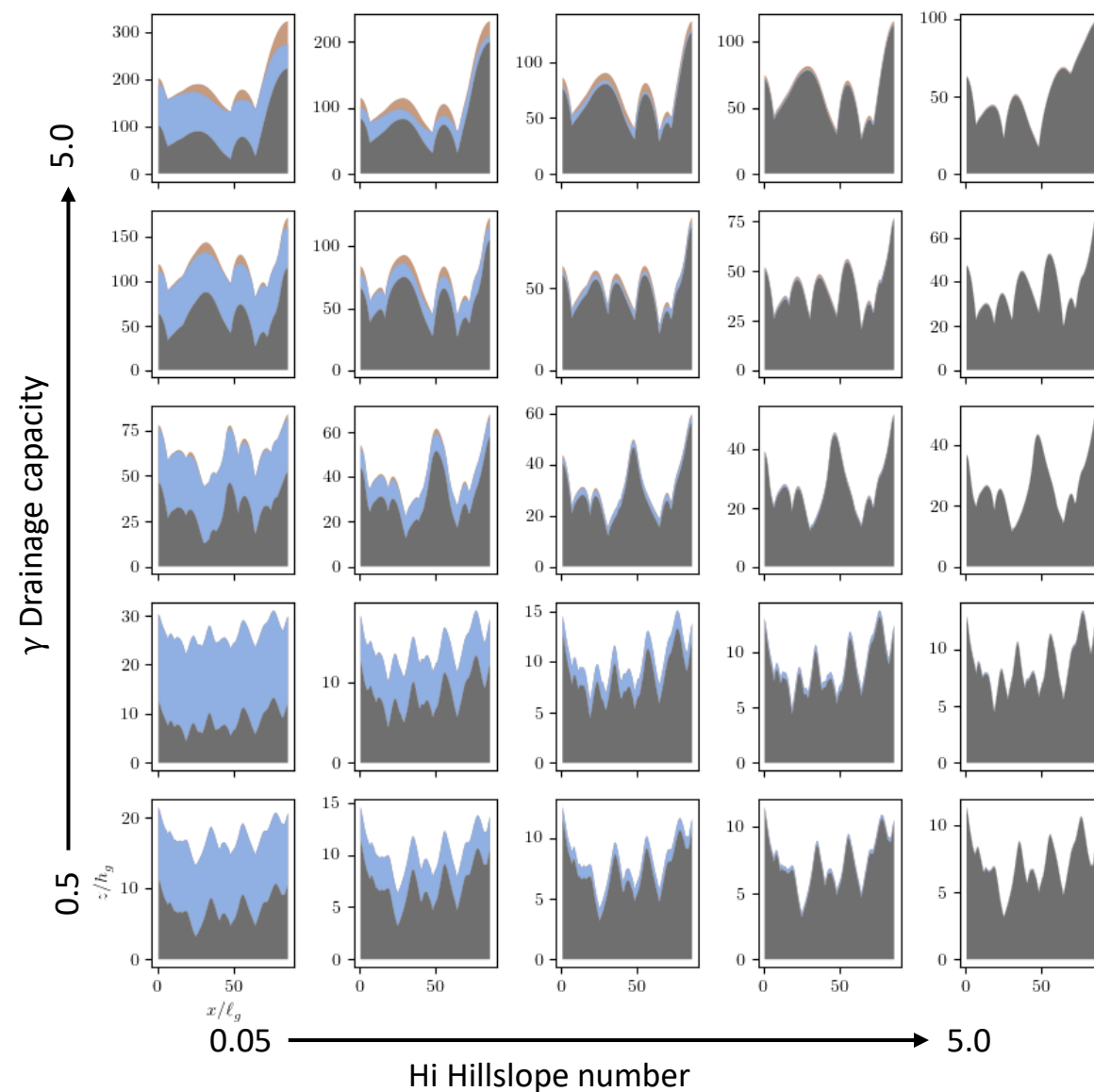
Drainage capacity index

$$\gamma = \frac{b}{h_c} = \frac{bk_s h_g}{p \ell_g^2}$$

Hillslope number



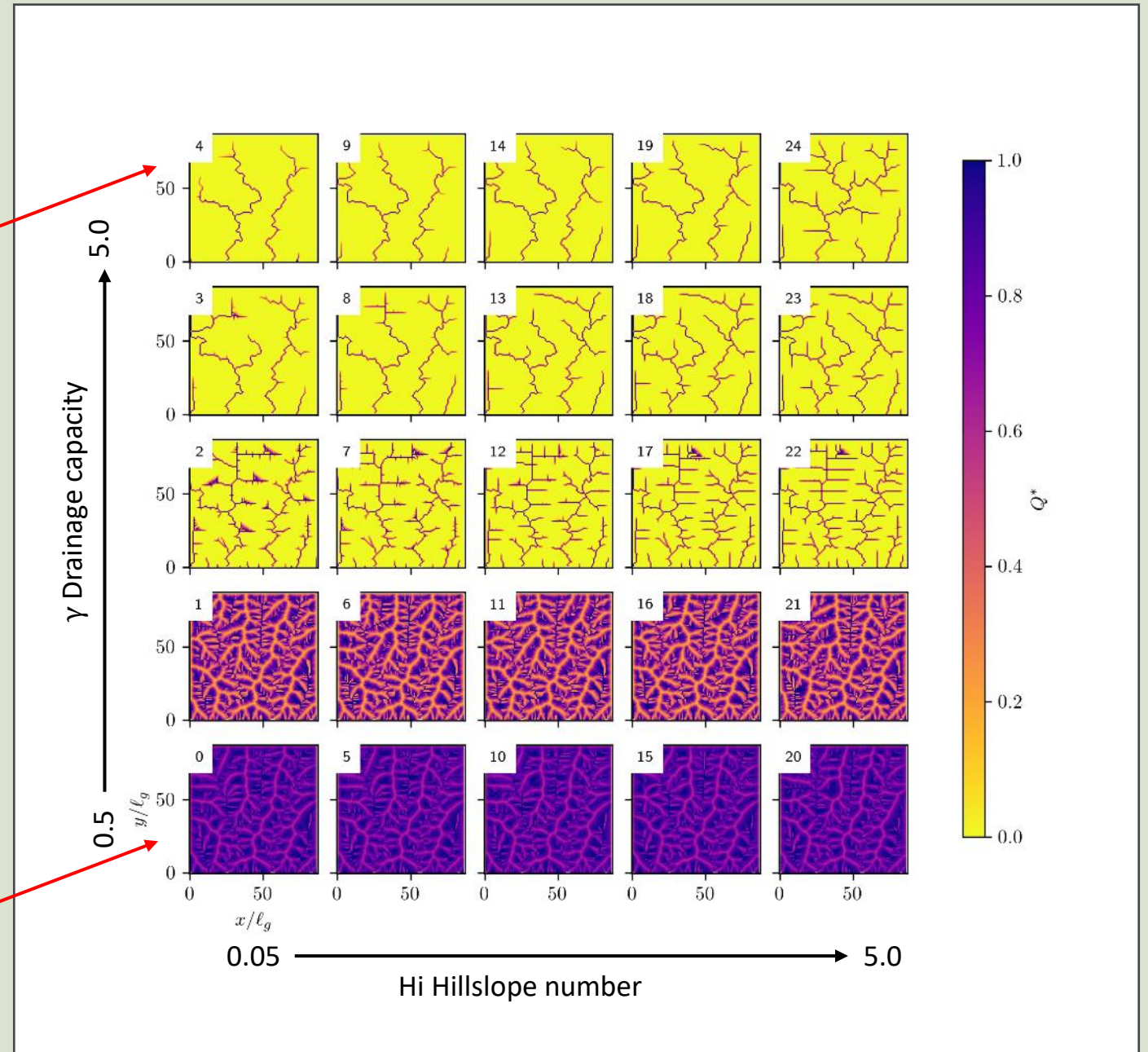
b = permeable thickness
 h_c = characteristic aquifer thickness
 k_s = hydraulic conductivity
 p = average precipitation rate
 h_g = characteristic height scale
 ℓ_g = characteristic length scale



