Modeling earth-surface dynamics with Landlab

The Landlab development team:

Jordan Adams (Tulane U.)

Nicole Gasparini (Tulane U.)

Dan Hobley (Univ. of Colorado)

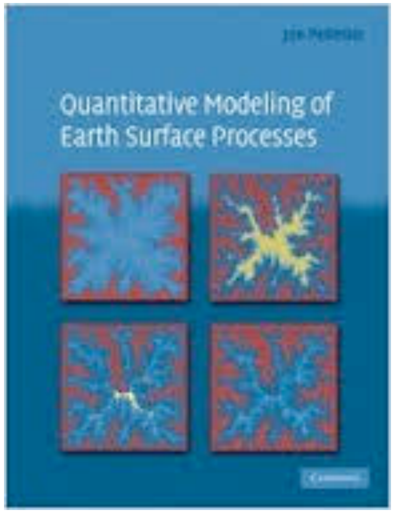
Eric Hutton (CSDMS)

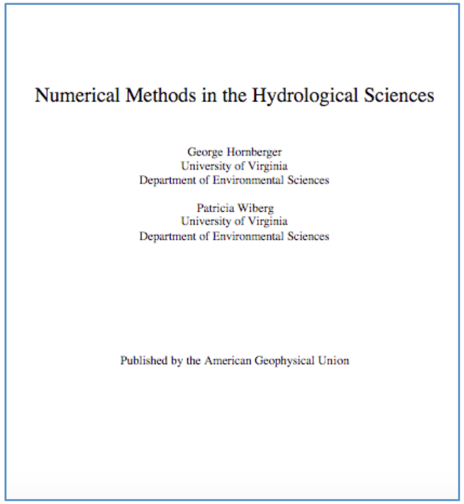
Erkan Istanbulluoglu (Univ. of Washington)

Jennifer Knuth (Univ. of Colorado)

Sai Siddharta Nudurupati (Univ. of Washington)

Greg Tucker (Univ. of Colorado)



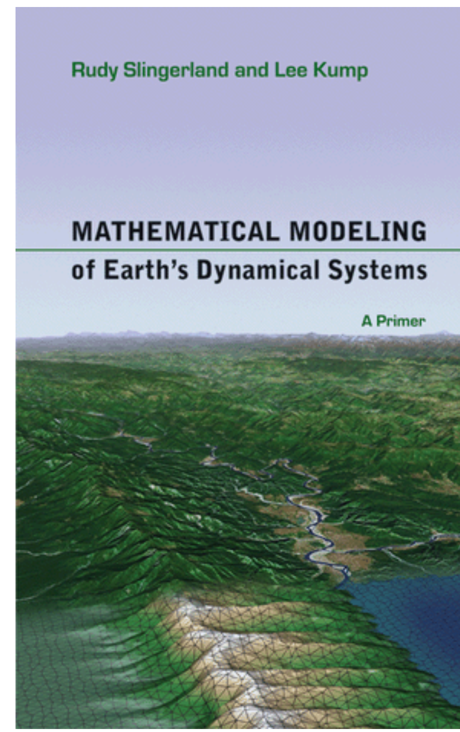

Numerical Methods in the Hydrological Sciences

George Hornberger
University of Virginia
Department of Environmental Sciences

Patricia Wiberg
University of Virginia
Department of Environmental Sciences

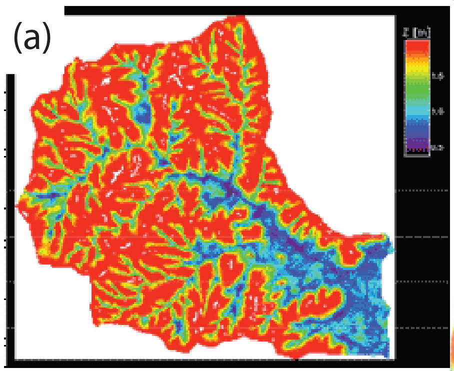
Published by the American Geophysical Union

NATURE → DYNAMICAL MODEL → NUMERICAL ALGORITHM → SOFTWARE

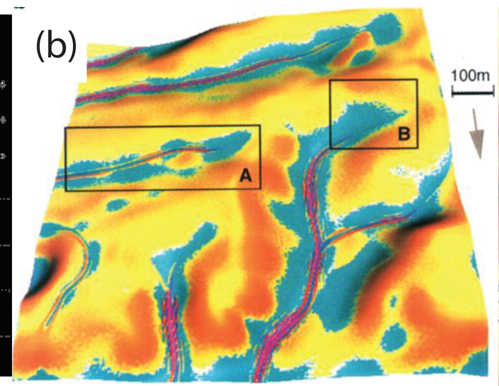


2D models of earth-surface processes

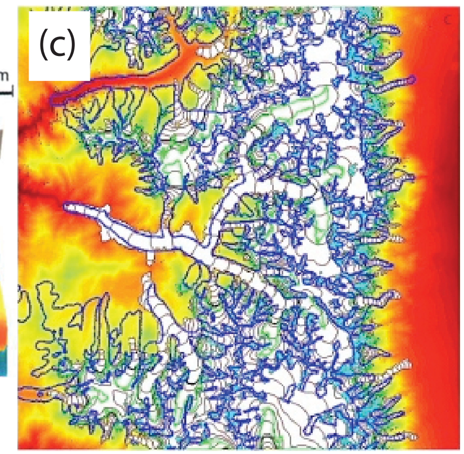
CATCHMENT HYDROLOGY
(Ivanov et al., 2004)

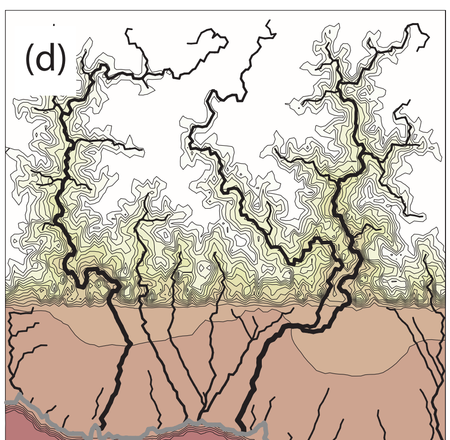


SOIL EROSION
(Mitas and Mitasova, 1998)

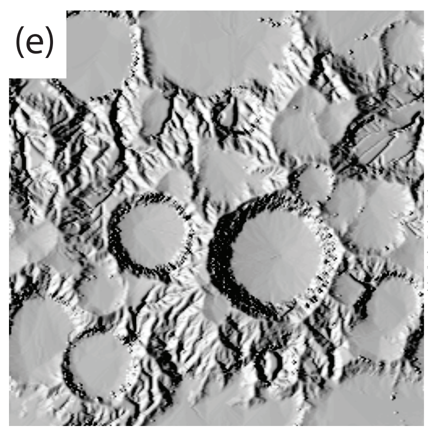


GLACIER DYNAMICS
(Kessler et al., 2006)

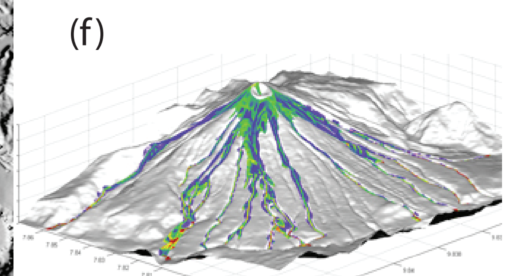




LANDSCAPE EVOLUTION
(Tucker and Hancock, 2010)



IMPACT CRATERING AND DEGRADATION
(Howard, 2007)



LAVA FLOWS
(Kelfoun et al., 2009)

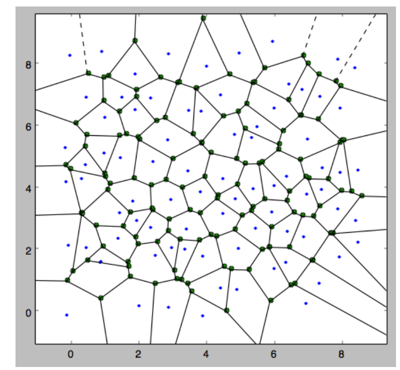
What is Landlab?

- A Python-language programming library
- Supports efficient creation and/or coupling of 2D numerical models
- Geared toward (but not limited to) earth-surface dynamics

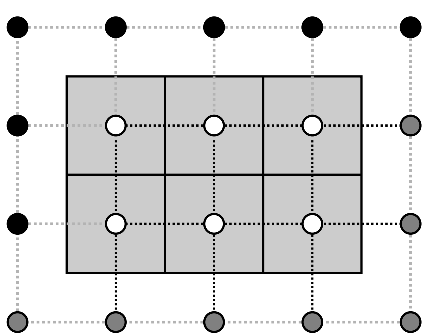
What Landlab provides

1. Grid creation and management
   - Create a structured or unstructured grid in one or a few lines of code
   - Attach data to grid elements
     - Facilitates staggered-grid schemes
     - Passing the grid = passing the data

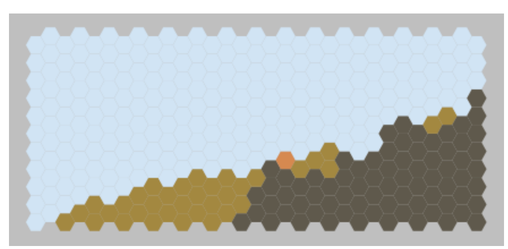
VORONOI / DELAUNAY



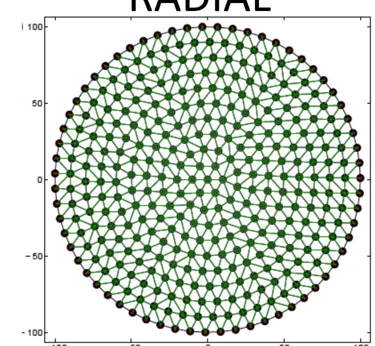
RASTER



HEXAGONAL



RADIAL



What Landlab provides

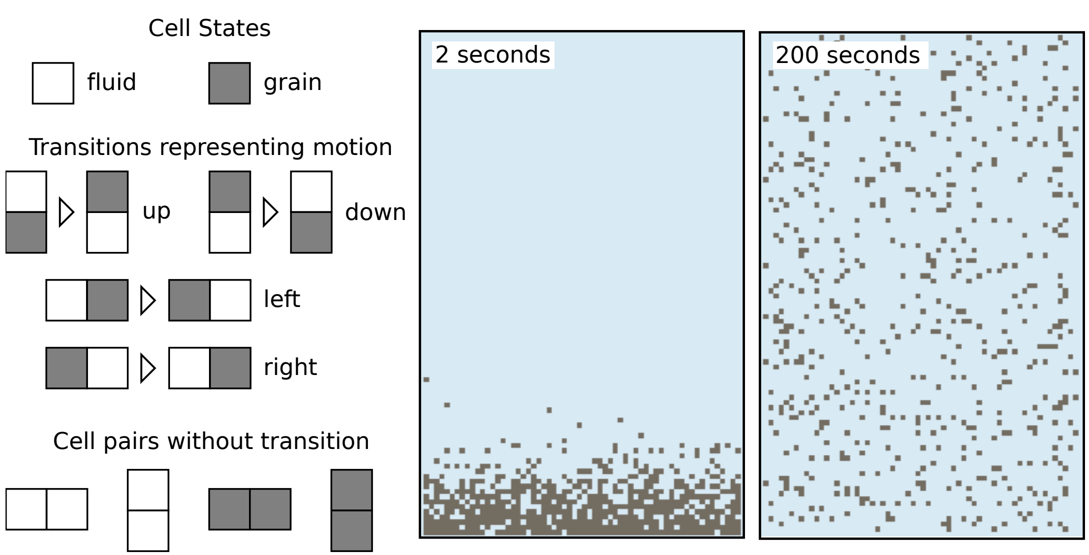
2. Coupling of components
   - A *component* models a single process (e.g., lithosphere flexure, incident solar radiation, flow routing across terrain)
   - Components have a standard interface and can be combined by writing a short Python script
   - Save development time by re-using components written by others

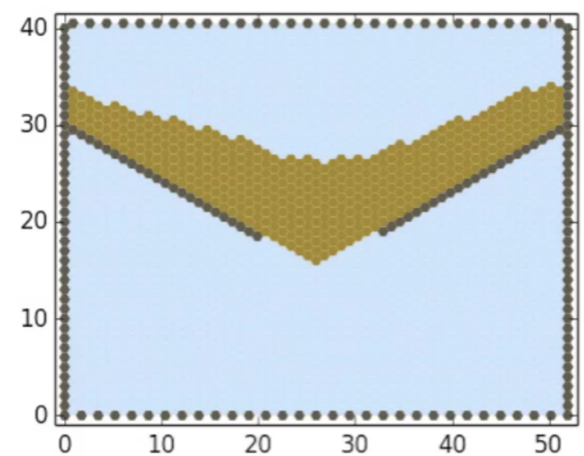
What Landlab provides

3. Input and output
   - Read model parameters from a formatted text file
   - Read in digital terrain data (e.g., DEMs) → grid
   - Write gridded output to files (netCDF format)
   - Plot data using Matplotlib graphics library

What Landlab provides

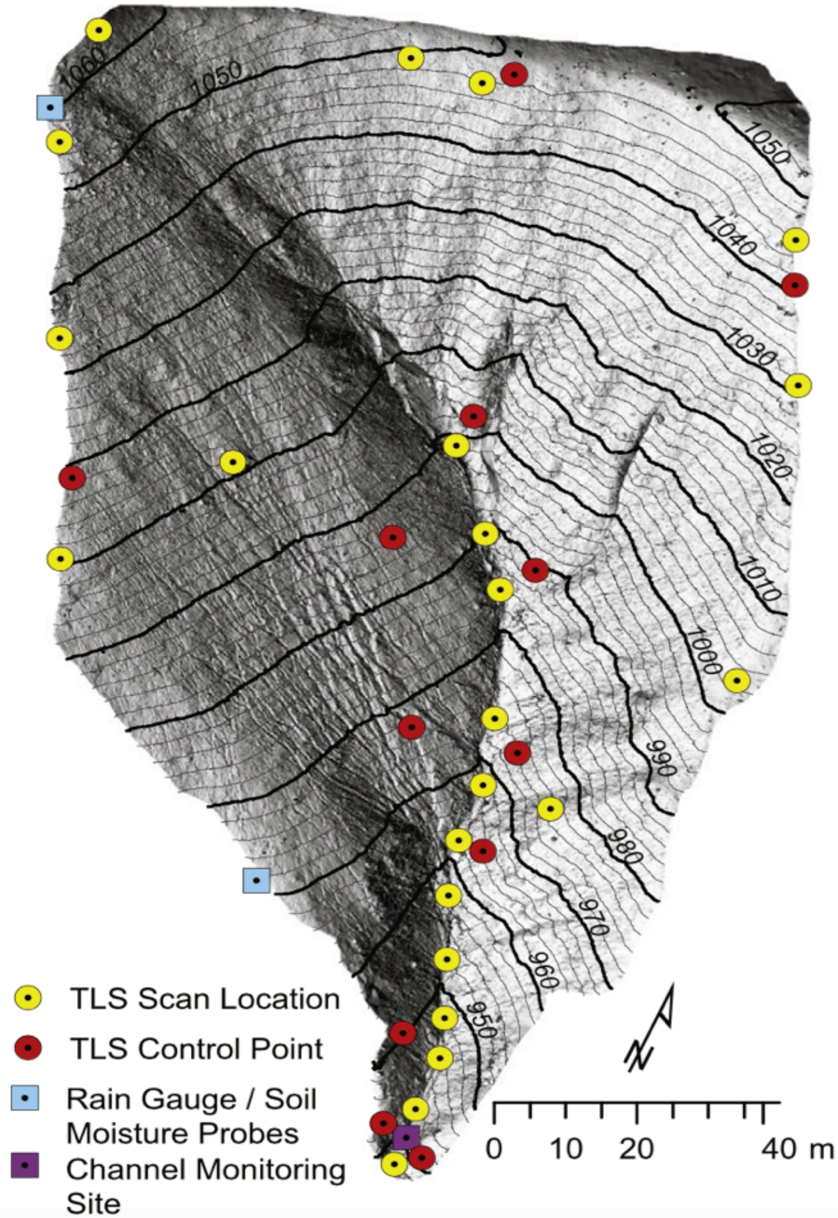
4. Support for cellular-automaton modeling
   – CellLab-CTS: Continuous-time stochastic CA model “engine”





