r.accumulate: Efficient computation of hydrologic parameters in GRASS

February 2, 2020
FOSDEM 2021

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GRASS GIS Core Developer

Me

- Huidae Cho /hidɛ t͡ɕo/
- Teaching geospatial science and computing at the University of North Georgia
- GRASS GIS core developer (20 years)
- ArcGIS developer (12 years)
- Water resources engineer (10 years)
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- grass4u@gmail.com

Source code

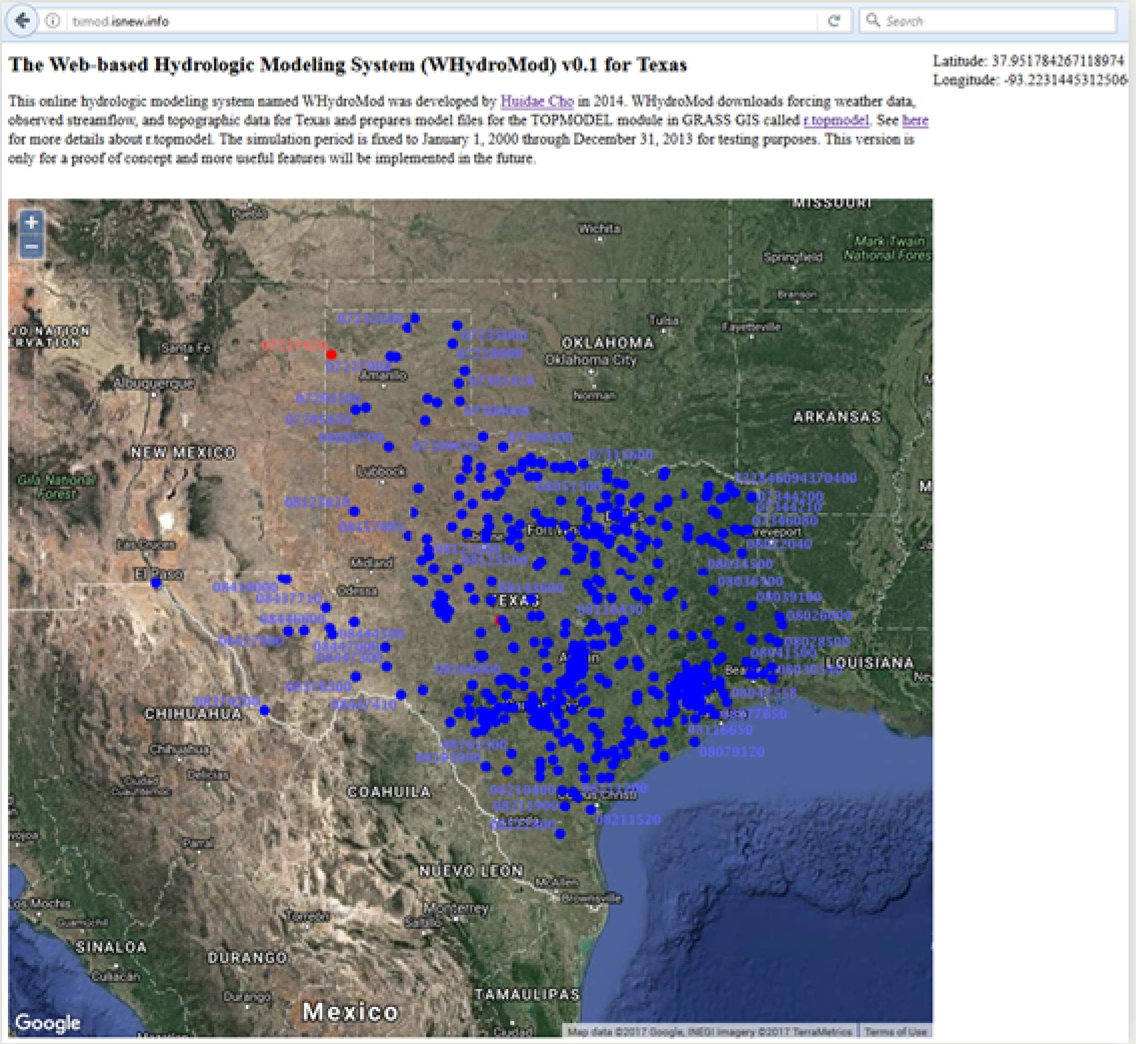
- https://github.com/OSGeo/grass-addons/tree/master/grass7/raster/r.accumulate