Runoff varies spatially with drainage capacity

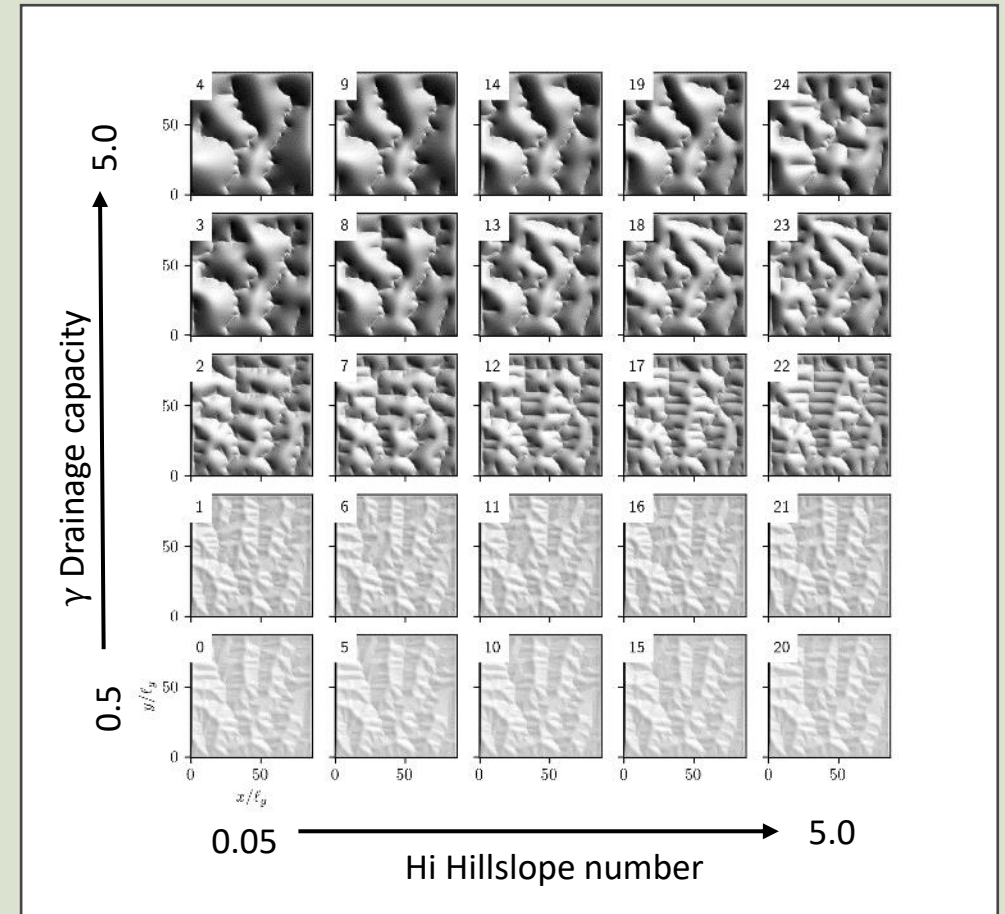
Only valleys contribute surface runoff

Every point contributes
surface runoff



Emergent properties

- How do feedbacks between hydrology and geomorphology affect emergent properties?
 - What metrics quantify these feedbacks?
- What can we infer about driving processes from observed topography?
 - Can we recover parameters from topographic analysis?



NoHyd model: linear relationship between steepness and curvature

0 (at steady state)

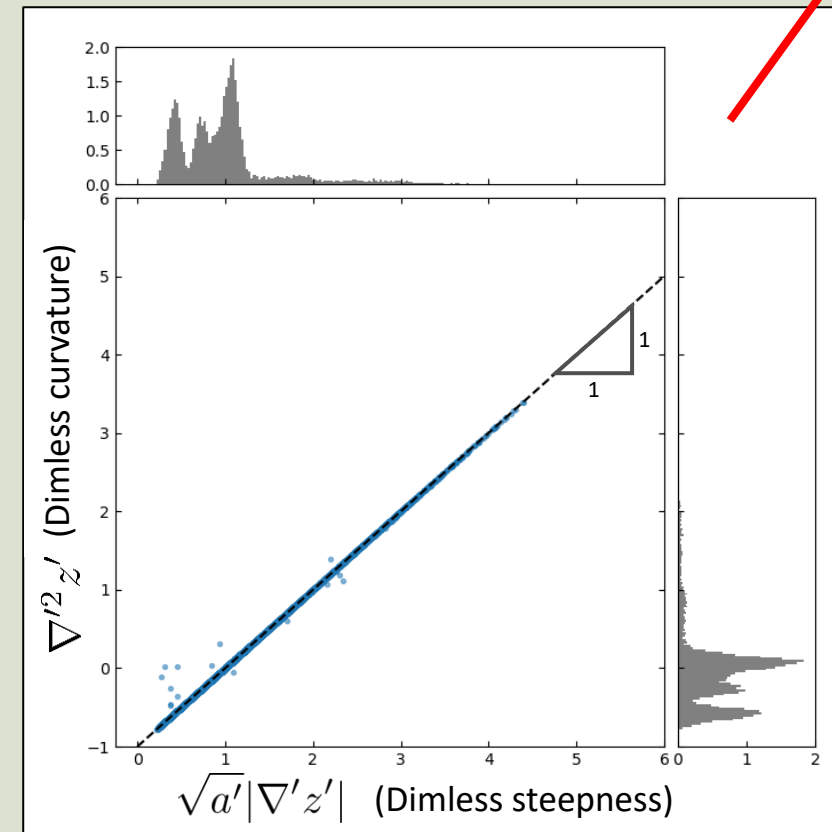
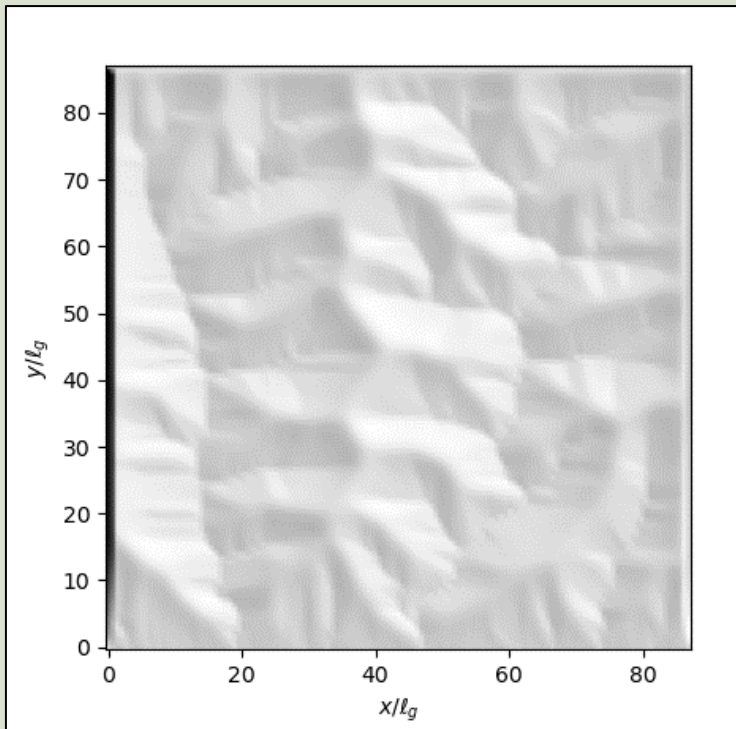
$$\frac{\partial z'}{\partial t'} = -\sqrt{a'}|\nabla' z'| + \nabla'^2 z' + 1$$