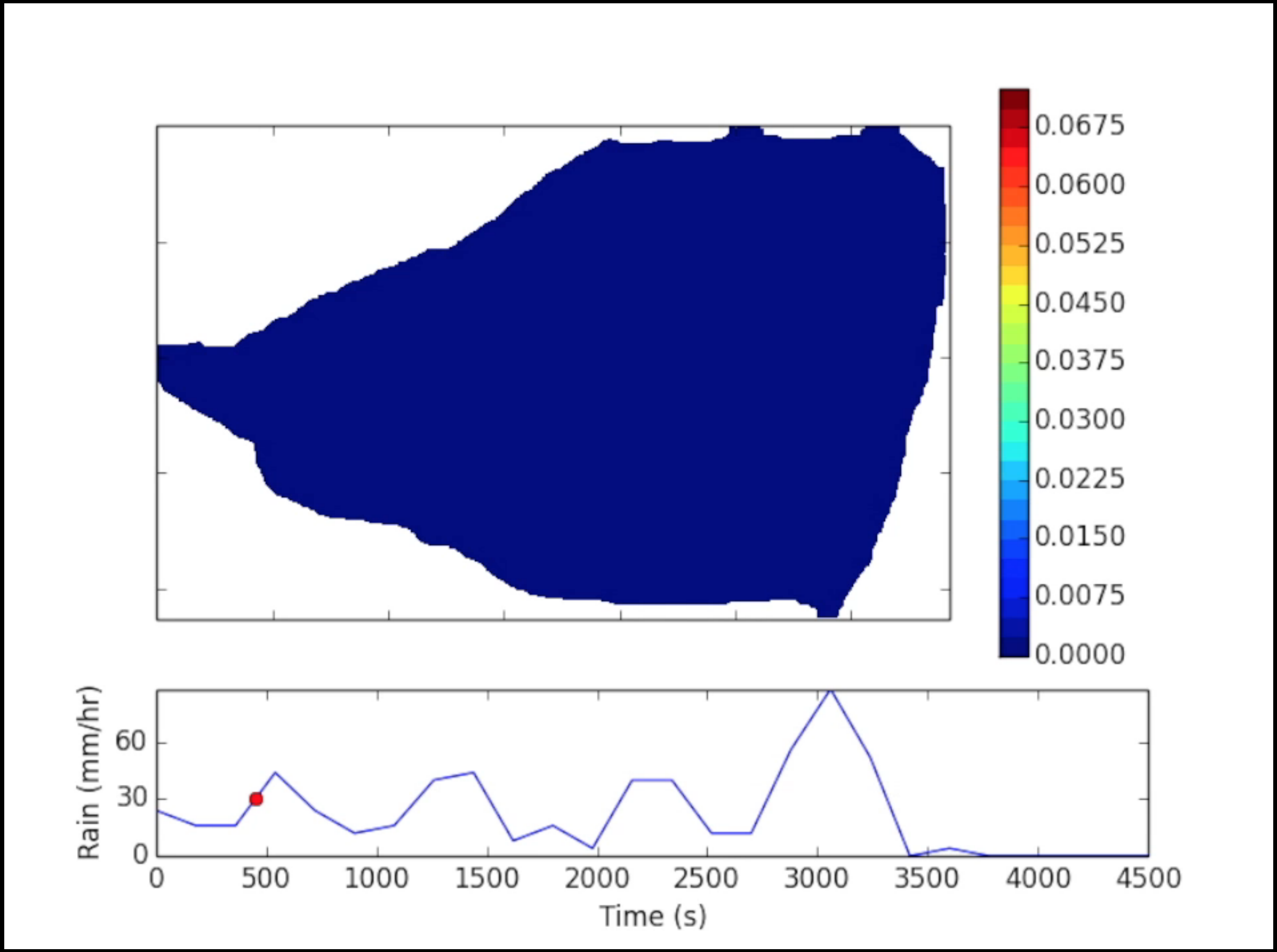
(Tucker et al., 2016 Geoscientific Model Development)

Examples of Landlab-built models



(Source: Francis Rengers, USGS)

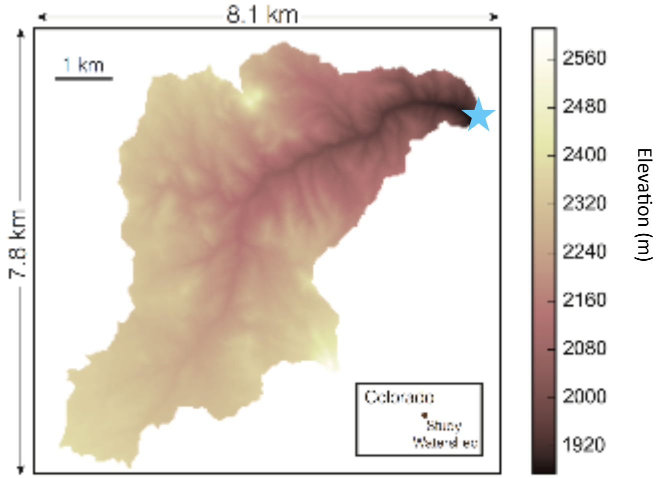
Storm runoff patterns in the Transverse Ranges

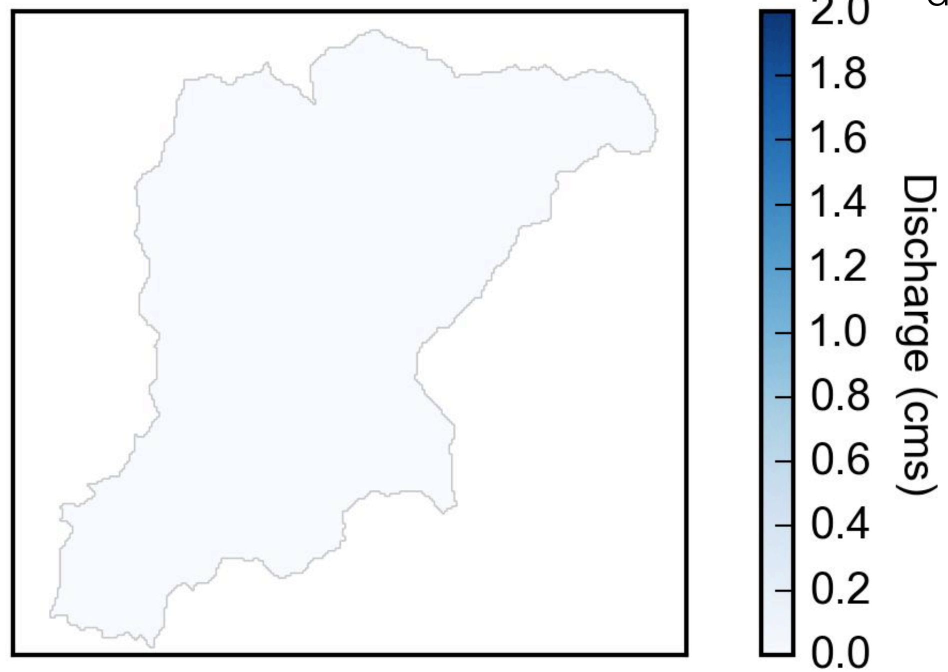


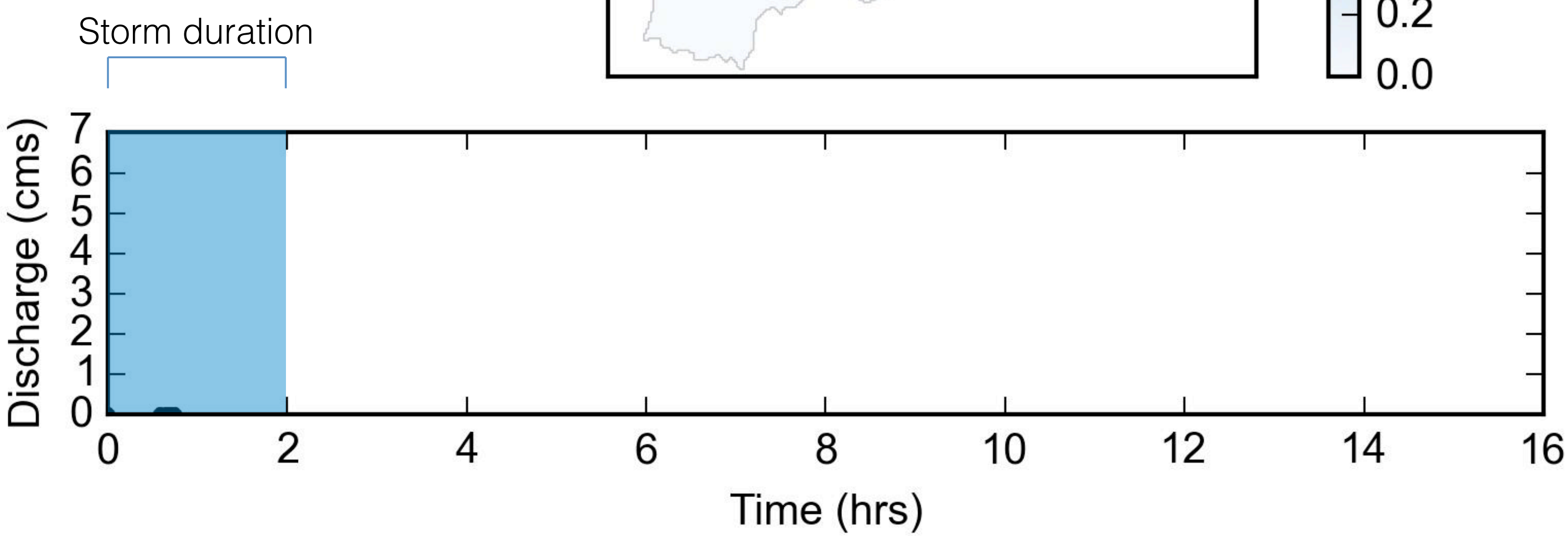
(Source: Francis Rengers, USGS)

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

*Note scale differences

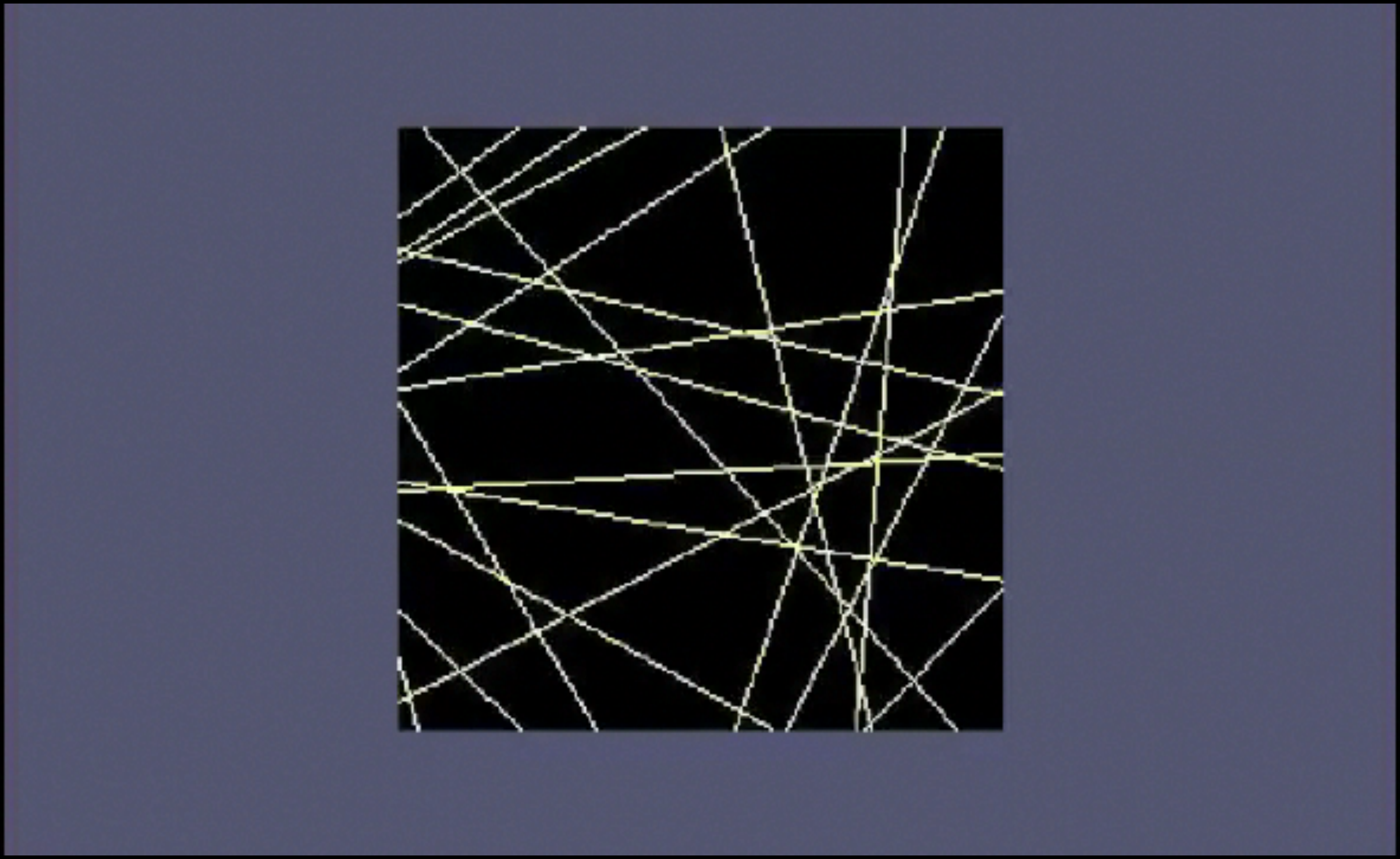




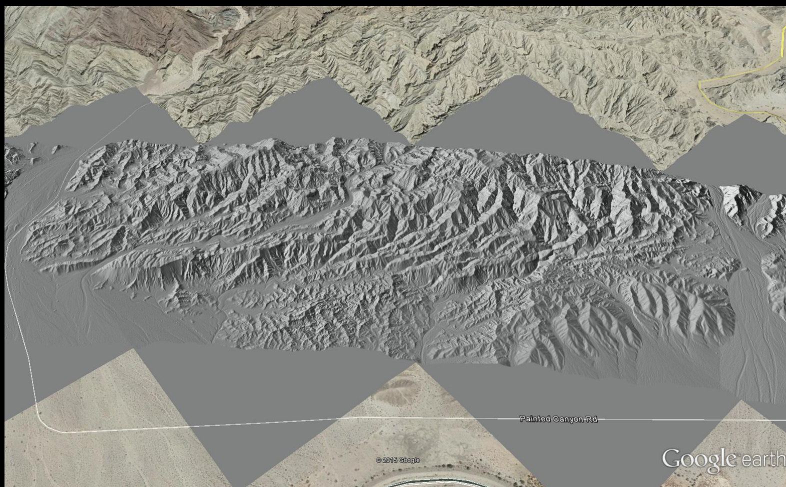


(source: Jordan Adams, Tulane University)