Web-based hydrologic modeling system (WHydroMod)

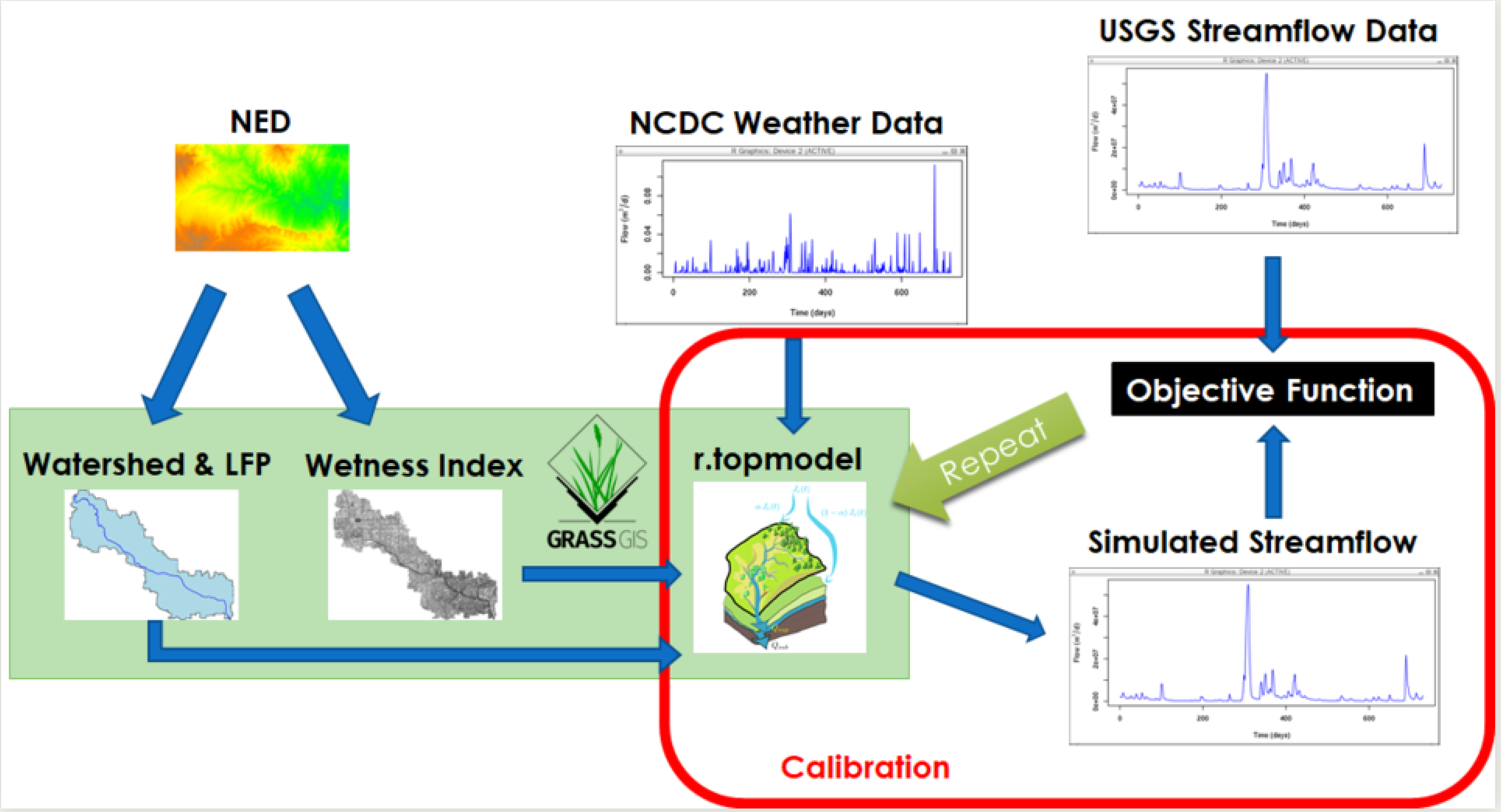
- r.topmodel: A GRASS module for the Topography Model (TOPMODEL)
- USGS online data
- NCDC web API