Rearrange

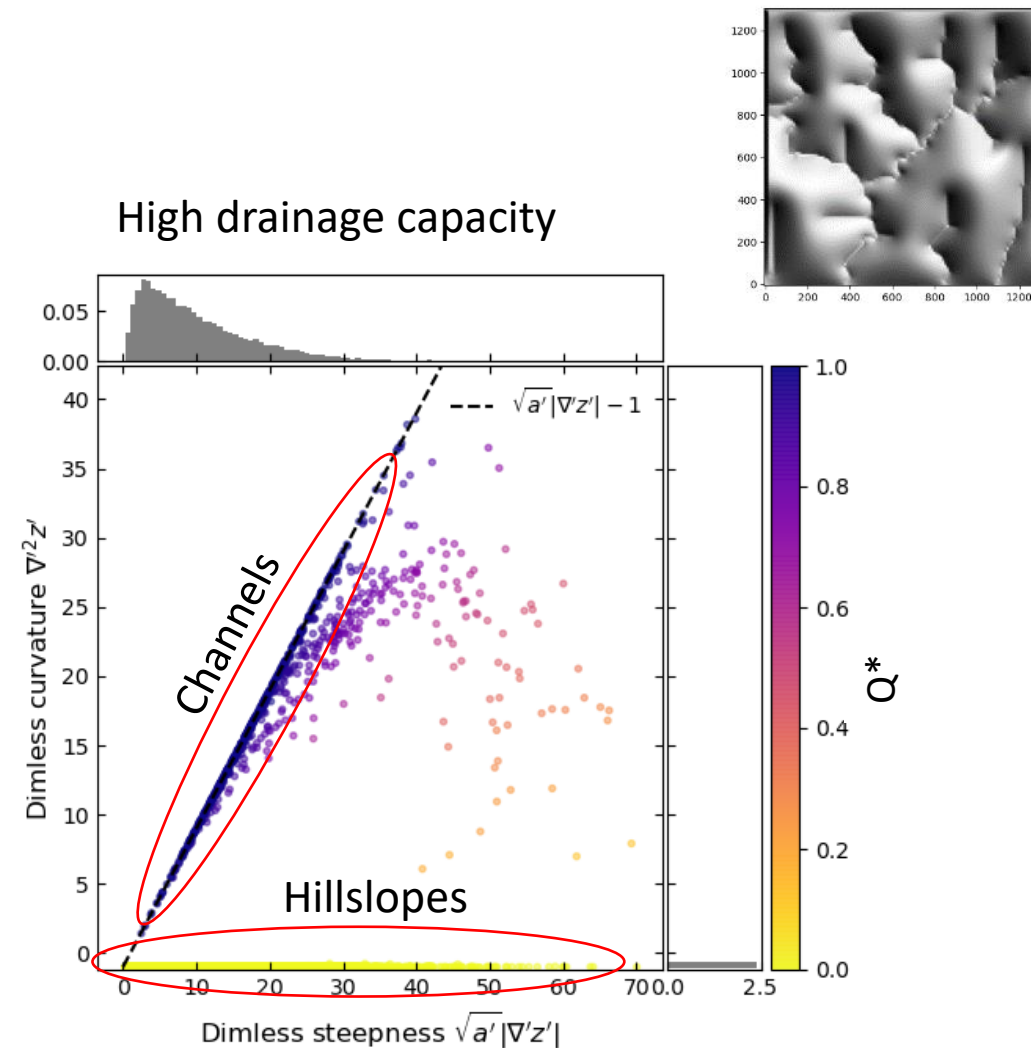
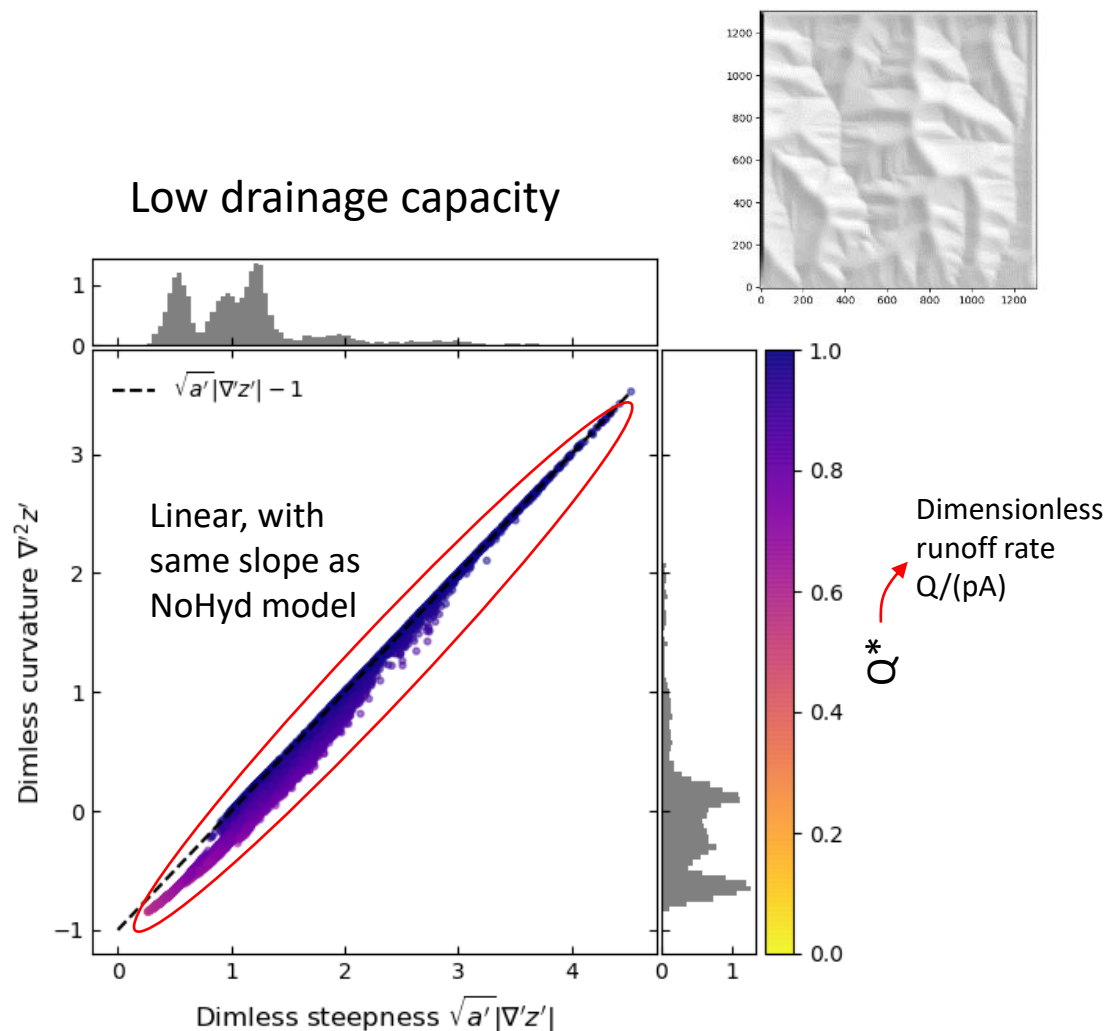
(curvature) = (steepness) - 1

$$\nabla'^2 z' = \sqrt{a'}|\nabla' z'| - 1$$

Linear relationship between steepness and curvature in the NoHyd model



Increasing subsurface drainage leads to non-unique relationship between steepness and curvature in DupuitLEM model