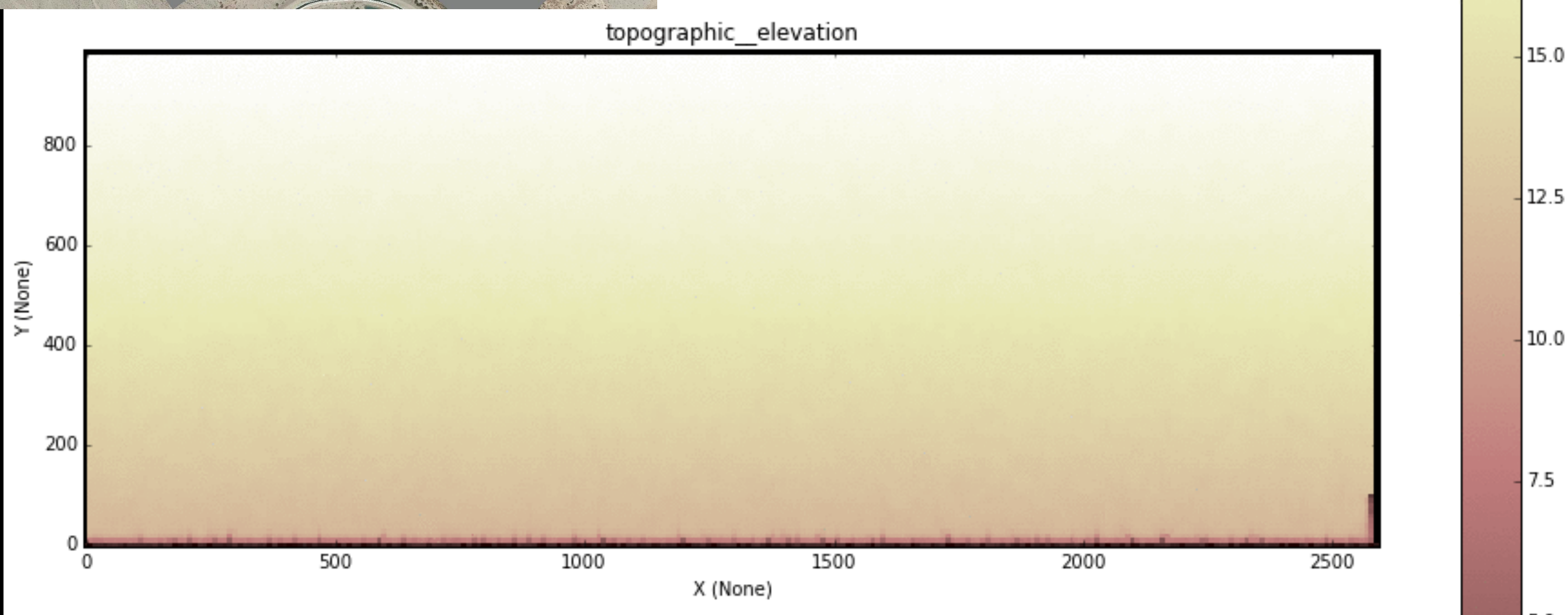
Cellular automaton model of weathering along fractures



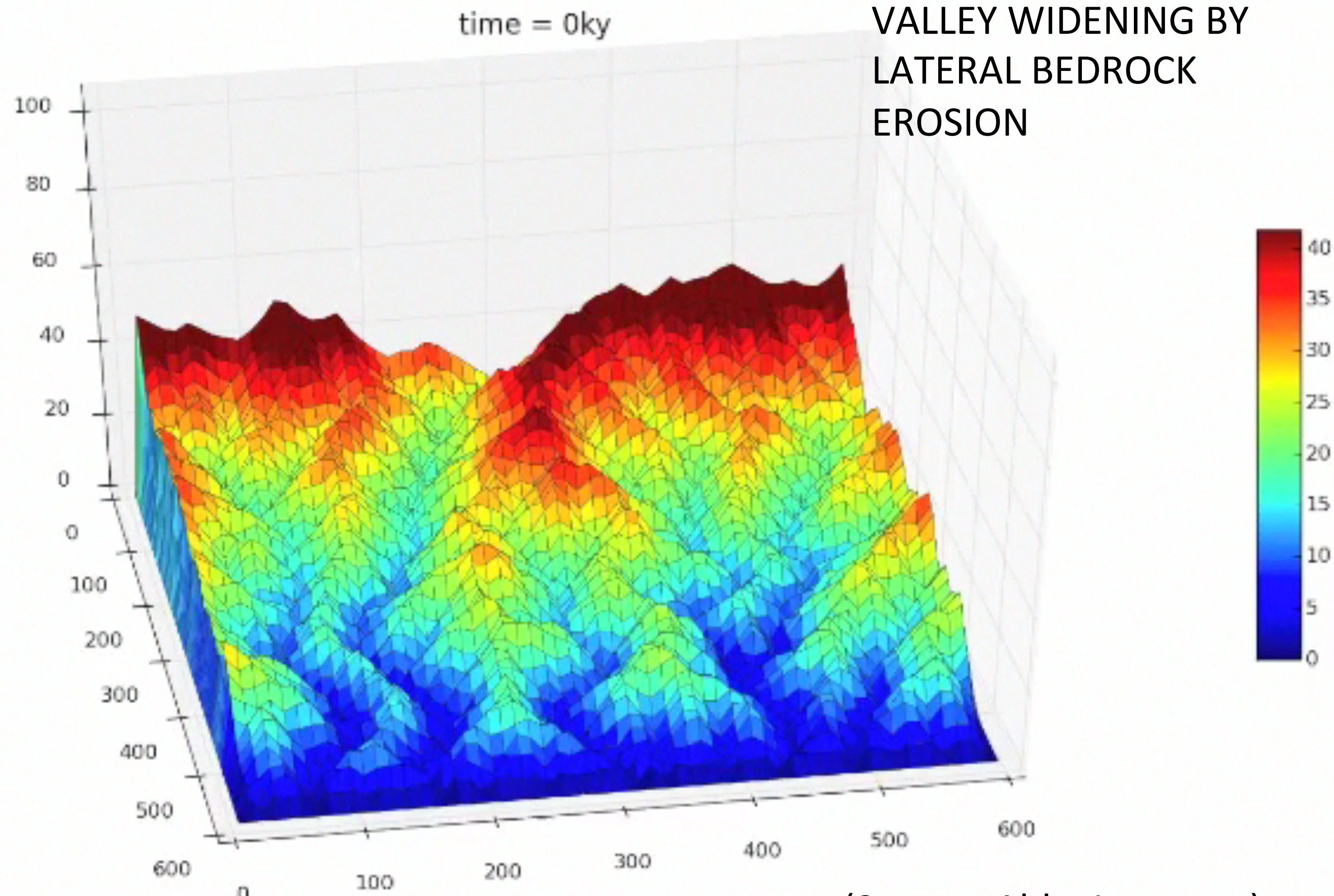
Why do strike-slip faults sometimes show distributed shear, and sometimes not?



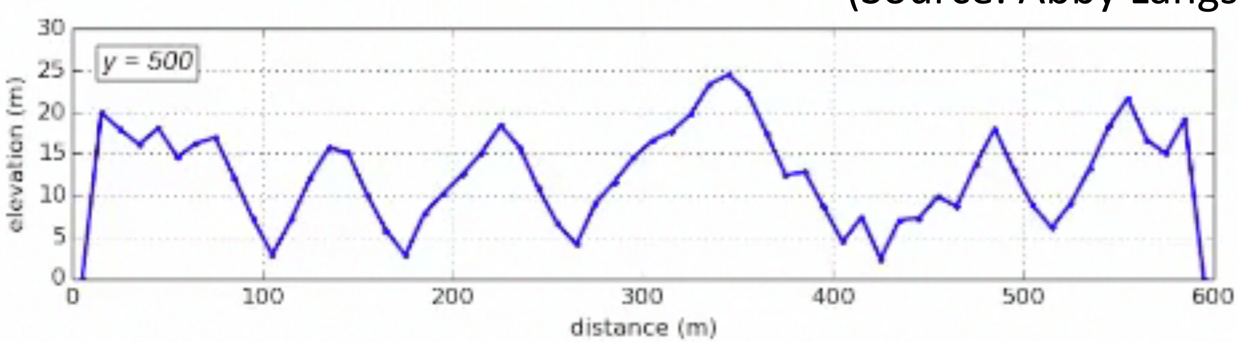
(Source: Harrison Gray, CU-Boulder)



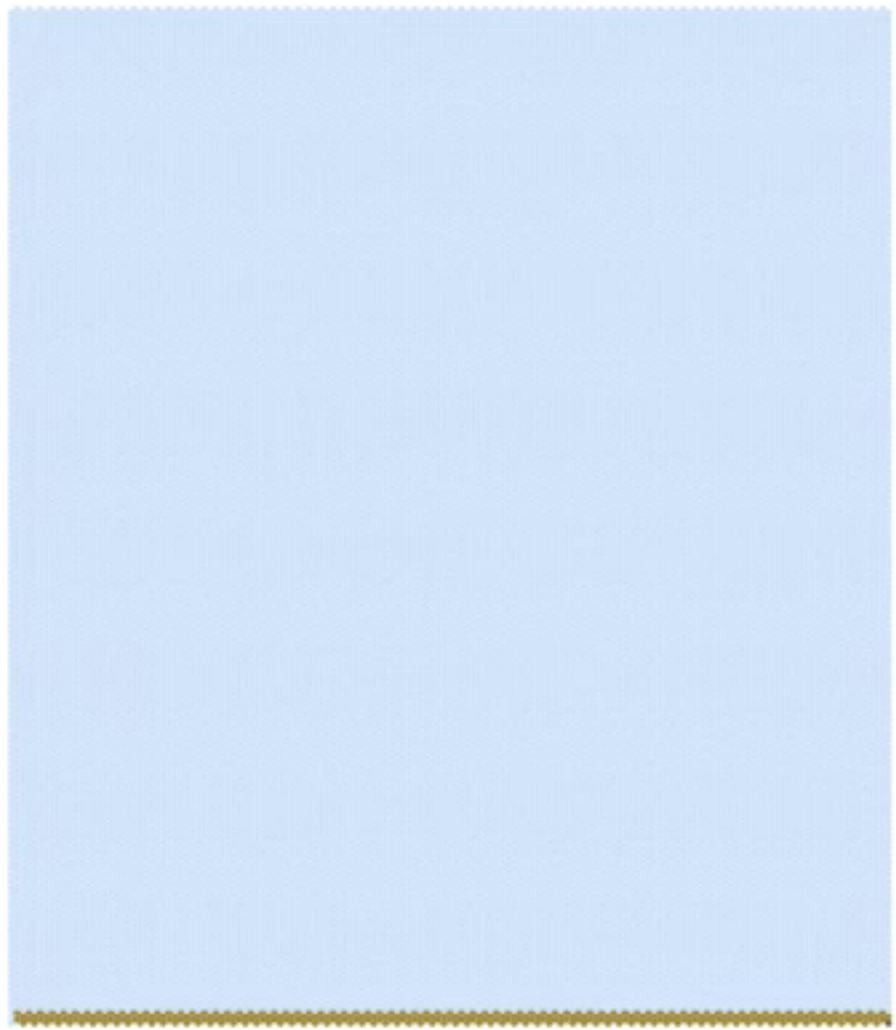
VALLEY WIDENING BY LATERAL BEDROCK EROSION



(Source: Abby Langston)

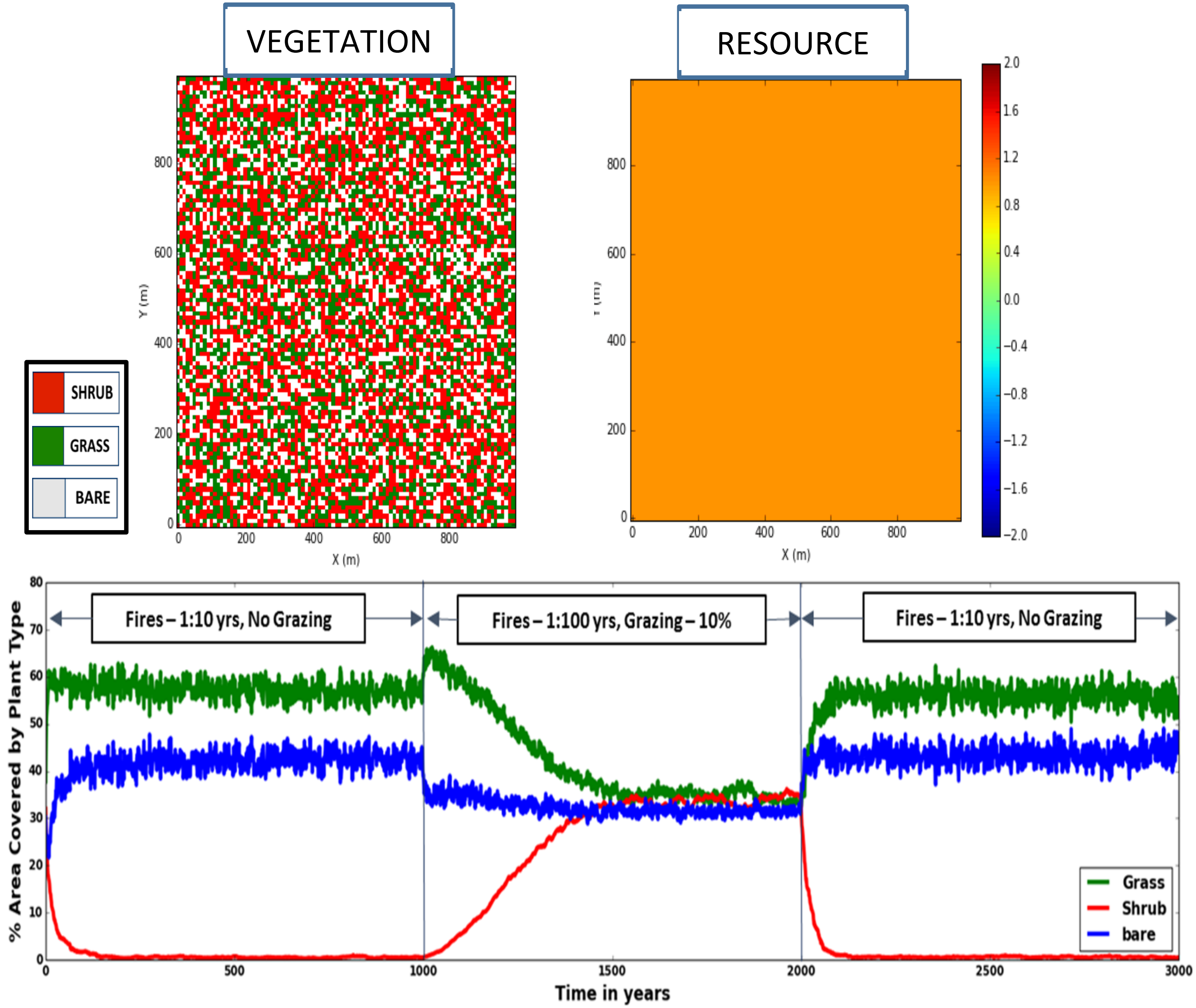


Weathering & disturbance similar to slip rate



$W' = D' = 1$

Climate Change Experiments #1



Using Landlab grids

- Aim: make it easier to set up a 2D numerical model grid
- Grid data and functions contained in a single Python object