WHydroMod for Texas

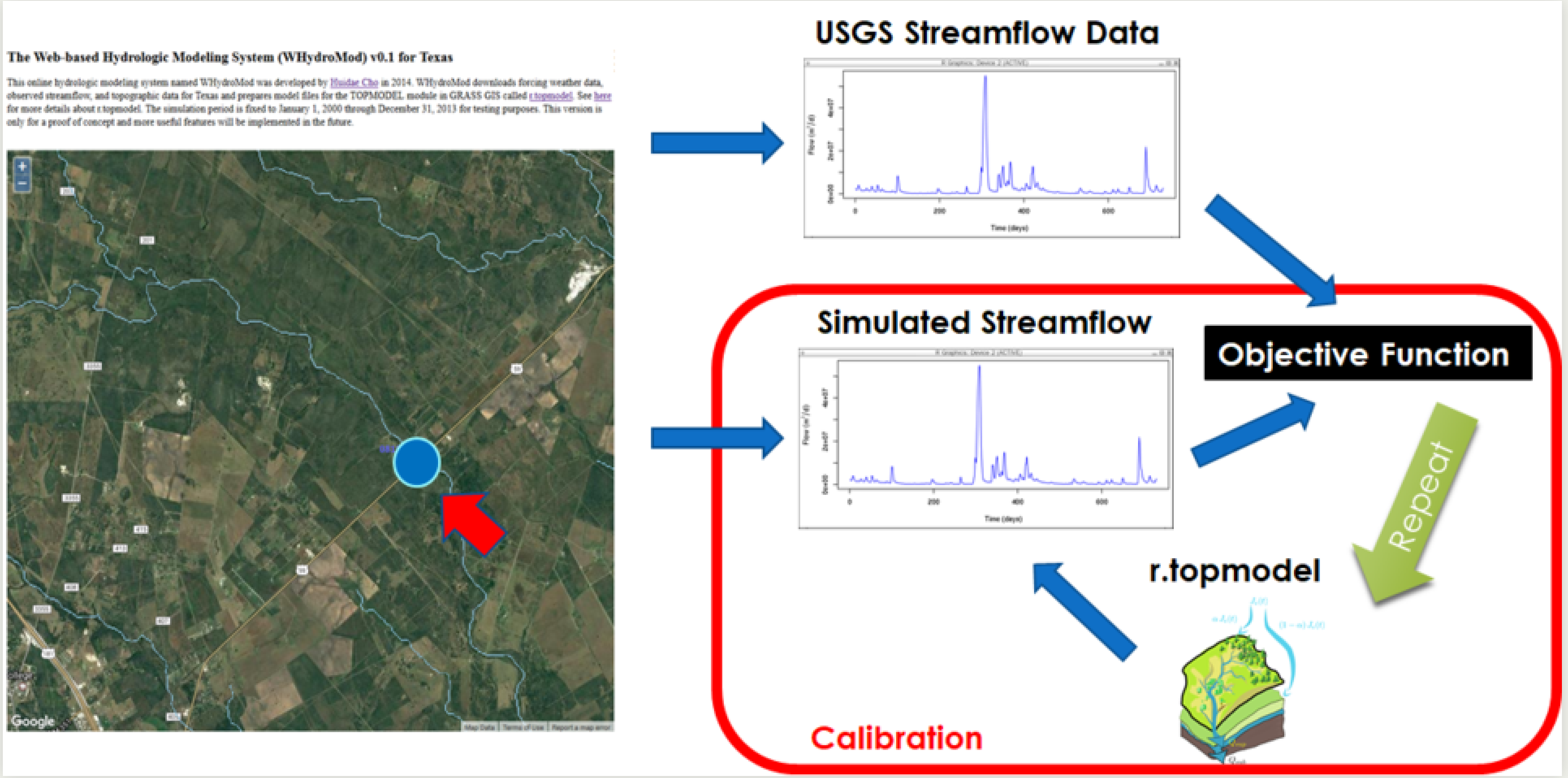
- http://txmod.isnew.info
- Proof-of-concept implementation for Texas
- GNU Affero General Public License Version 3
- Transparent system to the user
- Open source stack
  - GRASS GIS
  - PostgreSQL
  - PyWPS
  - MapServer
  - OpenLayers
  - Apache
- Bing Maps API for base maps