Analytical solutions for DupuitLEM model: Geomorphic balance

Steady state topography

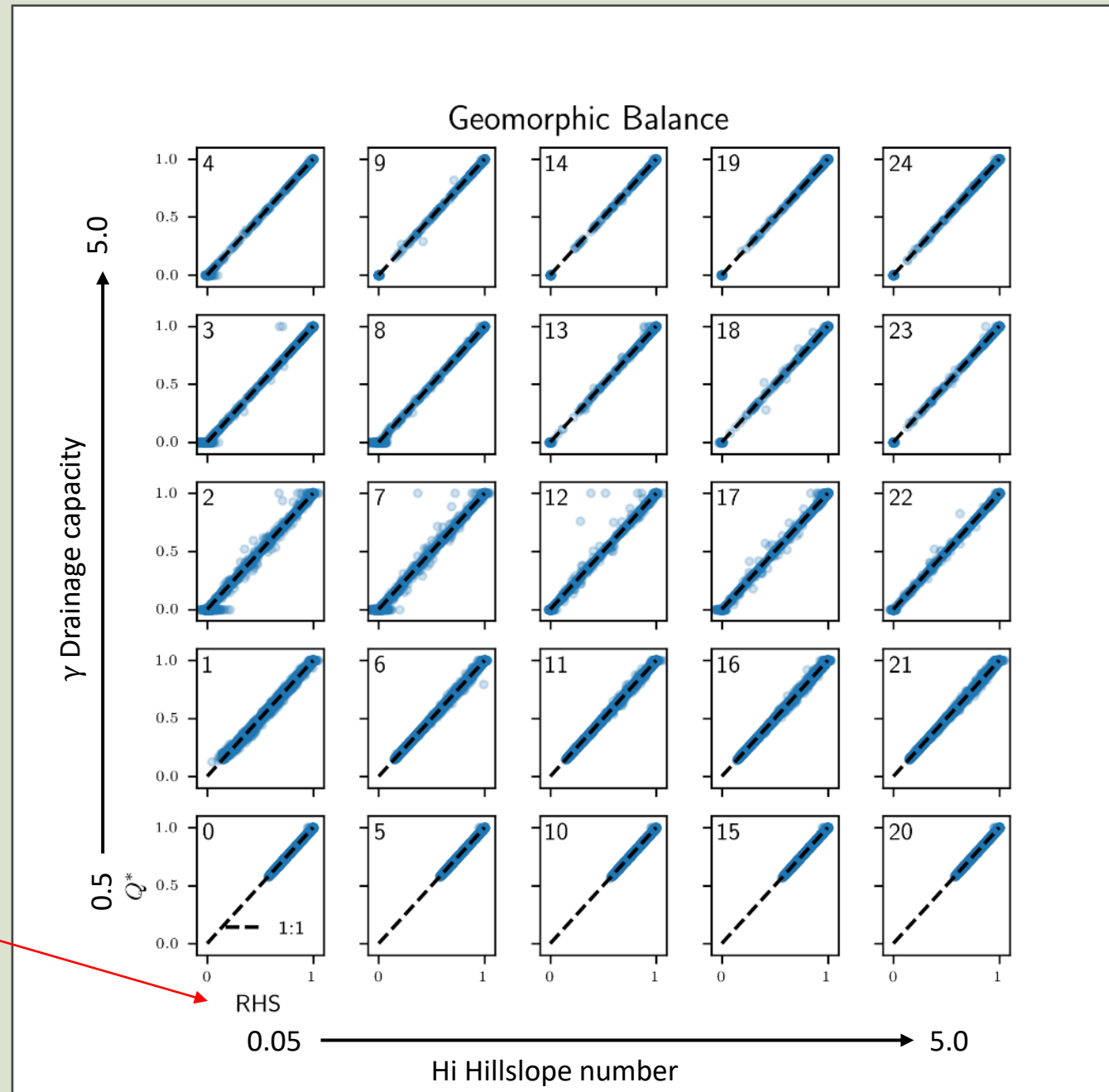
$$\frac{\partial z'}{\partial t'} = 0 = -Q^* \sqrt{a'} |\nabla' z'| + \nabla'^2 z' + 1$$

Geomorphic balance for Q^*

$$Q^* = \underbrace{\frac{\nabla'^2 z'}{\sqrt{a'} |\nabla' z'|}}_{\text{Actual } Q^*} + \underbrace{\frac{1}{\sqrt{a'} |\nabla' z'|}}_{Q^* \text{ from geomorphology}}$$

Actual Q^*

Q^* from geomorphology



Analytical solutions for DupuitLEM model: Hydrologic balance

Steady state water balance:

$$\int_A p dA = \int_A (\nabla \cdot q + q_s) dA$$

Hydrologic balance

Topographic index (TI)

$$Q^* = 1 - \gamma \frac{\nabla' z' \cos^2(\theta)}{a'}$$

Actual Q^* Q^* from hydrology

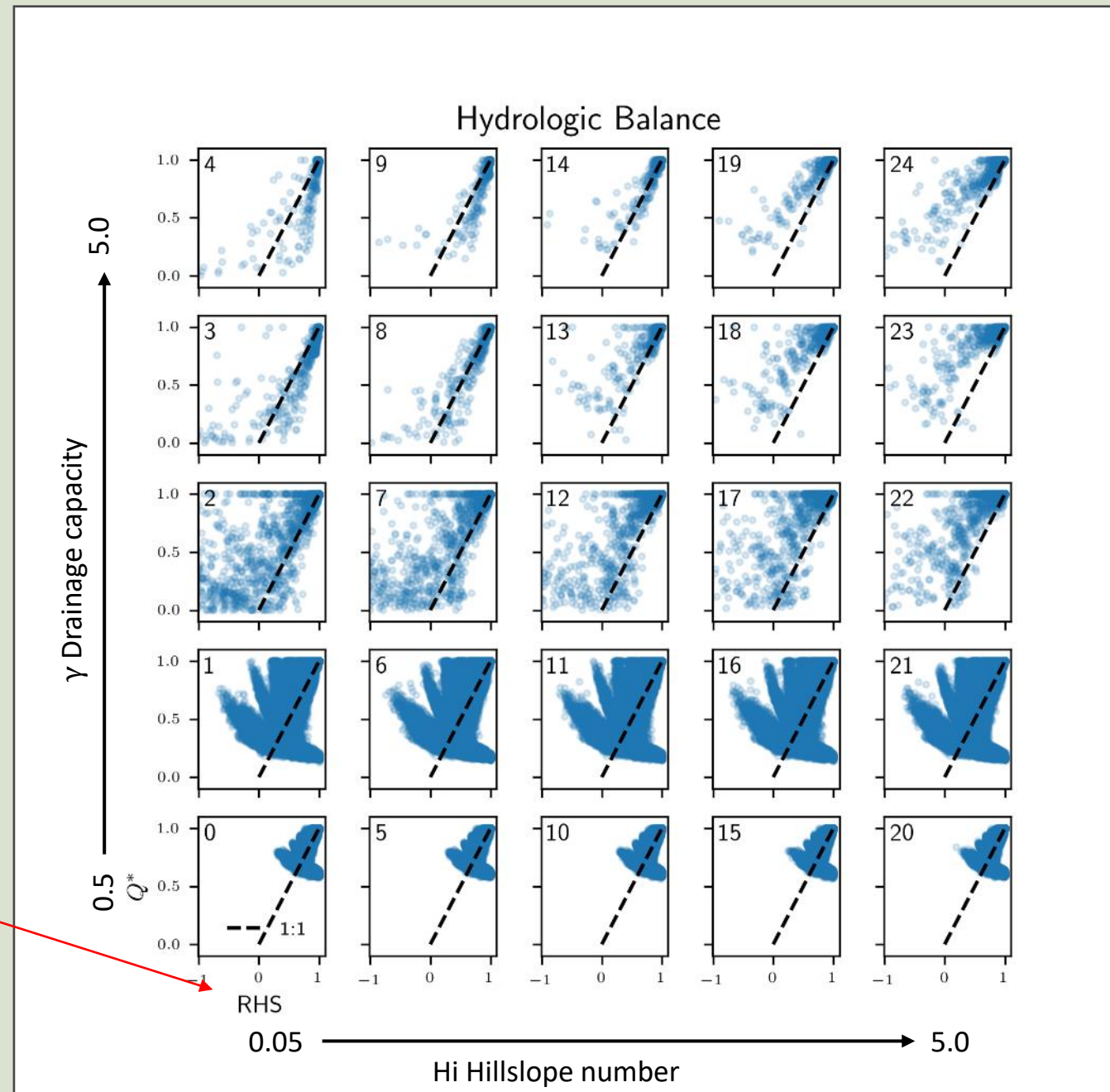
Assumptions made to get here:

- Aquifer thickness = permeable thickness
- Hydraulic gradient = topographic gradient

p = average precipitation rate

q = groundwater flux

q_s = local surface runoff



Combining the two: Hydromorphic balance

Combine and eliminate Q^*

$$0 = \underbrace{\gamma \left(\frac{\nabla' z' \cos^2(\theta)}{a'} \right)}_{1/TI} + \underbrace{\left(\frac{\nabla'^2 z'}{\sqrt{a'} |\nabla' z'|} \right)}_{\text{curvature/steepness}} + \underbrace{\left(\frac{1}{\sqrt{a'} |\nabla' z'|} \right)}_{1/\text{steepness}} - 1$$

Dimensioned form

$$0 = \underbrace{\left(\frac{bk_s}{p} \right)}_{\text{1/TI}} \left(\frac{\nabla z \cos^2(\theta)}{a} \right) + \underbrace{\ell_g^{3/2}}_{\text{curvature/steepness}} \left(\frac{\nabla^2 z}{\sqrt{a} |\nabla z|} \right) + \underbrace{\left(\frac{h_g}{\sqrt{\ell_g}} \right)}_{1/\text{steepness}} \left(\frac{1}{\sqrt{a} |\nabla z|} \right) - 1$$

We could solve for three unknowns in three dimensions

b = permeable thickness

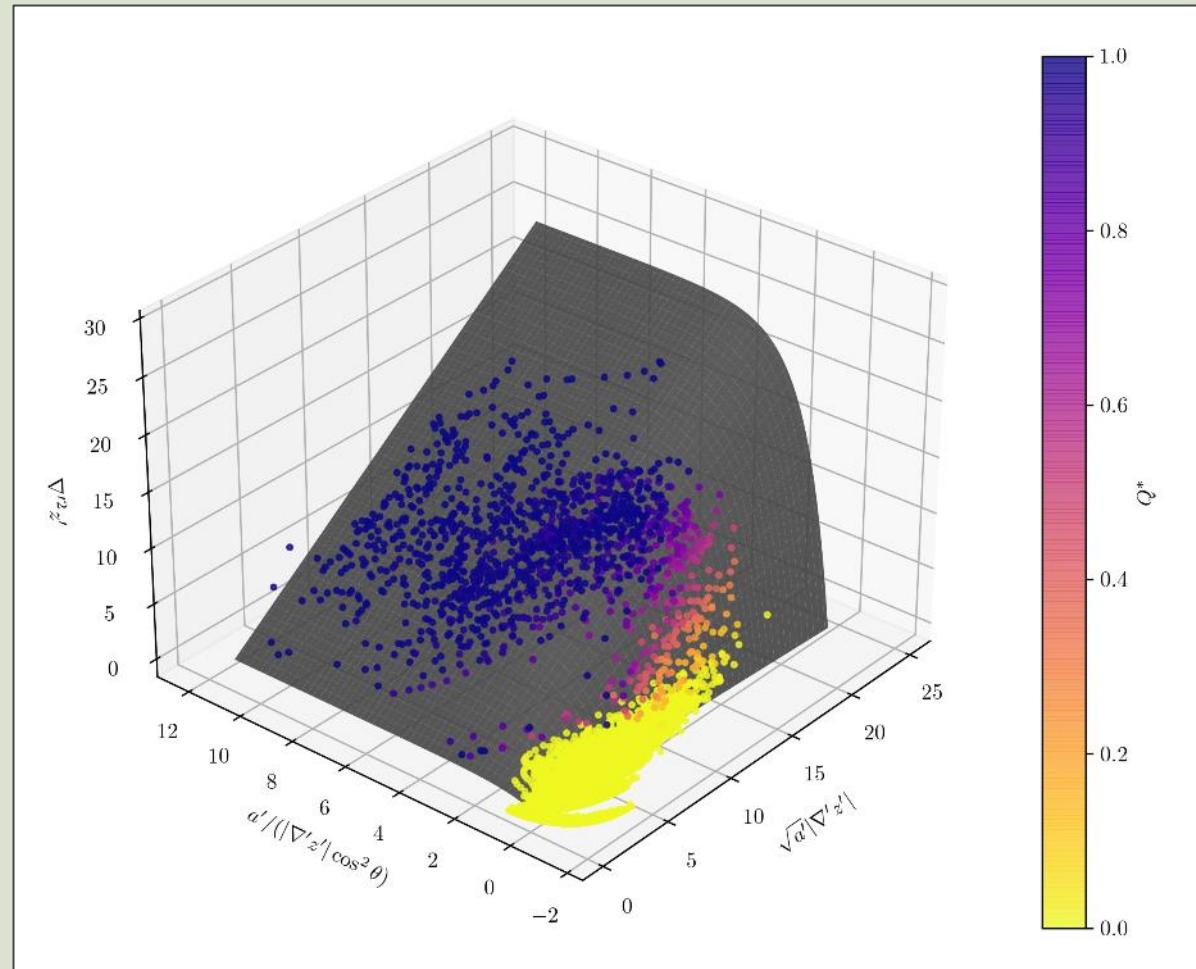
k_s = hydraulic conductivity

p = average precipitation rate

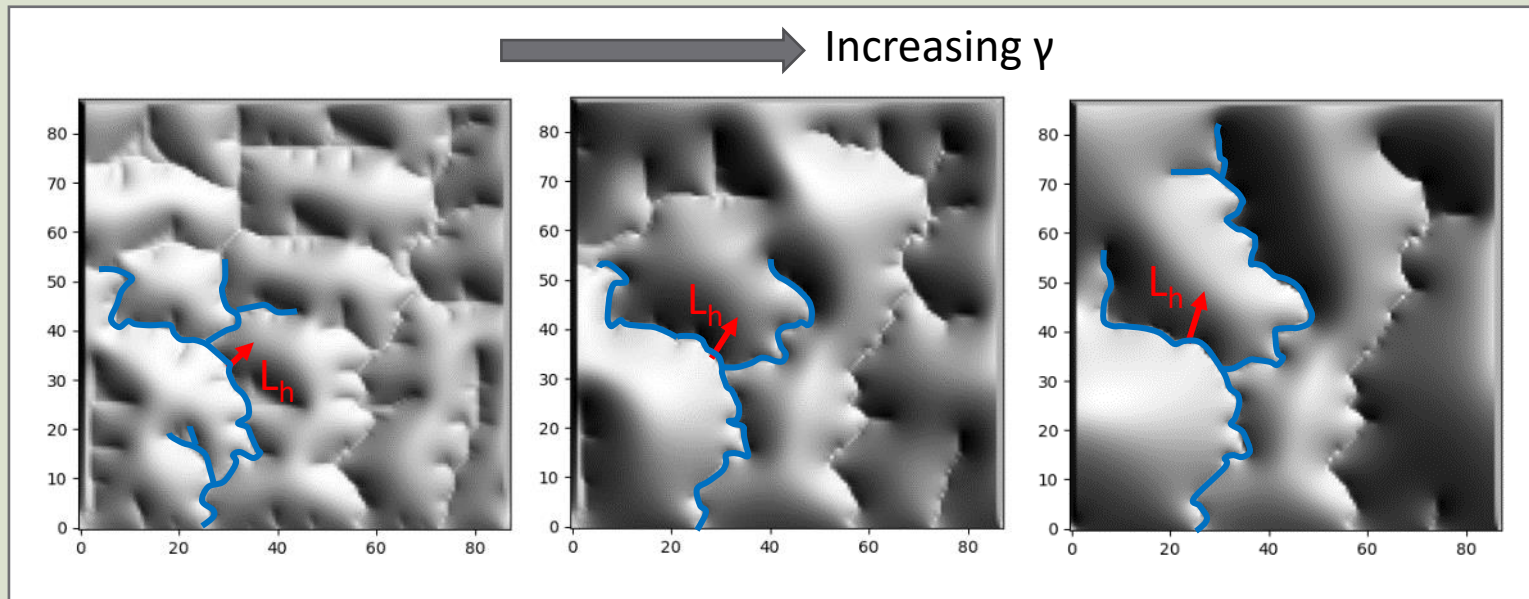
h_g = characteristic height scale

ℓ_g = characteristic length scale

Solution is a 3D manifold:



Hillslope length scales with drainage capacity



Mean hillslope length L_h

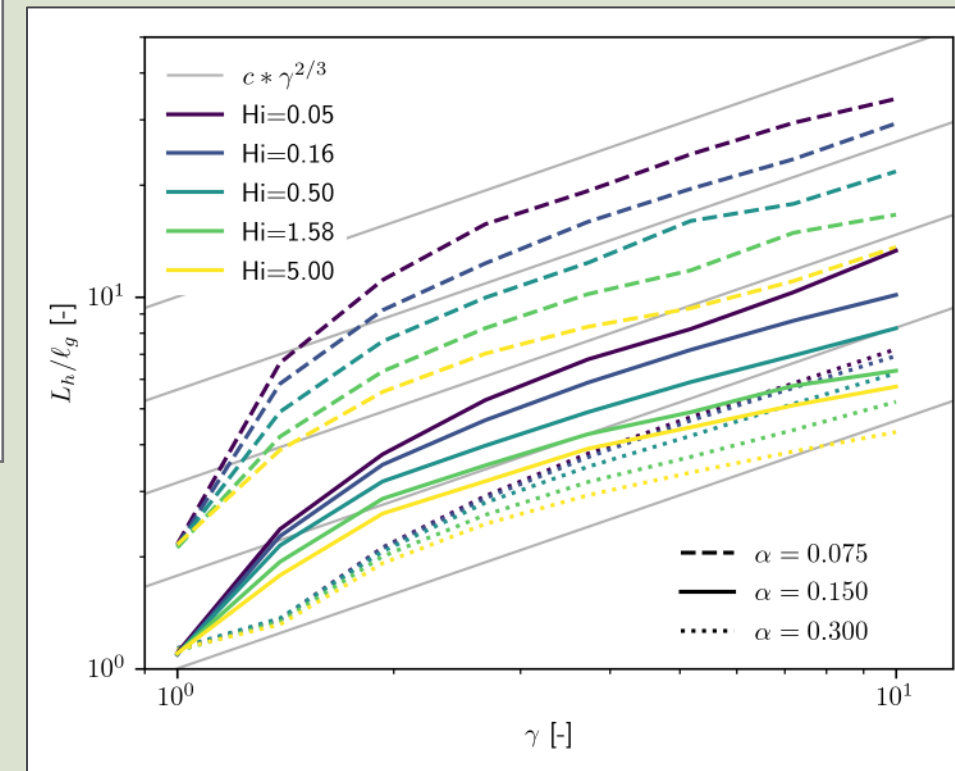
$$L_h \sim \ell_g \gamma^{2/3}$$

$$L_h \sim \frac{1}{v_0} \left(\frac{v_0 b k_s}{p} \frac{U}{K} \right)^{2/3}$$

Combine hydrologic and
geomorphic balances, eliminating
 ∇z ($\nabla^2 z = 0$, $Q^* = 1/2$)

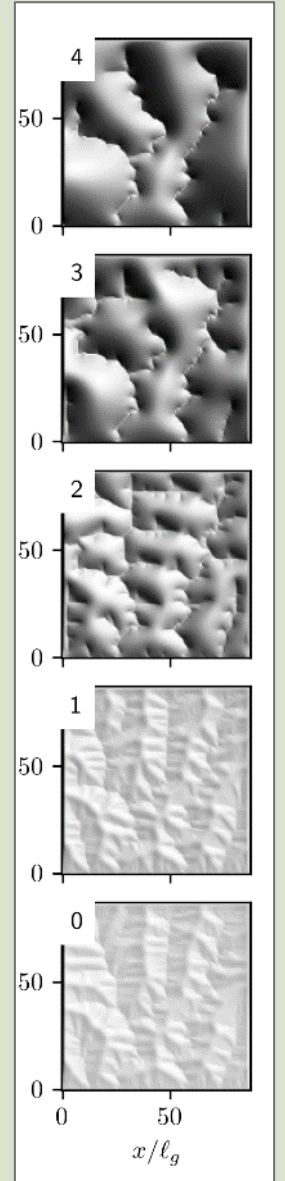
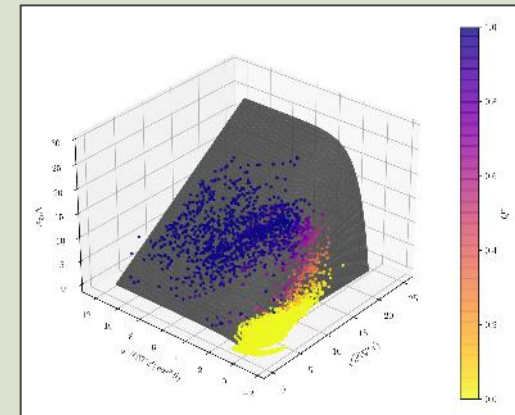
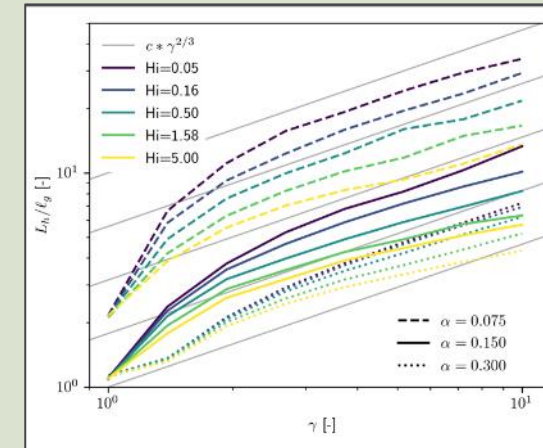
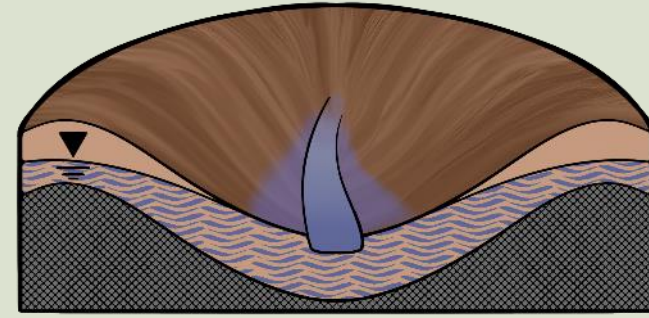
$(v_0 b k_s)$ = valley transmissivity [L³/T]
 p = mean precipitation rate [L/T]