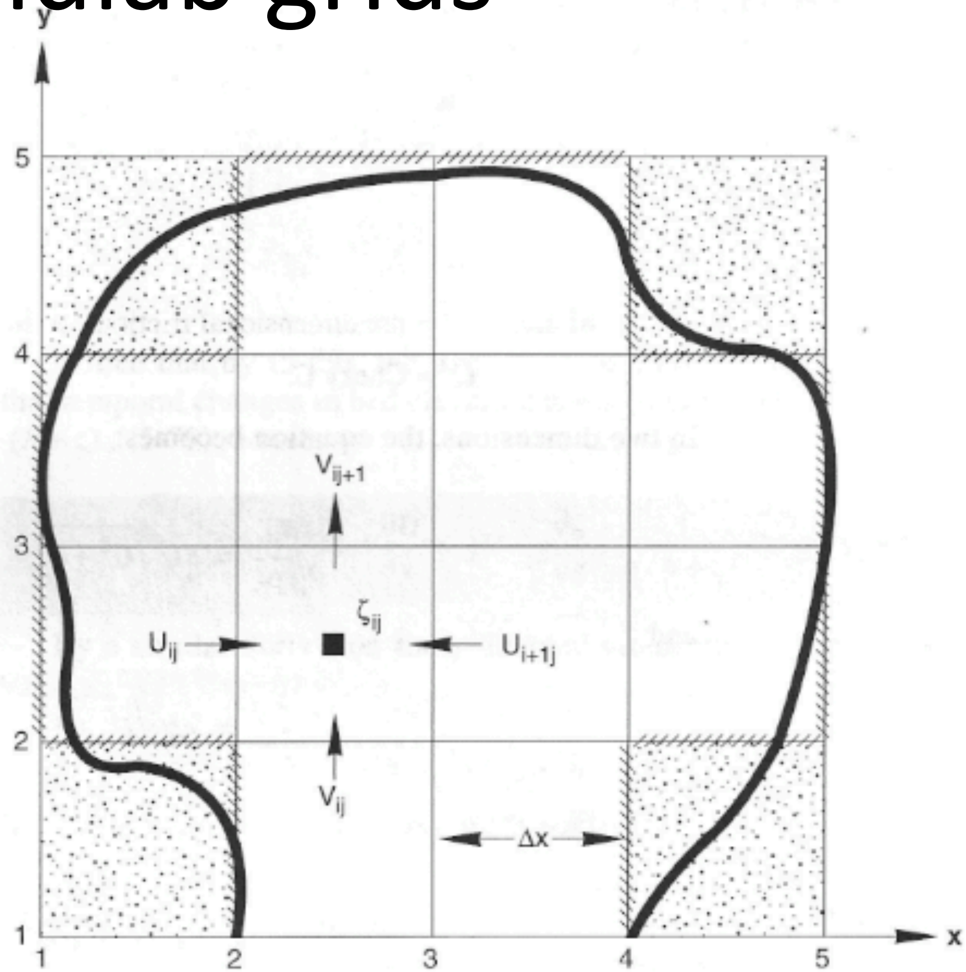
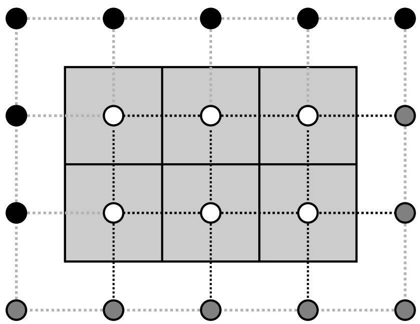


Figure 5-19 Discretization grid for 2-D circulation model.

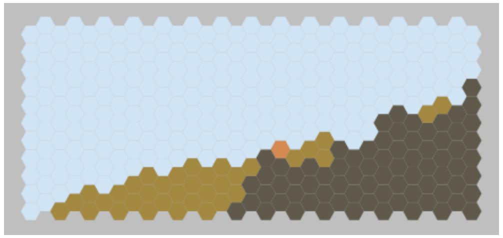
Slingerland, Harbaugh, and Furlong (1994)

Currently four grid types are available:

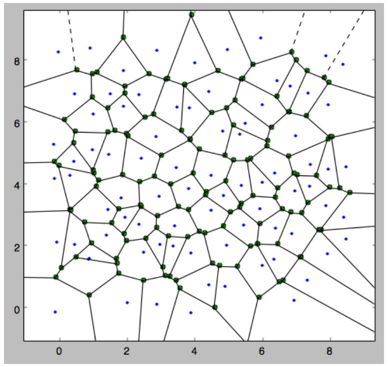
- `RasterModelGrid`



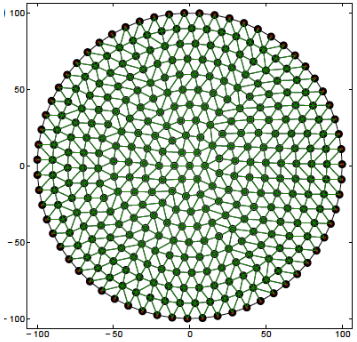
- `HexModelGrid`



- `VoronoiModelGrid`

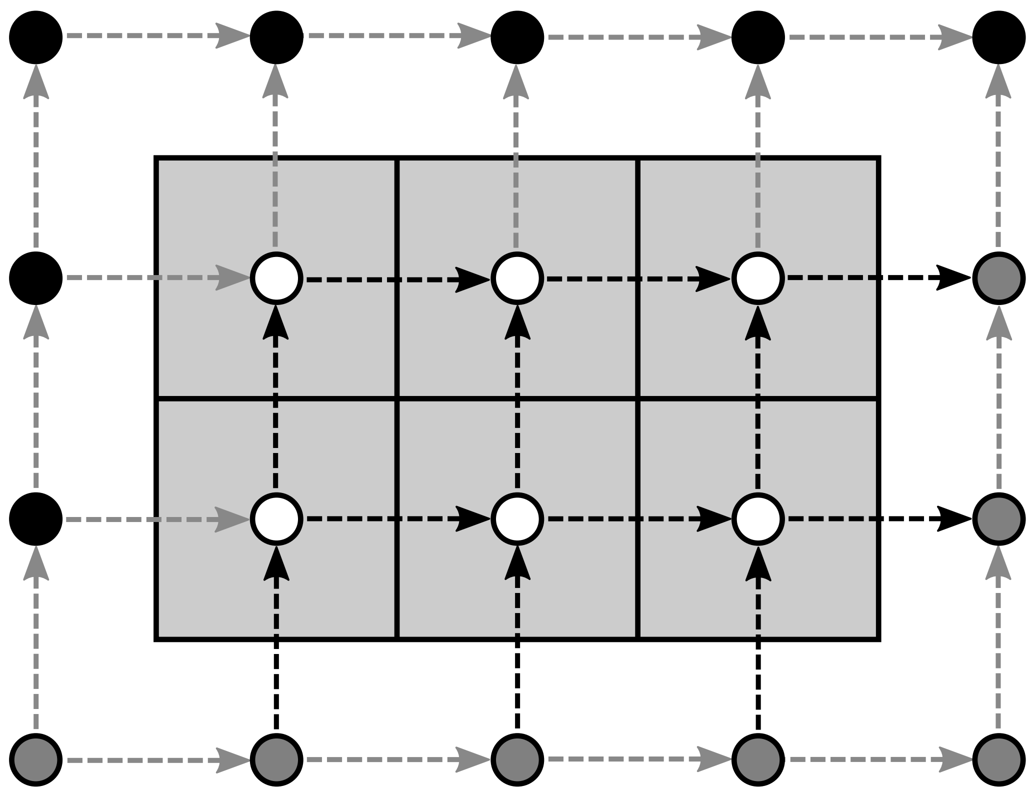


- `RadialModelGrid`

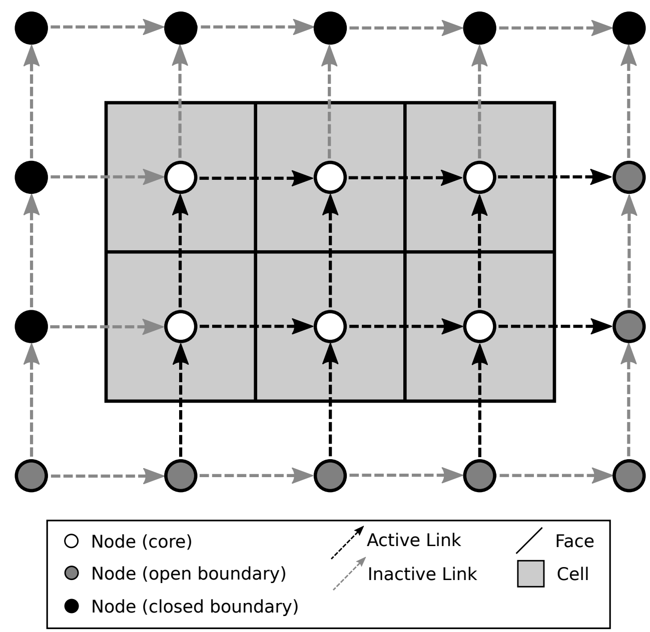


Example: creating a grid

```
>>> from landlab import RasterModelGrid
>>> rg = RasterModelGrid((4, 5), 10.0)
>>> rg.number_of_nodes
20
```



Grid elements: nodes

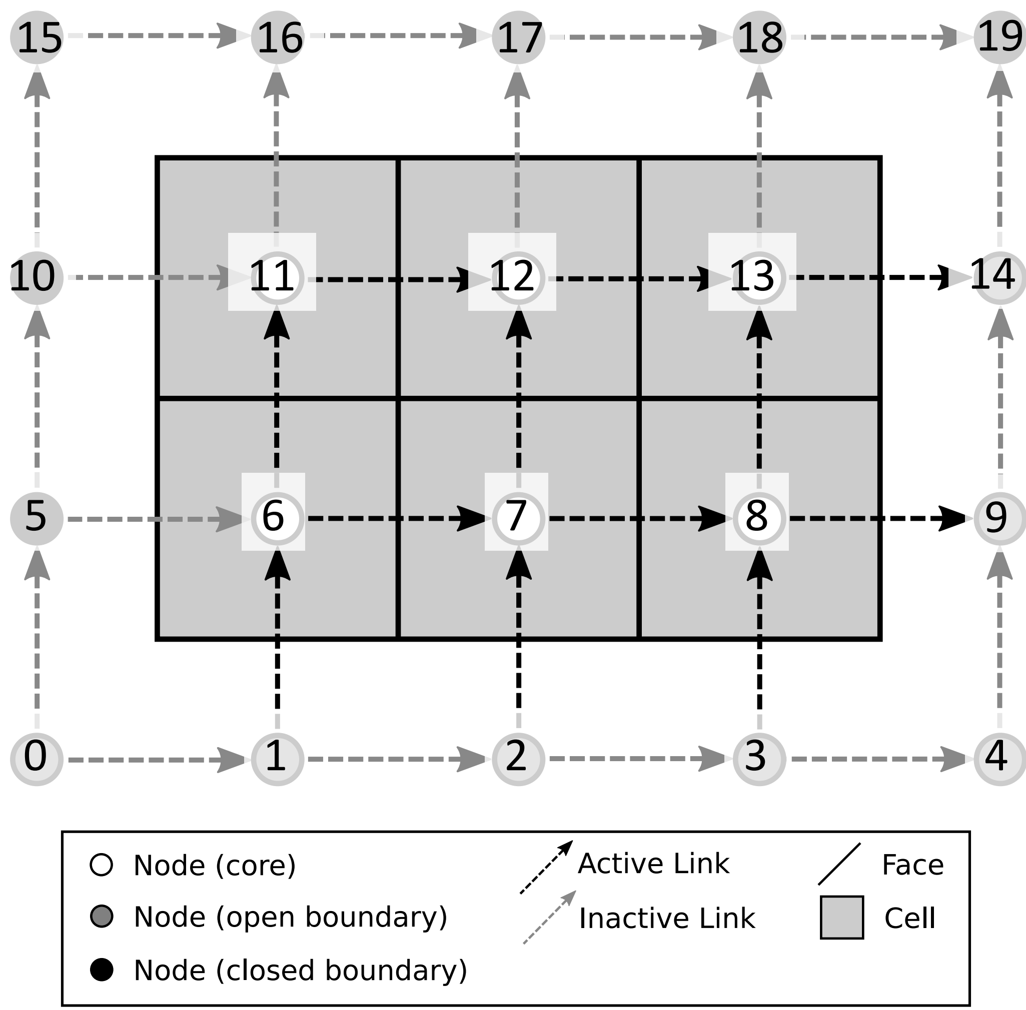



```
>>> rg.number_of_node_rows
4
>>> rg.number_of_node_columns
5
>>> rg.x_of_node
array([  0.,  10.,  20.,  30.,  40.,   0.,  10.,  20.,  30.,  40.,   0.,
        10.,  20.,  30.,  40.,   0.,  10.,  20.,  30.,  40.])
>>> rg.y_of_node
array([  0.,   0.,   0.,   0.,   0.,  10.,  10.,  10.,  10.,  10.,  20.,
        20.,  20.,  20.,  20.,  30.,  30.,  30.,  30.,  30.])
```