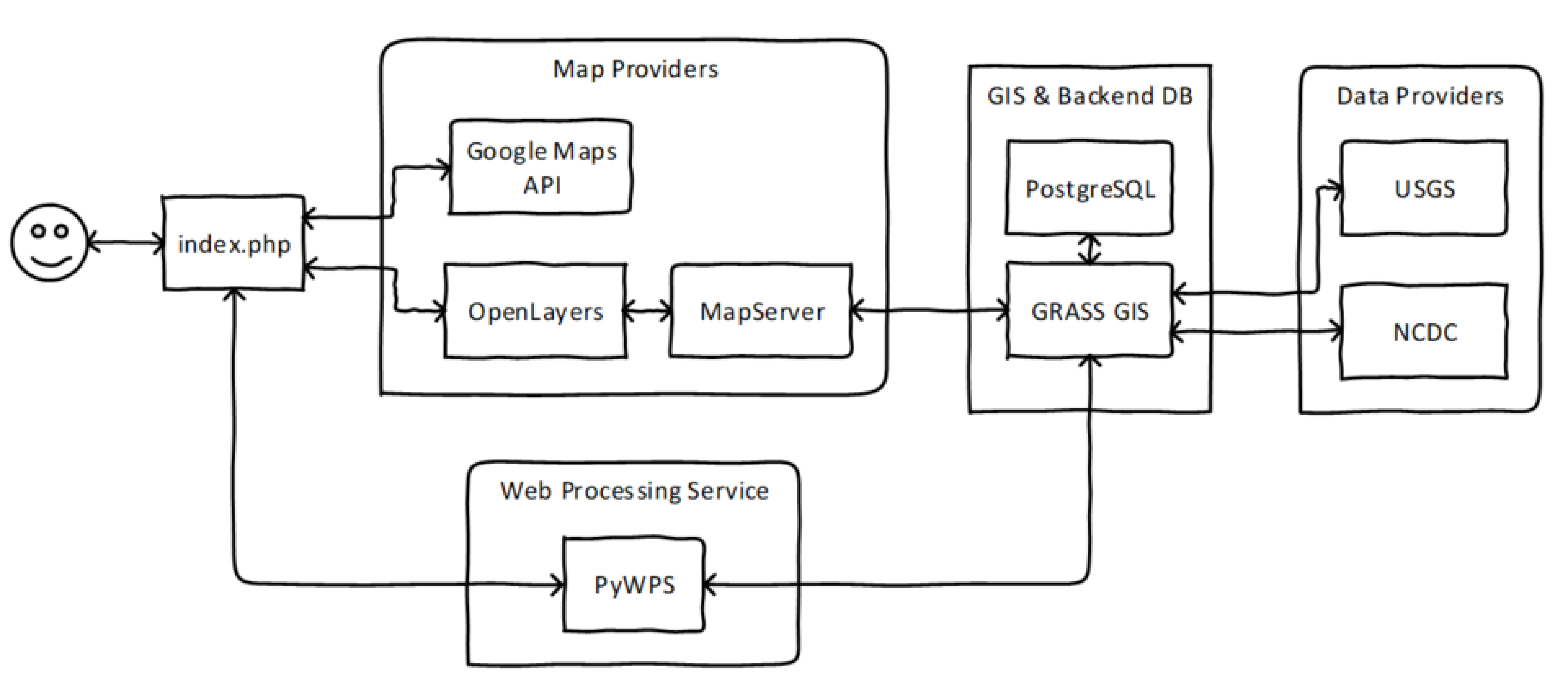
Typical TOPMODELing



The WHydroMod way



Data flow


Map Providers
Google Maps API
index.php
OpenLayers
MapServer
GIS & Backend DB
PostgreSQL
GRASS GIS
Data Providers
USGS
NCDC
Web Processing Service
PyWPS

Challenges

Web users are impatient

But it takes minutes to download online data & process DEM

- Blue & red USGS gages
- Automate heavy data processing over night
- Allow the user to initiate new processing and share results
- **Improve the performance of geospatial computation**