U = uplift rate [L/T]
 K = fluvial incision constant [1/T]

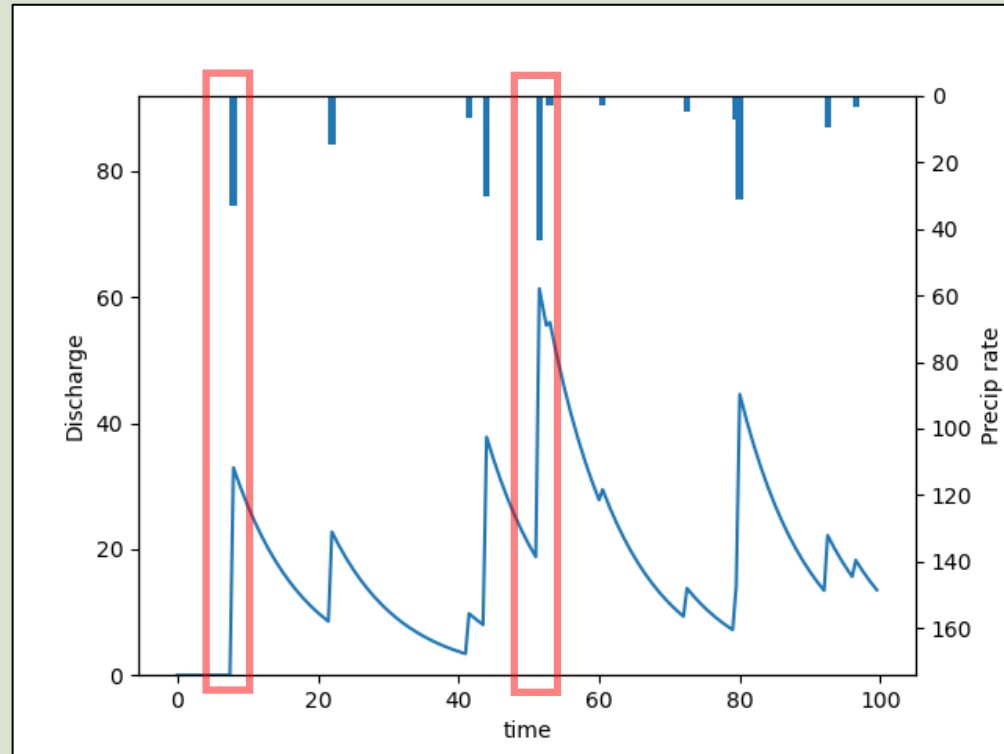


Takeaway points

- New model couples groundwater and surface water flow with evolving topography
- Multiple landscape “typologies” with spatially distributed runoff
- Hillslope length increases with subsurface drainage capacity
- Analytical solution of coupled model shows promise for estimating model parameters (including transmissivity) from topography



What about precipitation variability?



Antecedence matters!

Climate is expressed in stochastic rainfall

Recharge rate = Rainfall rate:

$$f(i) = \frac{1}{\langle i \rangle} \exp \left(- \frac{i}{\langle i \rangle} \right)$$

$$f(t_r) = \frac{1}{\langle t_r \rangle} \exp \left(- \frac{t_r}{\langle t_r \rangle} \right)$$

$$f(t_b) = \frac{1}{\langle t_b \rangle} \exp \left(- \frac{t_b}{\langle t_b \rangle} \right)$$

Characterize rainfall by
exponential distributions of
storm depth, duration, and
interstorm duration

$$\rho = \frac{p}{\langle i \rangle} = \frac{\langle t_r \rangle}{\langle t_r \rangle + \langle t_b \rangle}$$

Rainfall steadiness index

$$\beta = \frac{\langle t_r \rangle + \langle t_b \rangle}{t_d}$$

Storage variability index

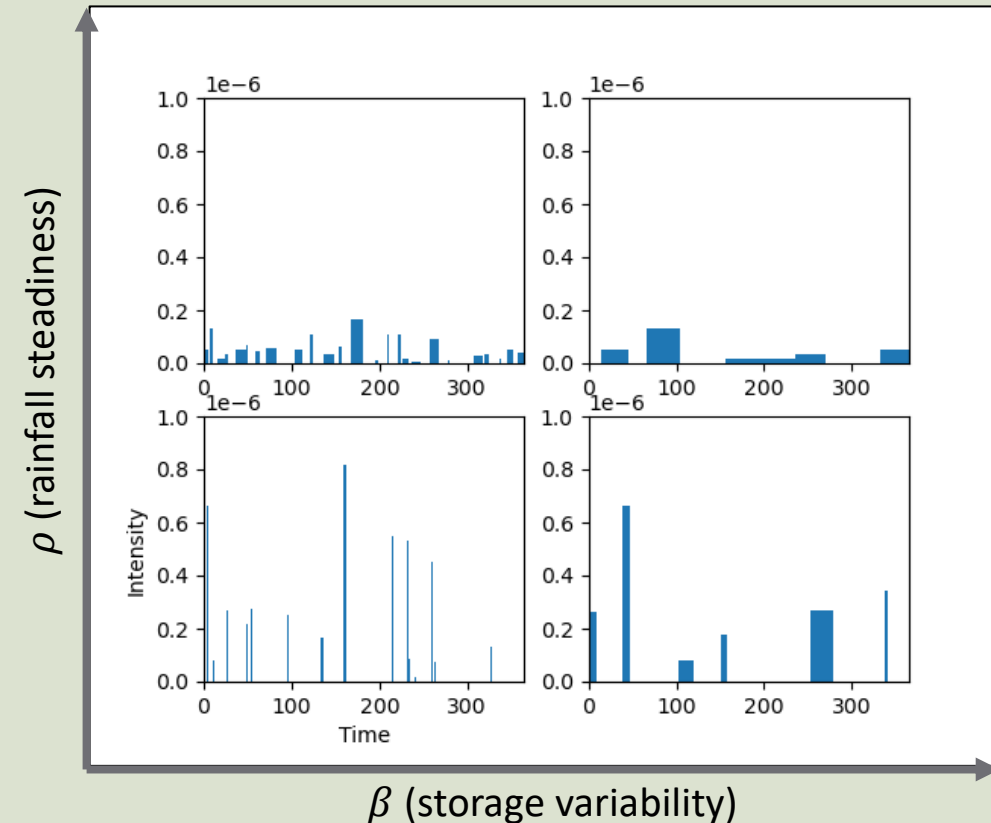
$\langle i \rangle$ = average storm intensity