Node numbering

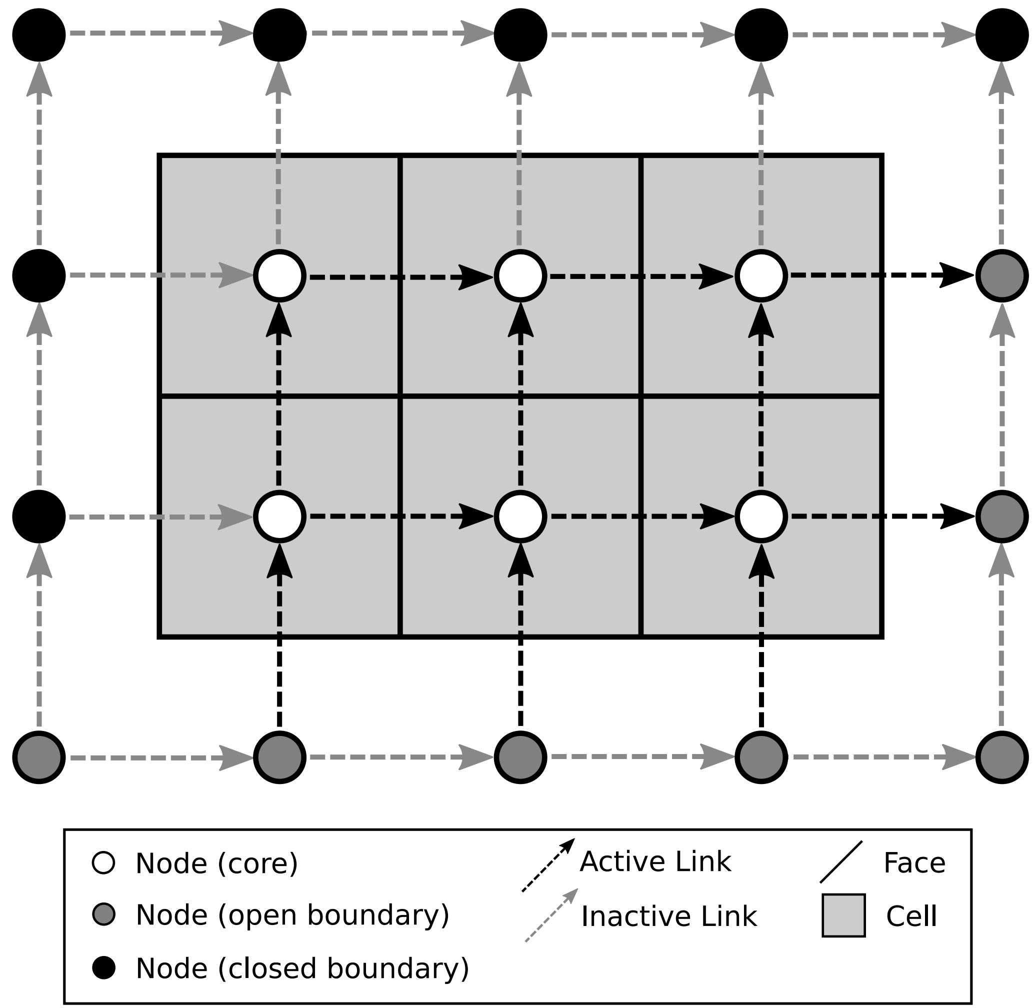
Nodes are always sorted by y coordinate

Nodes with equal y are sorted by x



Core and boundary nodes

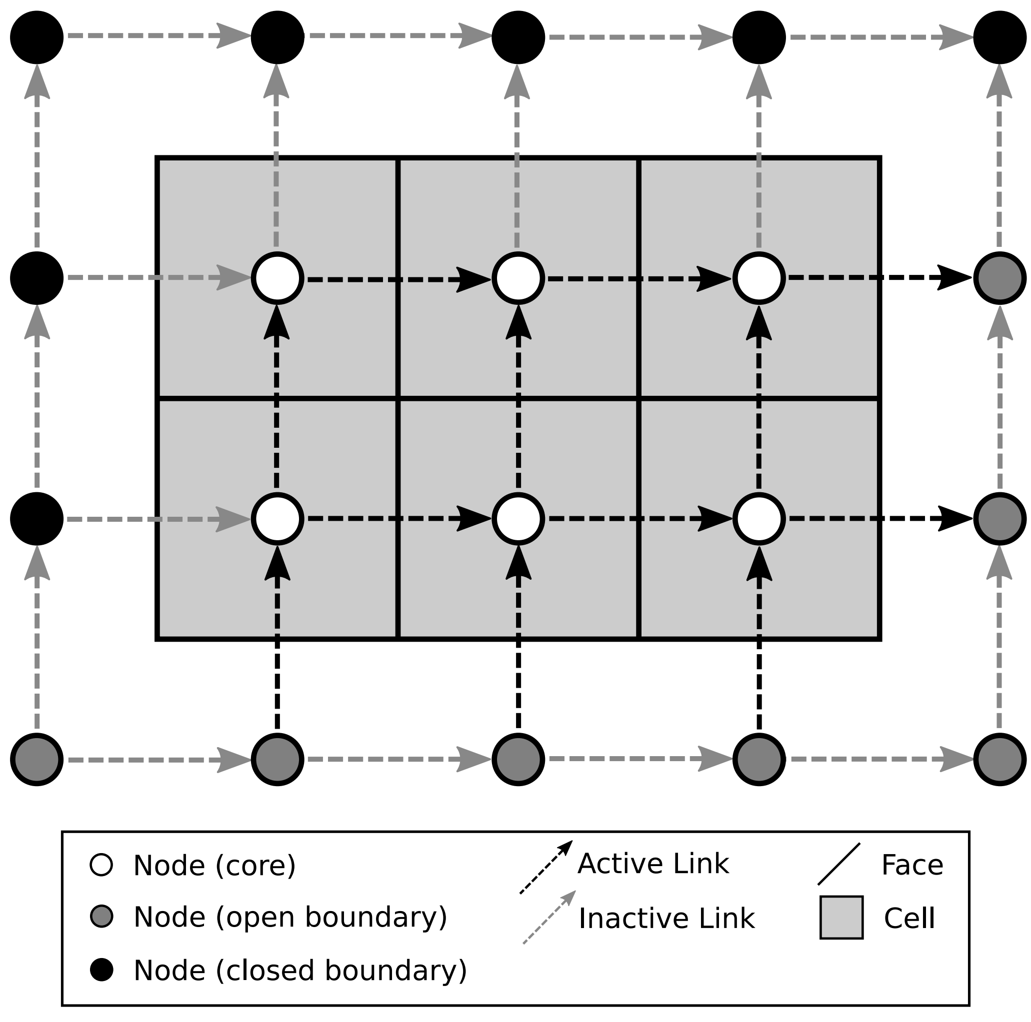
- Core nodes
- Boundary nodes
  - Open
    - **Fixed value**
    - Fixed gradient
    - Looped
  - Closed



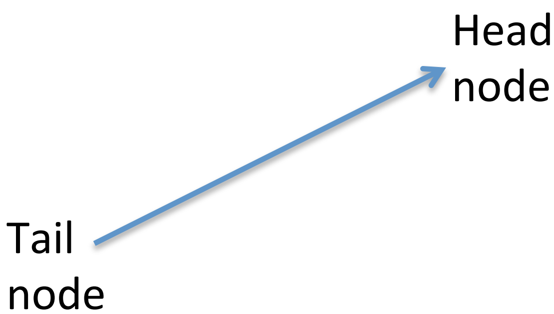
Grid elements: **links**

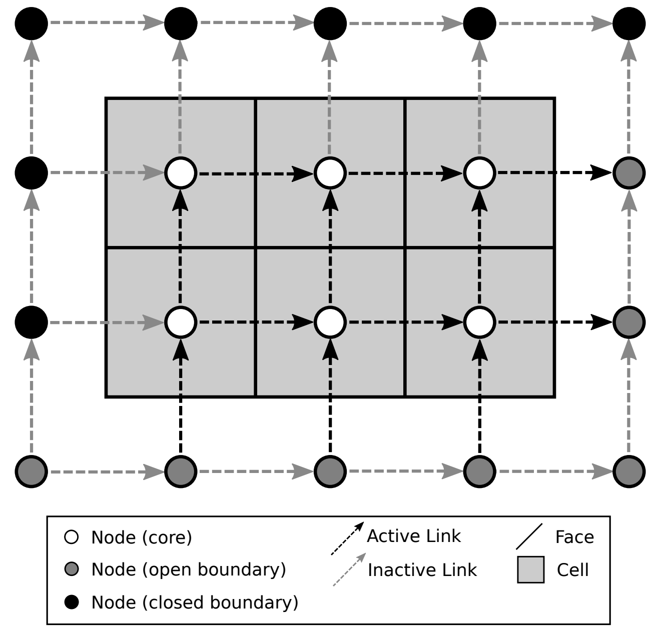
***Link* =**
directed line segment connecting two adjacent nodes

Link direction is toward upper right half-space by default



Grid elements: links



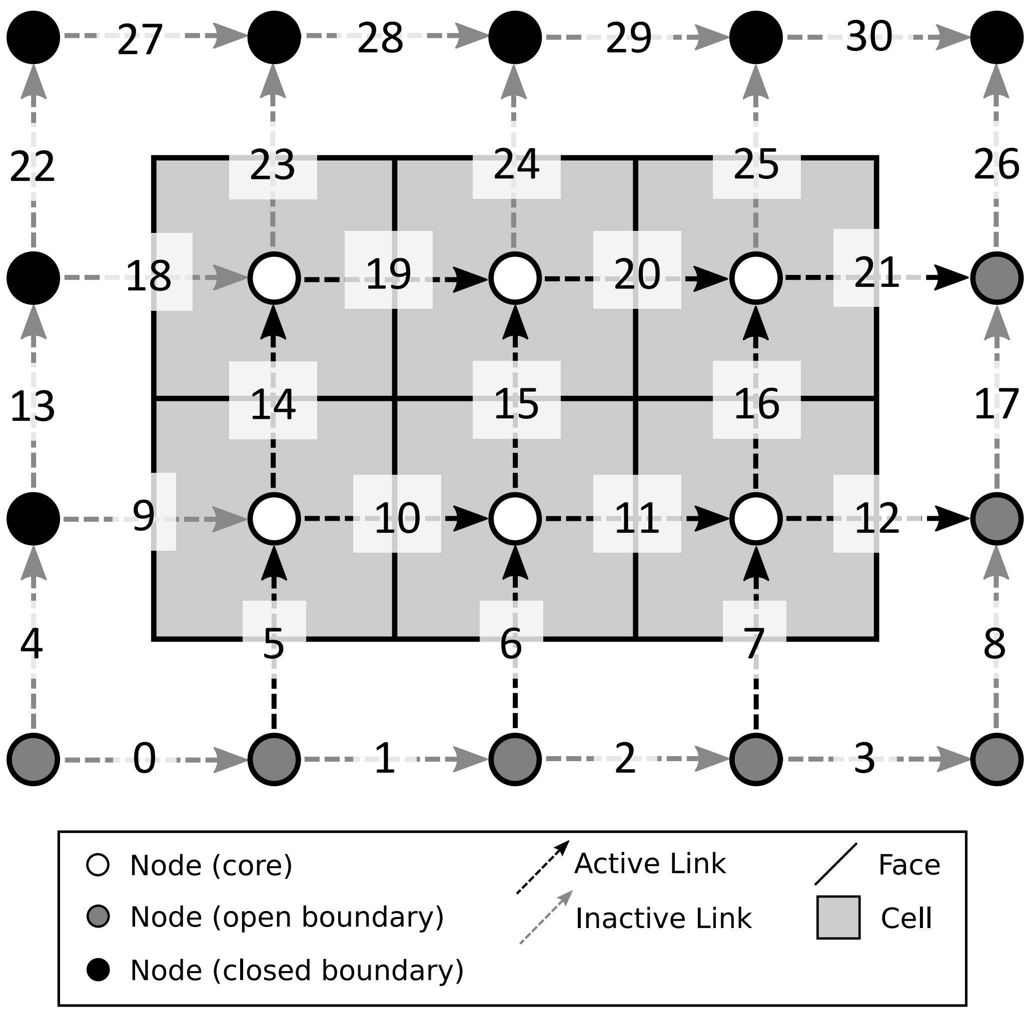



```
>>> rg.number_of_links
31
>>> rg.node_at_link_head
array([ 1,  2,  3,  4,  5,  6,  7,  8,  9,  6,  7,  8,  9, 10, 11, 12, 13,
       14, 11, 12, 13, 14, 15, 16, 17, 18, 19, 16, 17, 18, 19])
>>> rg.node_at_link_tail
array([ 0,  1,  2,  3,  0,  1,  2,  3,  4,  5,  6,  7,  8,  5,  6,  7,  8,
        9, 10, 11, 12, 13, 10, 11, 12, 13, 14, 15, 16, 17, 18])
```

Link numbering

Links are sorted by mid-point y coordinate

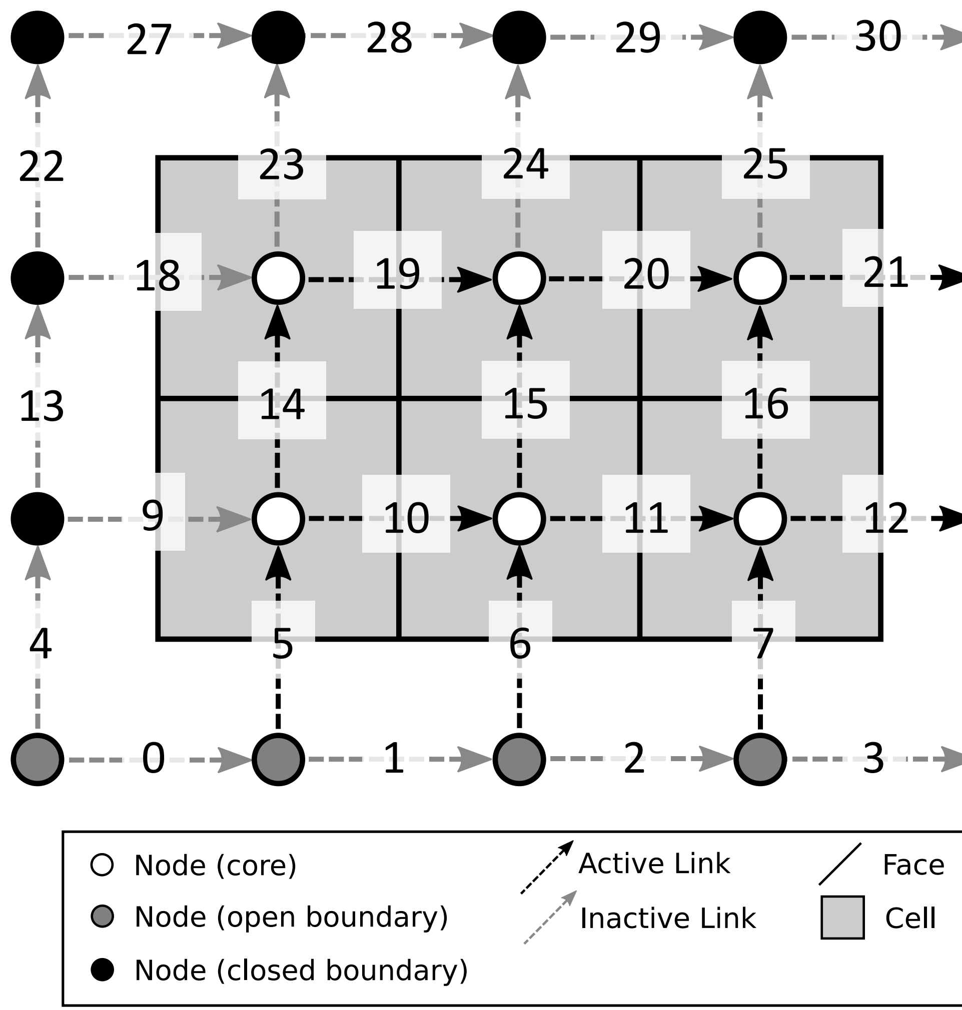
Links with equal y are sorted by x



Active and inactive links

ACTIVE:
Connects two core nodes OR a core and an open boundary

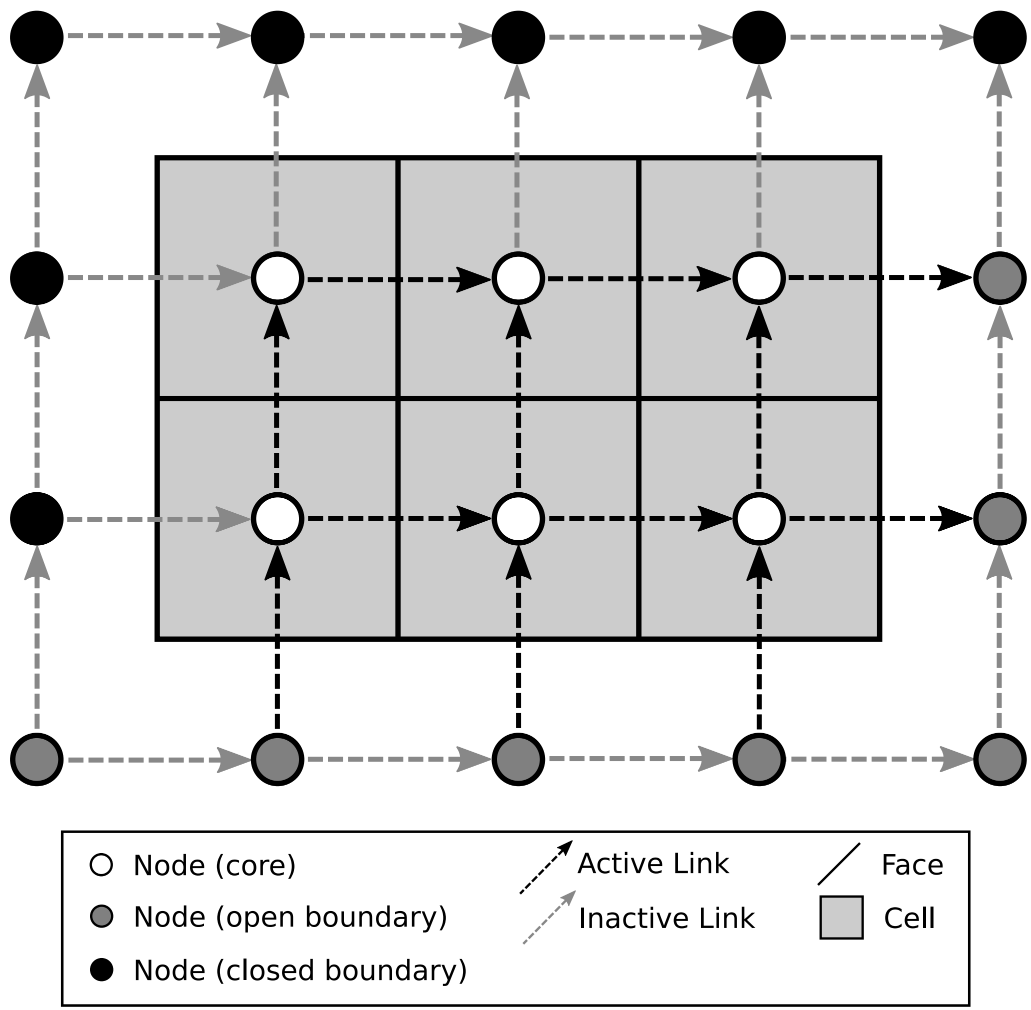
INACTIVE:
Connects to one or more closed boundary nodes OR Connects two open boundary nodes