Important hydrologic parameters

- Flow direction
- Flow accumulation
- Longest flow path

Flow direction

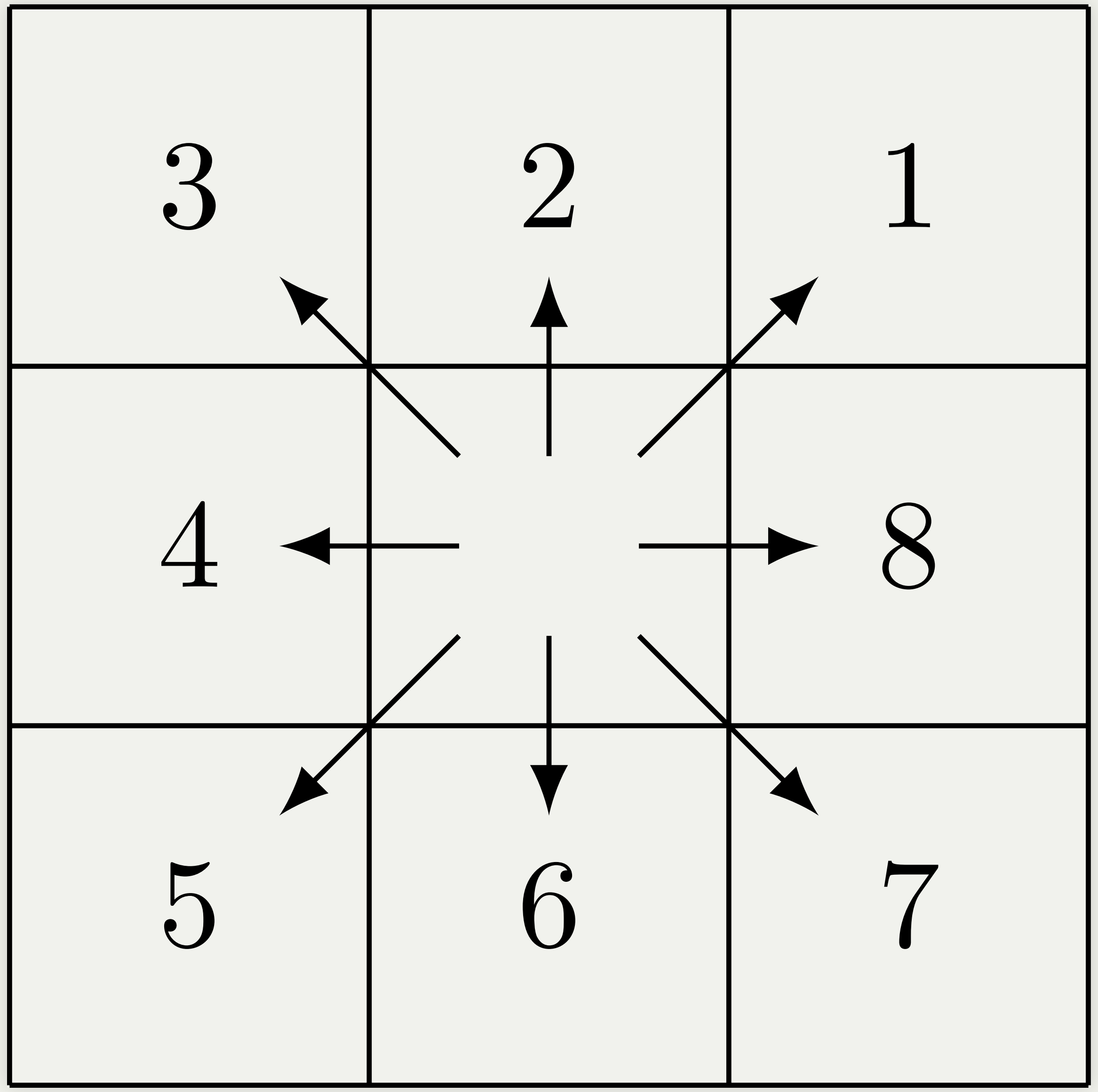
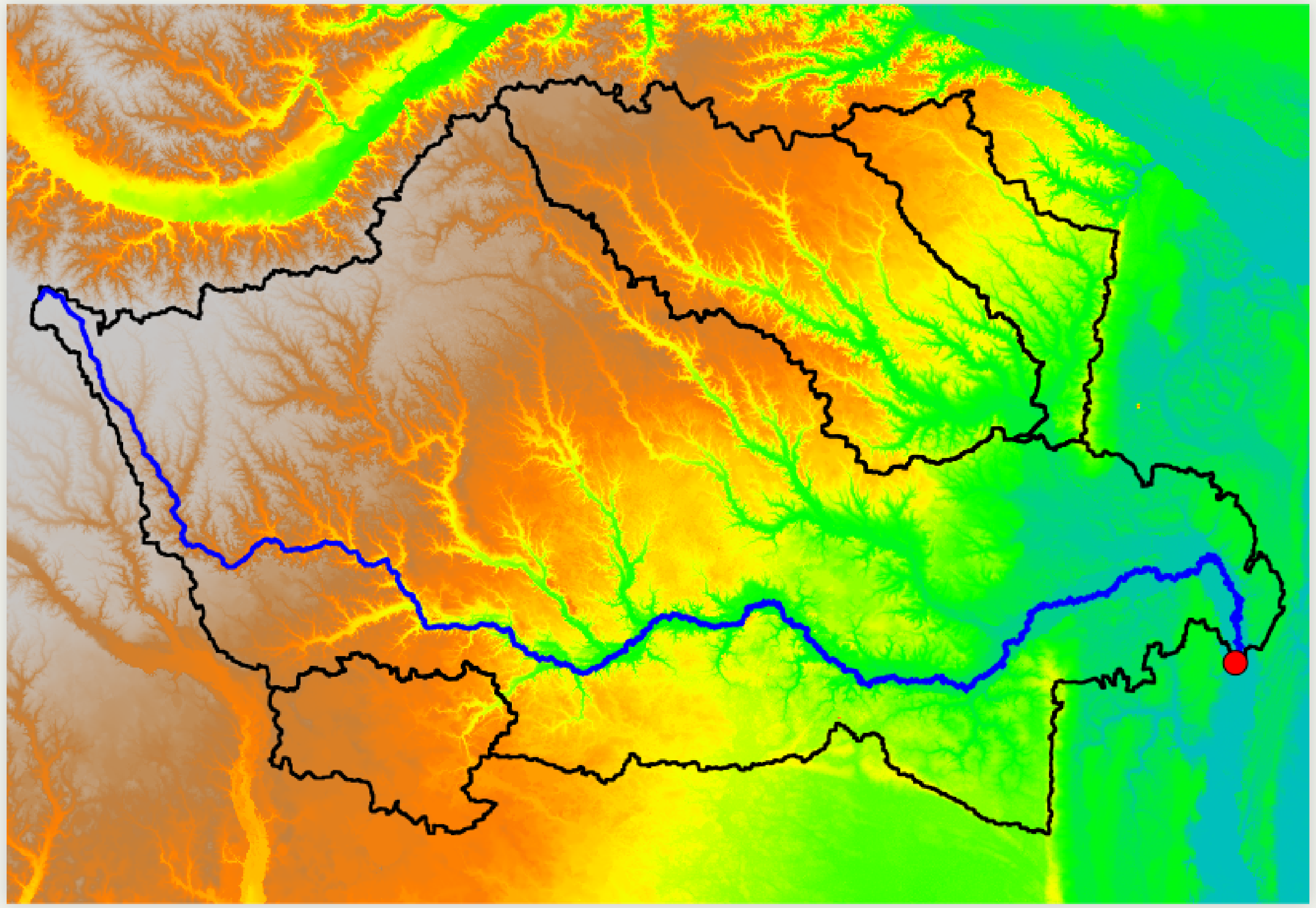