$\langle t_r \rangle$ = average storm duration

$\langle t_b \rangle$ = average time between storms

p = long term average rainfall rate

t_d = characteristic aquifer drainage time

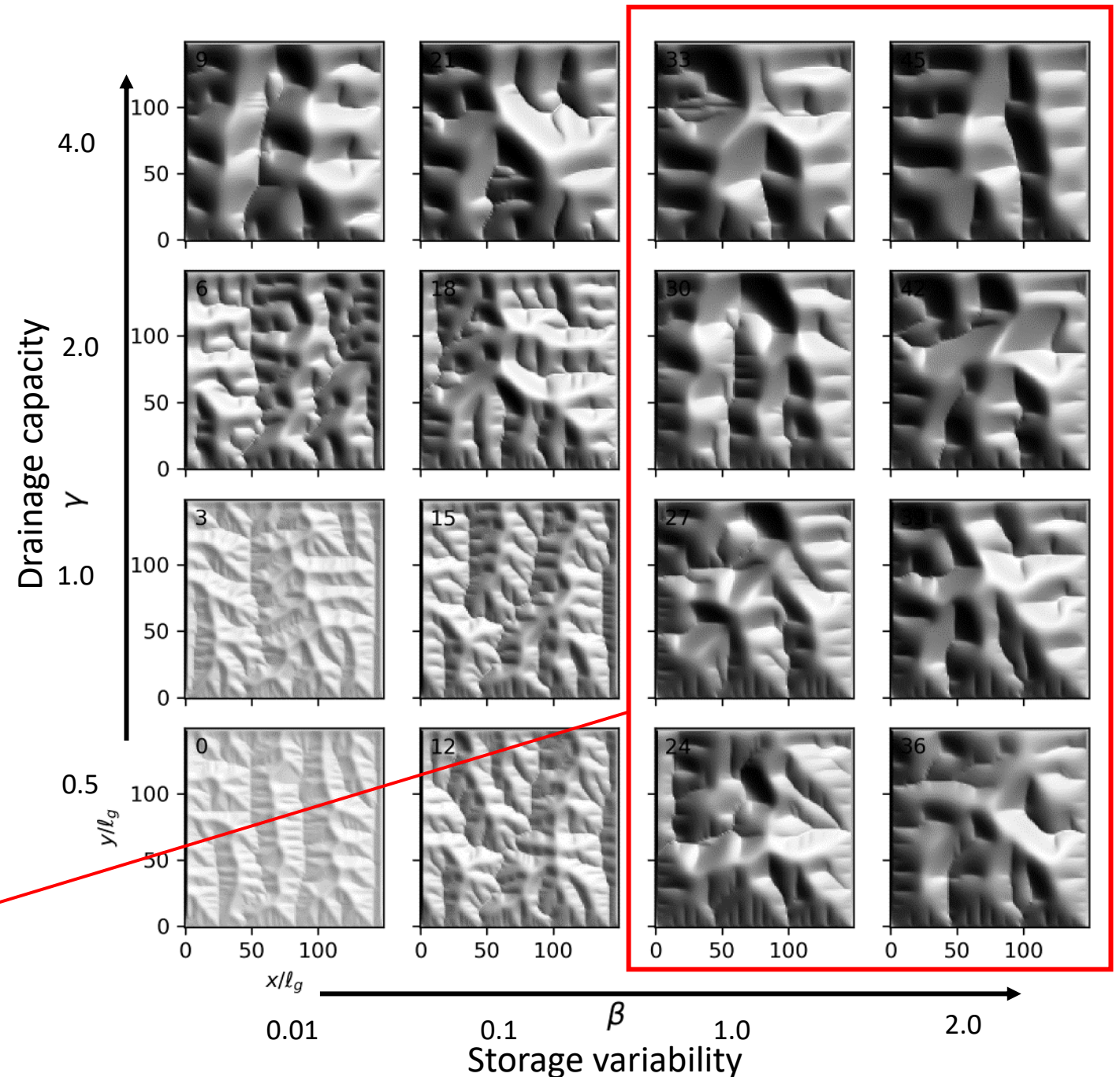


Stochastic rainfall model: sensitivity to drainage capacity and storage variability

$\rho = 0.01 \rightarrow$ Near instantaneous storms

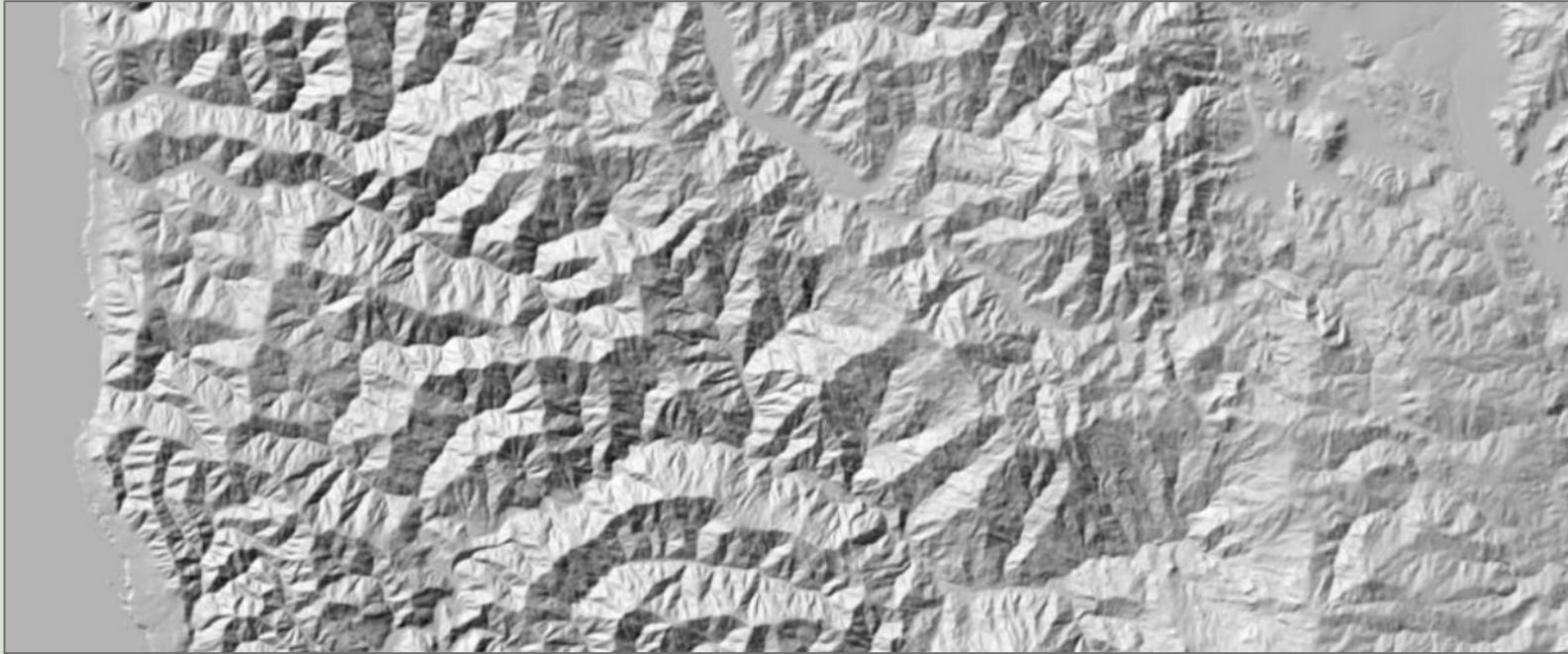
$H_i = 5.0 \rightarrow$ Topographic gradients drive
groundwater flow

When storage variability is
large, the subsurface drainage
capacity doesn't have as
strong an effect on
topography as it does when
storage is relatively constant



Looking forward: application to field data

Eel River headwaters, CA. Can we understand the subsurface based on this topography?



USGS National Map

Questions?

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