Grid elements: **cells**

Cell* = polygon bounded by *faces* and containing a *node

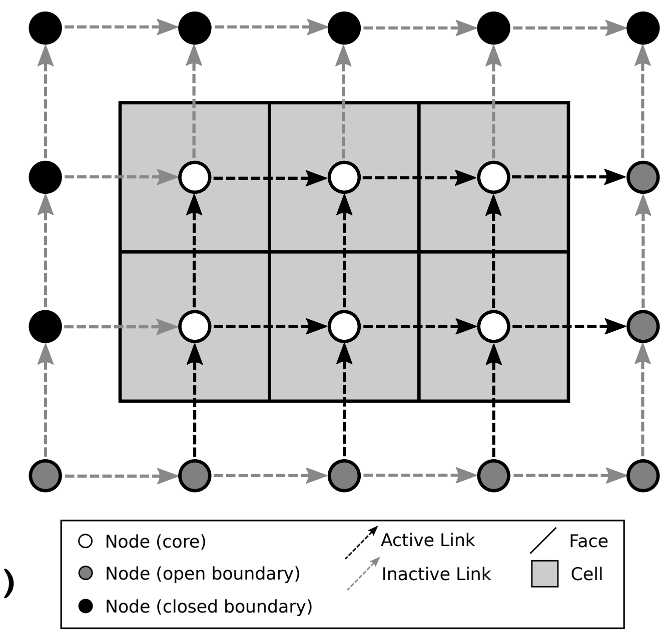
Perimeter nodes do not have cells



Grid elements: cells

Cells have:

- Area
- Faces
- A node

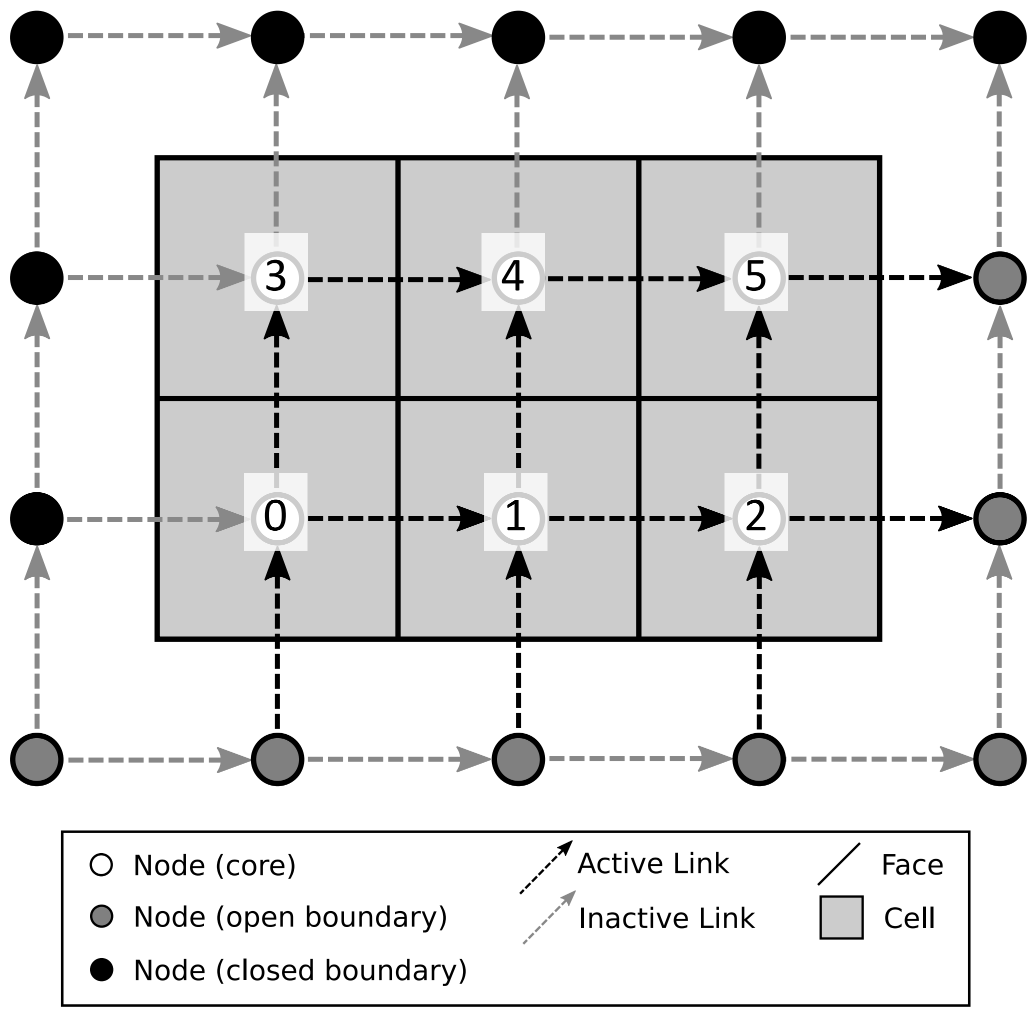



```
>>> rg.number_of_cells
6
>>> rg.area_of_cell
array([ 100.,  100.,  100.,  100.,  100.,  100.])
>>> rg.faces_at_cell
array([[ 4,  7,  3,  0],
       [ 5,  8,  4,  1],
       [ 6,  9,  5,  2],
       [11, 14, 10,  7],
       [12, 15, 11,  8],
       [13, 16, 12,  9]])
>>> rg.node_at_cell
array([ 6,  7,  8, 11, 12, 13])
```

Cell numbering

Cells are sorted by y coordinate

Cells with equal y are sorted by x



Fields: attaching data to the grid

- A **field** is a NumPy array containing data that are associated with a particular type of grid element (typically nodes or links)
- Fields are 1D arrays
- Values correspond to the element with the same ID. Example: value 5 of a node field belongs to node #5.
- Fields are "attached" to the grid (the grid object includes dictionaries listing all the fields)
- Fields have names (as strings)
- Create fields with grid functions `add_zeros`, `add_ones`, or `add_empty`

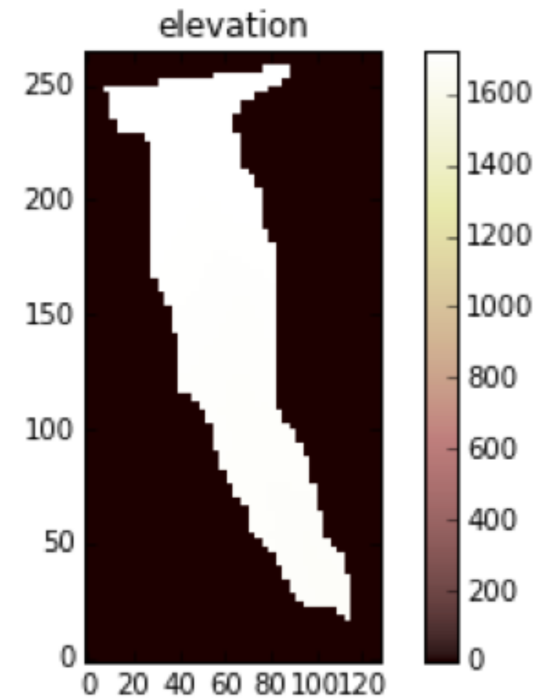
Fields: example

```
>>> h = rg.add_zeros('water__depth', at='node')
>>> h
array([ 0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,  0.,
        0.,  0.,  0.,  0.,  0.,  0.,  0.])
>>> h[1] = 100.0
>>> h
array([   0.,  100.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,
          0.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,
          0.,    0.])
>>> rg.at_node['water__depth']
array([   0.,  100.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,
          0.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,    0.,
          0.,    0.])
```

Reading raster digital terrain data

Landlab's read_esri_ascii function:

- Reads data from ESRI ASCII raster file
- Creates a RasterModelGrid and a data field
- Also: read/write netCDF files
- Example:




```
>>> from landlab.io import read_esri_ascii
>>> (mg, z) = read_esri_ascii('west_bijou_gully.asc',
                               name='elevation')
```

Staggered-grid schemes: Scalars at nodes, vectors at links

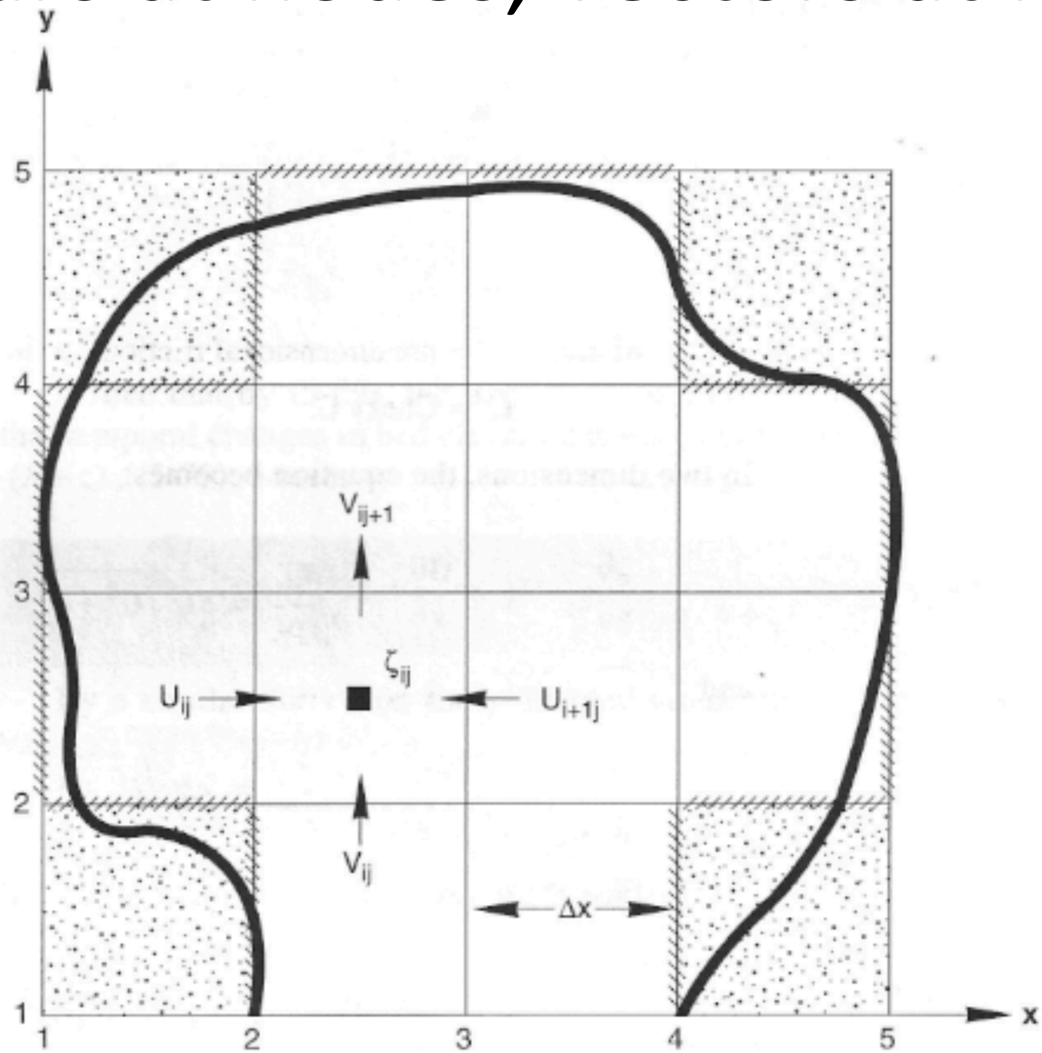


Figure 5-19 Discretization grid for 2-D circulation model. Slingerland, Harbaugh, and Furlong (1994)

Linear diffusion example

$$\boxed{\frac{\partial \eta}{\partial t} = -\nabla \mathbf{q}_s}$$

$\eta =$ land-surface elevation

$t =$ time

$\mathbf{q}_s =$ sediment flux $[L^2/T]$

$$\boxed{\mathbf{q}_s = -D\nabla\eta}$$

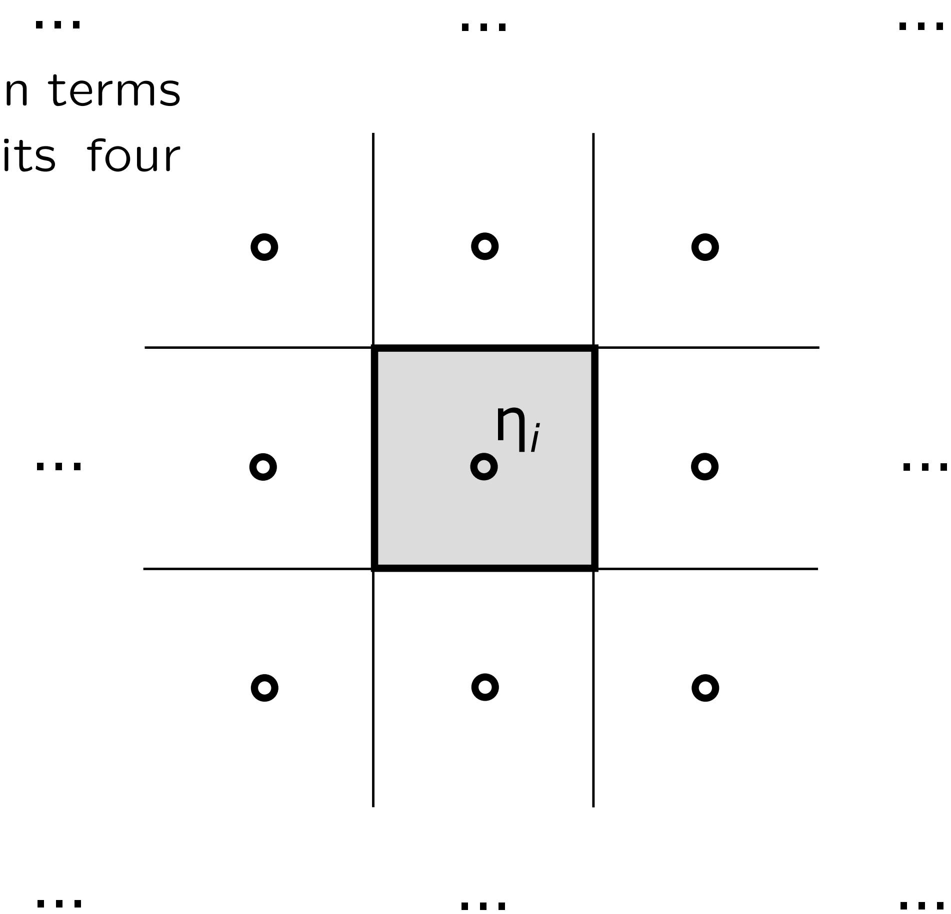
$D =$ transport coefficient $[L^2/T]$

The numerical problem: finite-volume solution scheme

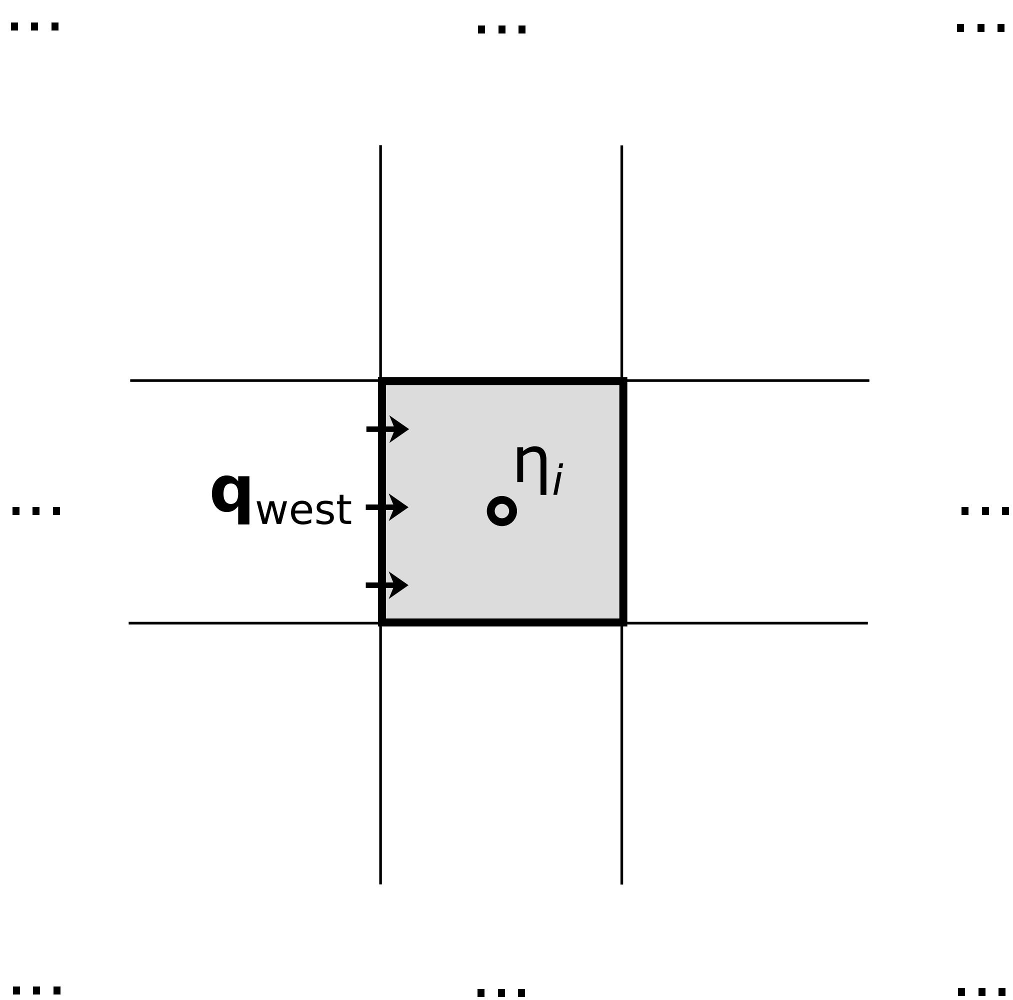
Each interior node i lies within a *cell* whose surface area is A_i.

We can write mass balance for cell i in terms of sediment fluxes across each of its four faces:

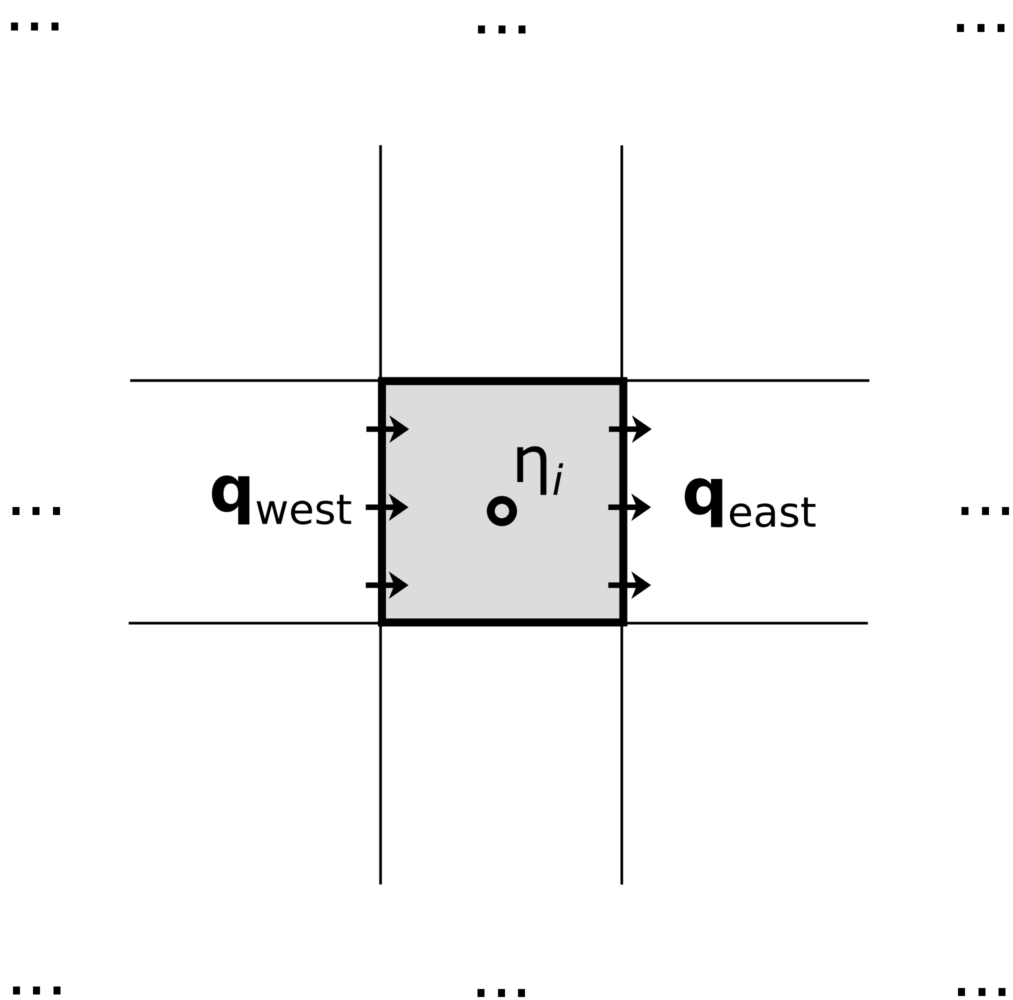
$$\boxed{\frac{d\eta_i}{dt} = \frac{1}{A_i}\sum_{j=1}^{4} \Delta x q_j}$$



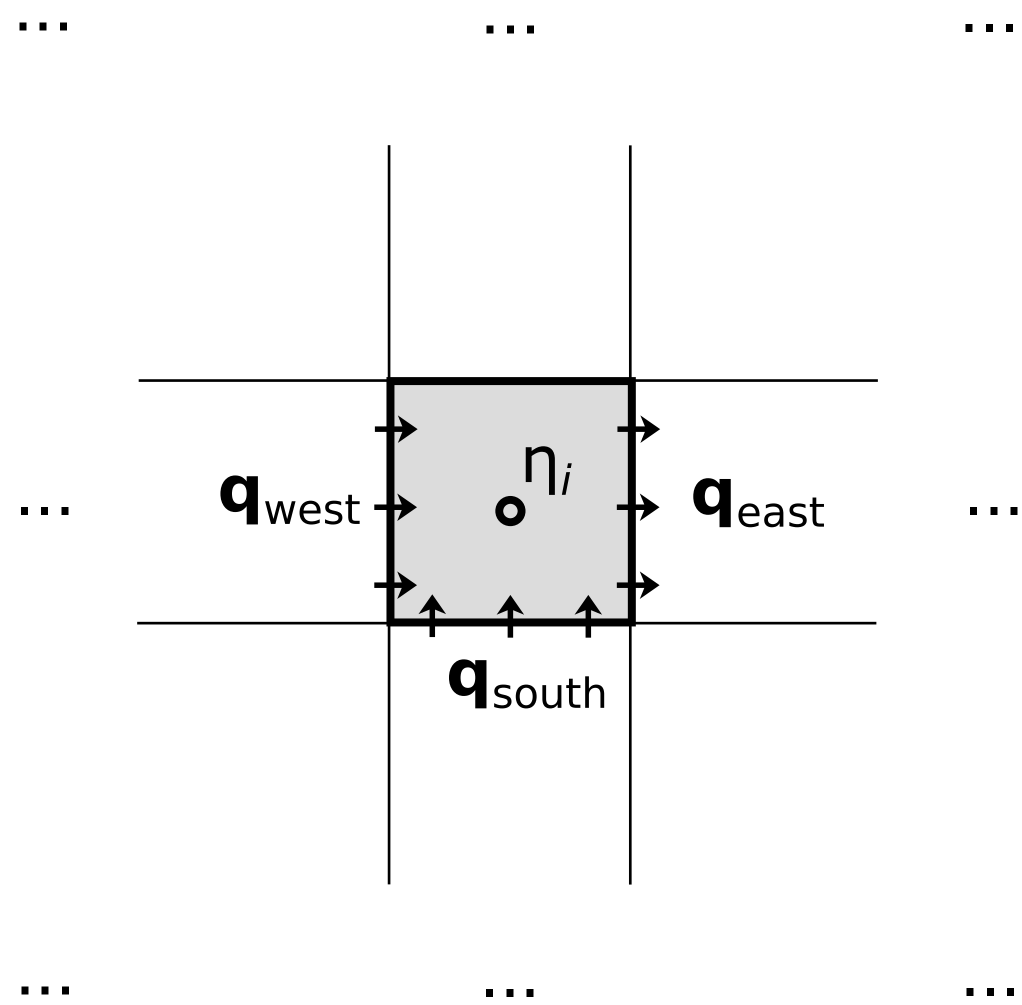
$$\frac{d\eta_i}{dt} = \frac{\Delta x}{A_i}[\mathbf{q}_{\mathrm{west}} \cdots$$



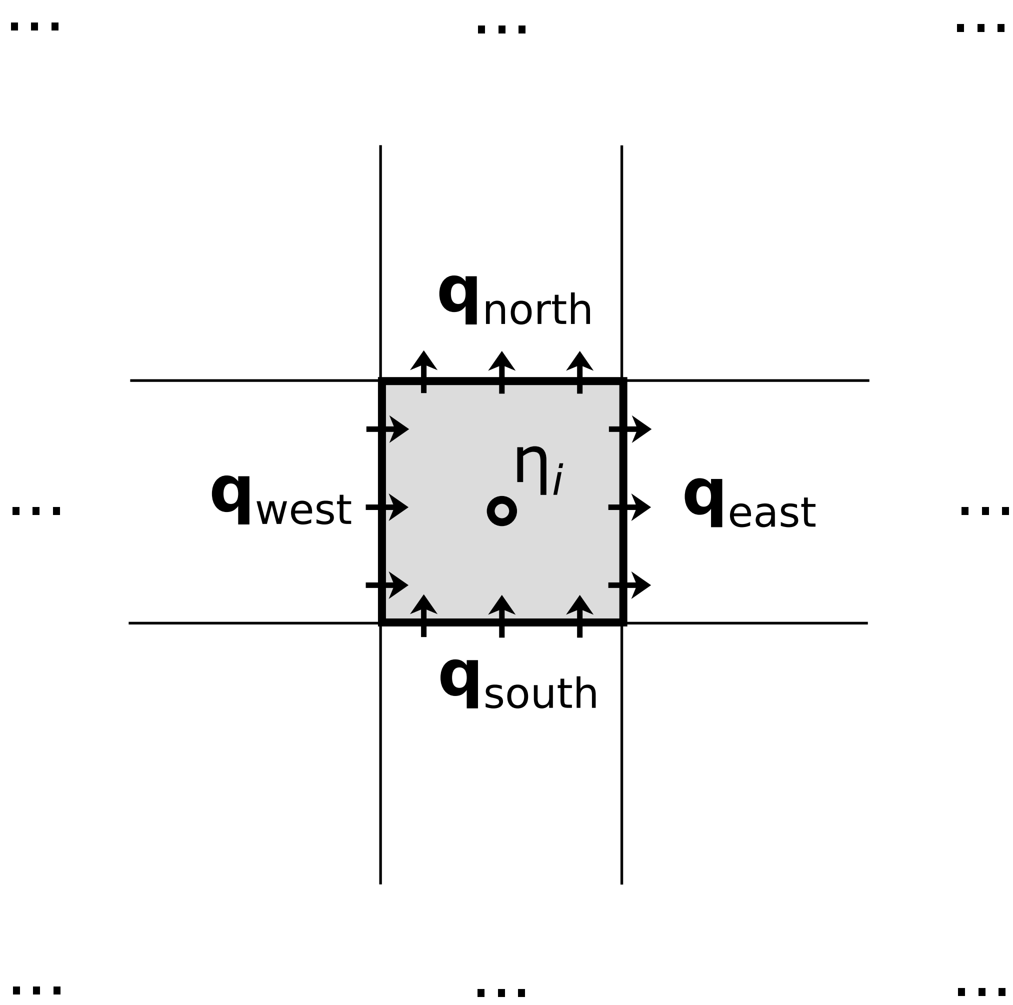
$$\frac{d\eta_i}{dt} = \frac{\Delta x}{A_i}[\mathbf{q}_{\mathrm{west}} - \mathbf{q}_{\mathrm{east}} \cdots$$



$$\frac{d\eta_i}{dt} = \frac{\Delta x}{A_i}[\mathbf{q}_{\text{west}} - \mathbf{q}_{\text{east}} + \mathbf{q}_{\text{south}} \cdots$$

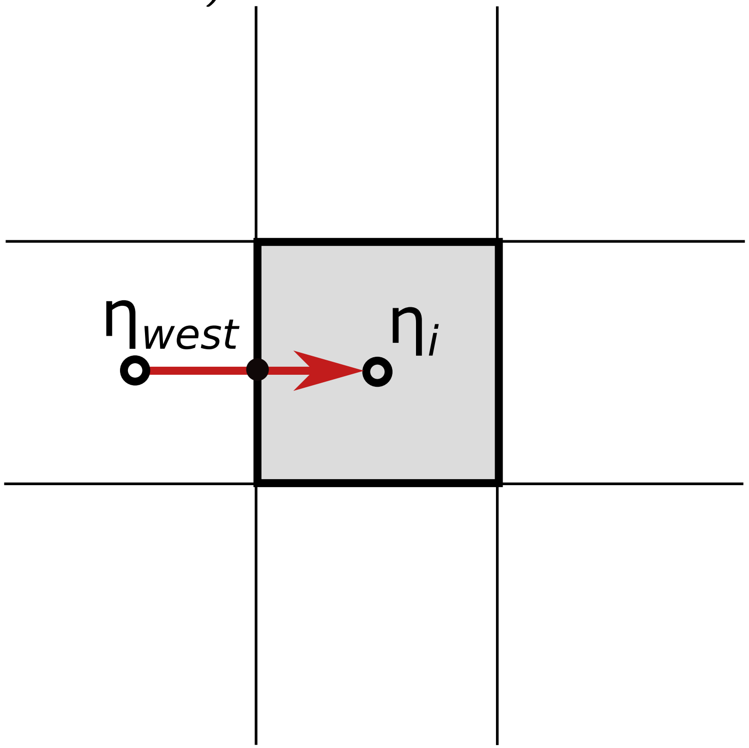


$$\frac{d\eta_i}{dt} = \frac{\Delta x}{A_i}[\mathbf{q}_{\text{west}} - \mathbf{q}_{\text{east}} + \mathbf{q}_{\text{south}} - \mathbf{q}_{\text{north}}]$$



Flux depends on gradient, which is calculated between adjacent nodes:

$$\mathbf{q}_{\text{west}} = -D\left.\frac{\partial \eta}{\partial x}\right|_{\text{(west face)}} \approx -D\left(\frac{\eta_i - \eta_{\text{west}}}{\Delta x}\right)$$

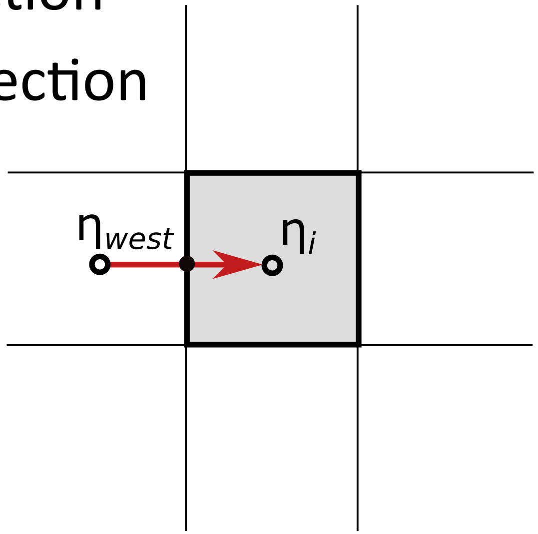


link from η_{west} to η_i

Calculating the gradient of a scalar field

```
>>> deta_dx = rg.calc_grad_at_link(eta)
```

- *eta* is a scalar defined at nodes
- One value of *deta_dx* for every link
- Positive when *eta* increases in the link direction
- Negative when *eta* decreases in the link direction

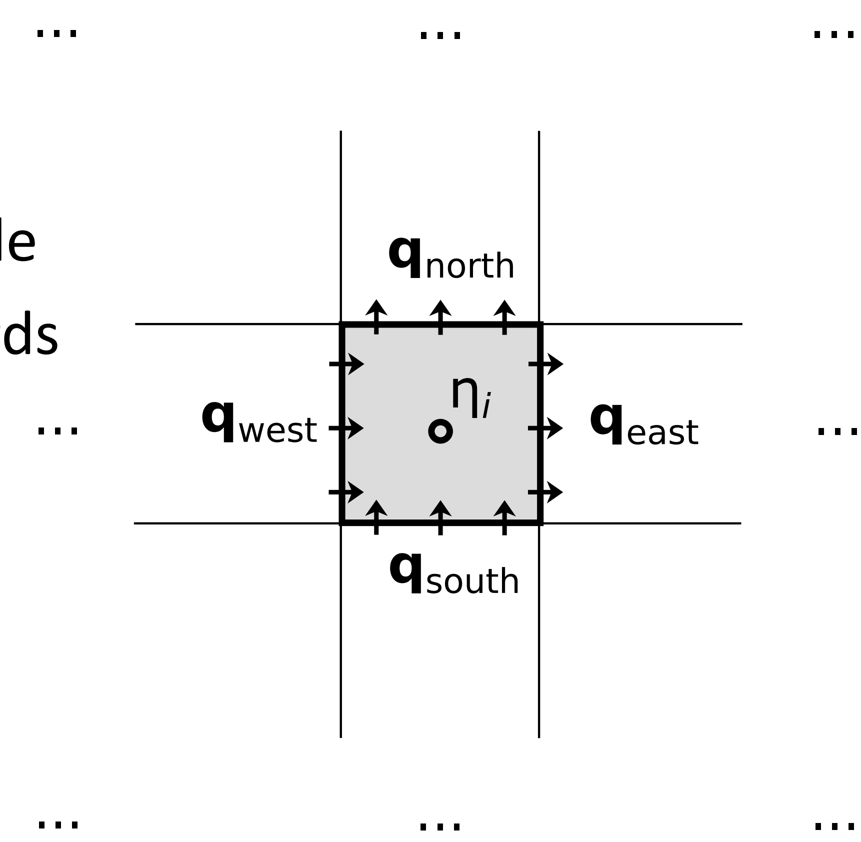


link from η_{west} to η_i

Calculating the divergence of a gradient field

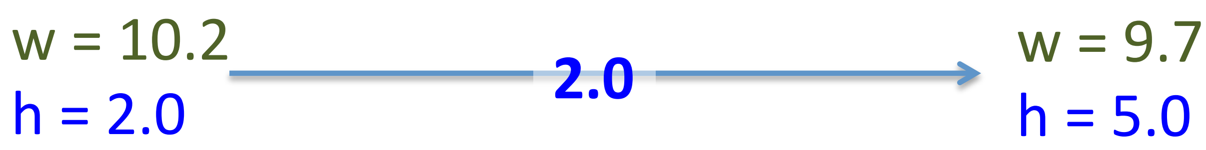
```
>>> q = -D * deta_dx
>>> dqdx = rg.calc_flux_div_at_node(q)
```

- *q* is a vector defined at links
- One value of *dqdx* for every node
- Positive when net flux is outwards



Q: What if you need a scalar value at a link?
A: Landlab's mapping functions


```
>>> h_link = rg.map_mean_of_link_nodes_to_link(h)
```




```
>>> h_link = rg.map_value_at_max_node_to_link(w, h)
```

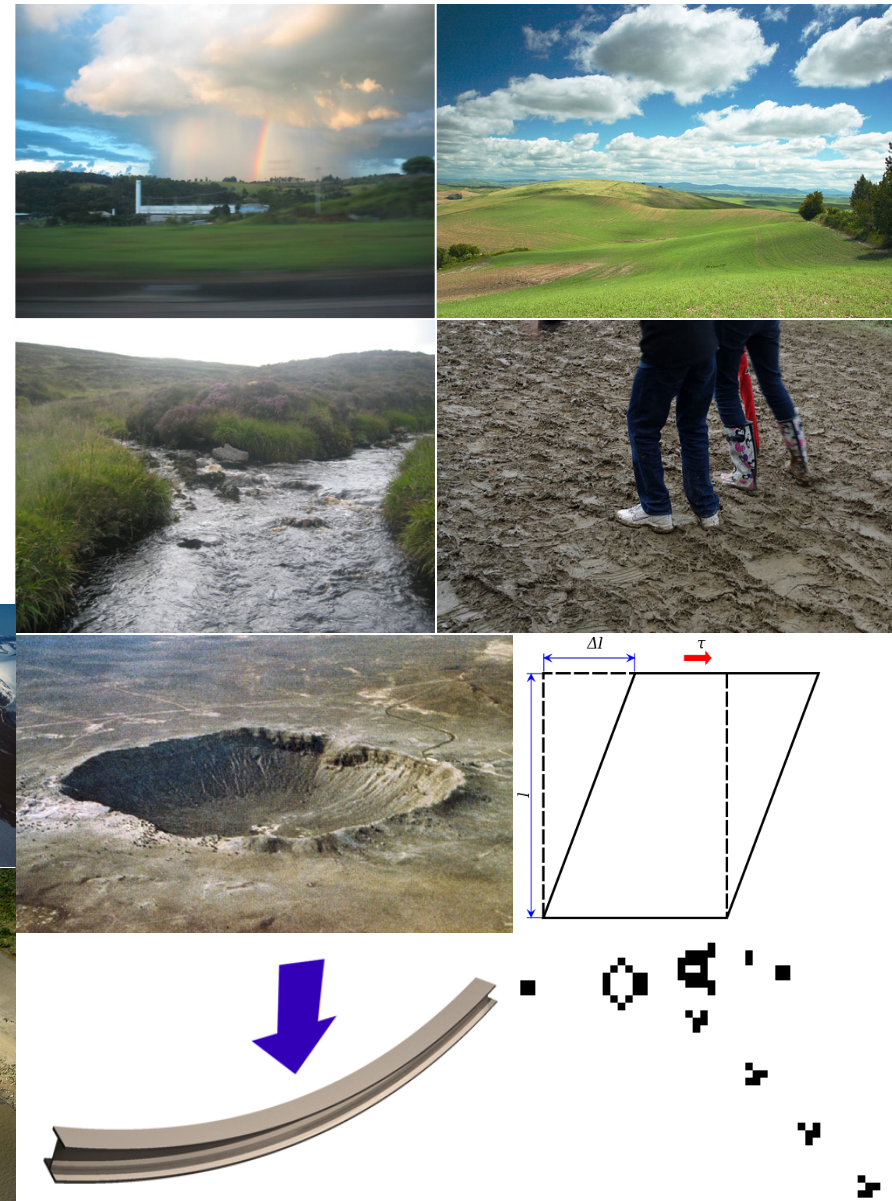
Components

- A **component** is a self-contained piece of code that typically represents one process
- Components have a standardized interface that allows them to be easily coupled with one another using a Python script
- Components are normally implemented as Python classes. For example:

```
>>> ld = LinearDiffuser(rg, linear_diffusivity=0.01)
>>> ld.run_one_step(dt=1.0)
```

The components

- Describe individual surface processes
- “Plug & Play”
- Standard interface
- Use the library, or BYO



Documentation: Users' Guide

GitHub, Inc. (US) https://github.com/landlab/landlab/wiki/User-Guide

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User Guide

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Jenny Knuth edited this page on Mar 1 · 53 revisions

https://github.com/landlab/landlab/wiki/User-Guide

Landlab | About | Examples | User Guide | Developer API | Tutorials | FAQs

Installation

- Instructions for a standard install
- Installing from source code, "developer install"

Basics of Python

If you are new to Python or scientific programming, start with an intro to the nuts and bolts of Landlab:

Python, NumPy, SciPy, and Cython

- Why Python?
- Getting to know Python
  - If you know MatLab...
- NumPy, SciPy, and efficient coding style
- Cython

Landlab's grid

Documentation: Reference / API

landlab.readthedocs.io/en/latest/#developer-documentation

Landlab Reference Manual and API Documentation

http://landlab.readthedocs.io

The *Landlab Developer API* is a general reference manual for Landlab.

Grids

Grid types

As of Landlab version 0.2, there are four types of Landlab grid:

- Raster
- Voronoi-Delaunay
- Hex
- Radial

The base class is *`ModelGrid`* with subclasses *`RasterModelGrid`* and *`VoronoiDelaunayGrid`*.

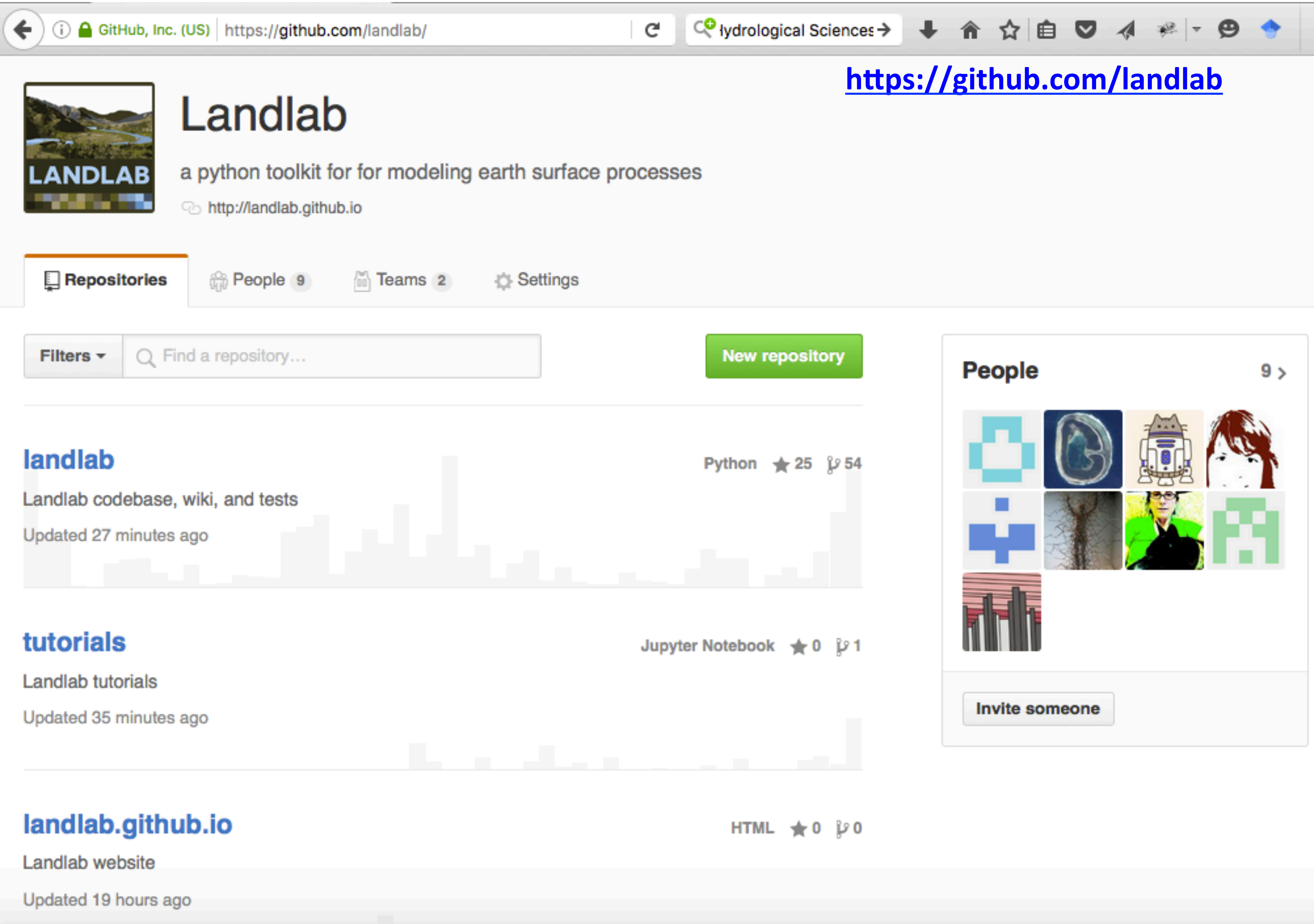
`VoronoiDelaunayGrid` has two further specialized subclasses: *`HexModelGrid`* and *`RadialModelGrid`*.

Methods and properties common to all grids

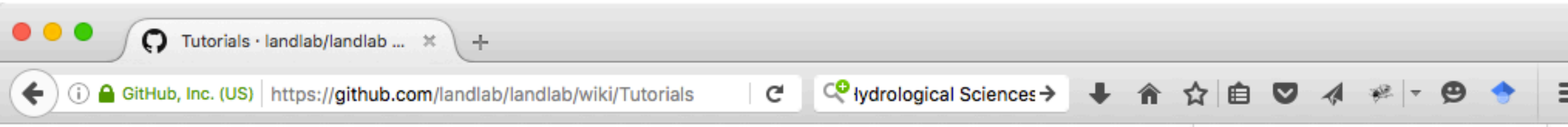
- Mapping data between different grid elements
  - Grid mapping functions
- Gradient calculators
  - Gradient calculation functions
- Divergence calculation functions
- Grid creation from a formatted input file
- General class methods and attributes of the *`landlab.grid.base`* module
  - Getting Information about a Grid

Documentation: source code, tutorials, etc., publicly available on GitHub

https://github.com/landlab



https://github.com/landlab/landlab/wiki/Tutorials



IPython notebook tutorials

Instructions on how to run an IPython notebook can be found here: https://github.com/landlab/tutorials/blob/master/README.md

A short IPython notebook tutorial along with a screencast can be found here (the tutorial uses an example with statistics, but you can substitute Landlab!): http://www.randalolson.com/2012/05/12/a-short-demo-on-how-to-use-ipython-notebook-as-a-research-notebook/

Click here to download all the tutorials

A suggested introduction to Landlab follows roughly this order:

- Introduction to Python and NumPy
- Introduction to Landlab: example model of fault-scarp degradation
- Introduction to the model grid object
- Introduction to Landlab data fields
- Introduction to plotting output with Landlab
- Introduction to using the Landlab component library
- Using the gradient and flux-divergence functions
- Mapping values from nodes to links
- Setting boundary conditions on Landlab grids (several tutorials)
- reading DEMs into Landlab
- How to write a Landlab component

CellLab CTS 2015 Users Manual
Components
Correcting Python Version
Developing with github and git
Examples
FAQs
Grid
Installing Landlab
Installing Landlab from source code ("developer install")
Installing Landlab with Anaconda
Installing Python
Introducing Landlab 1.0beta
Show 8 more pages…

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Clone this wiki locally

`https://github.com/landlab/`

If you still need to install:

http://landlab.github.io

➔Install

Follow instructions

How to update Landlab

In terminal window or command prompt:

pip uninstall landlab

conda install landlab –c landlab

How to download and run tutorials

- Go to: https://github.com/landlab/landlab/wiki/Tutorials
- Click:

  Click here to download all the tutorials
- Save ZIP
- Double-click to unpack
- In terminal or command window, **navigate to new folder**
- Enter: `jupyter notebook`
- Shift-Enter to move through each cell