Figure 1: GRASS GIS drainage encoding

Flow accumulation

A raster (think of a matrix with cell values) that downtraces rain drops following flow directions.

Longest flow path



FP is the watercourse from one point to another.

$$\overrightarrow{\mathbf{LFP}} \in \left\{ \overrightarrow{\mathbf{FP}}_i \;\middle|\; \left\| \overrightarrow{\mathbf{FP}}_i \right\| \geq \left\| \overrightarrow{\mathbf{FP}}_j \right\| \; \forall j \neq i \right\}$$

Yes! LFP is the “longest” flow path.

There can be more than one in some case.

Motivation

The current LFP algorithm

- Peter Smith (1995) $\rightarrow$ the resolution of DEM was limited
- grid-based $\rightarrow$ can take a long time
- grid output $\rightarrow$ potentially **invalid** vector output
- calculation of two flow length grids for each outlet
- not for **a large number of watersheds**

Smith, P. N. H., 1995. Hydrologic data development system. Transportation Research Record: Journal of the Transportation Research Board 1599, 118–127.

Peter Smith’s method

Downstream flow length

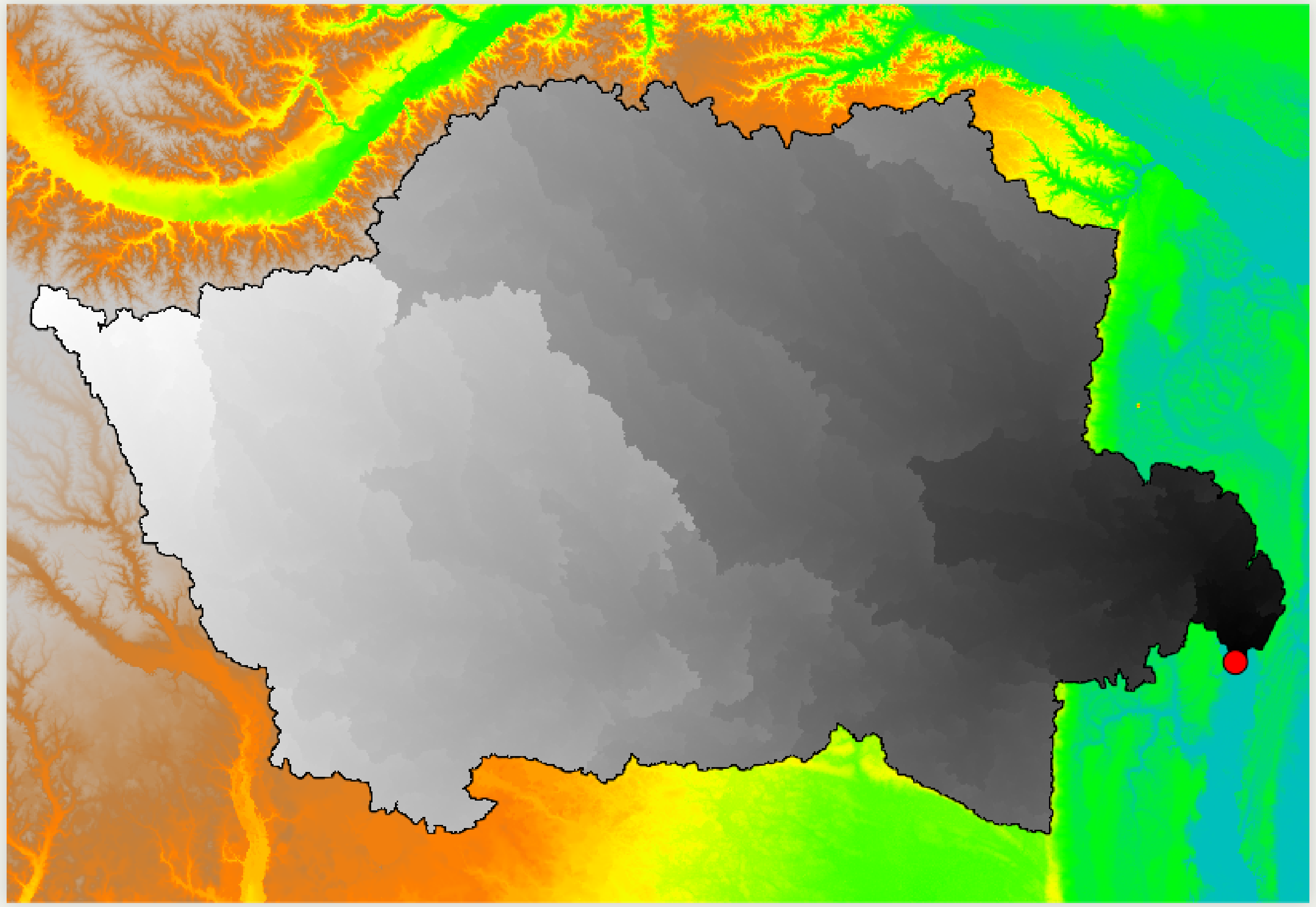
Flow length starting from the outlet

$\text{FL}_{i,j}$ is the flow length from cell i to cell j.

$$\text{DFL}_i = \begin{cases} 0 & i = 0 \text{ at the outlet} \\ \text{FL}_{i-1,i} + \text{DFL}_{i-1} & i \geq 1 \end{cases}$$

Note

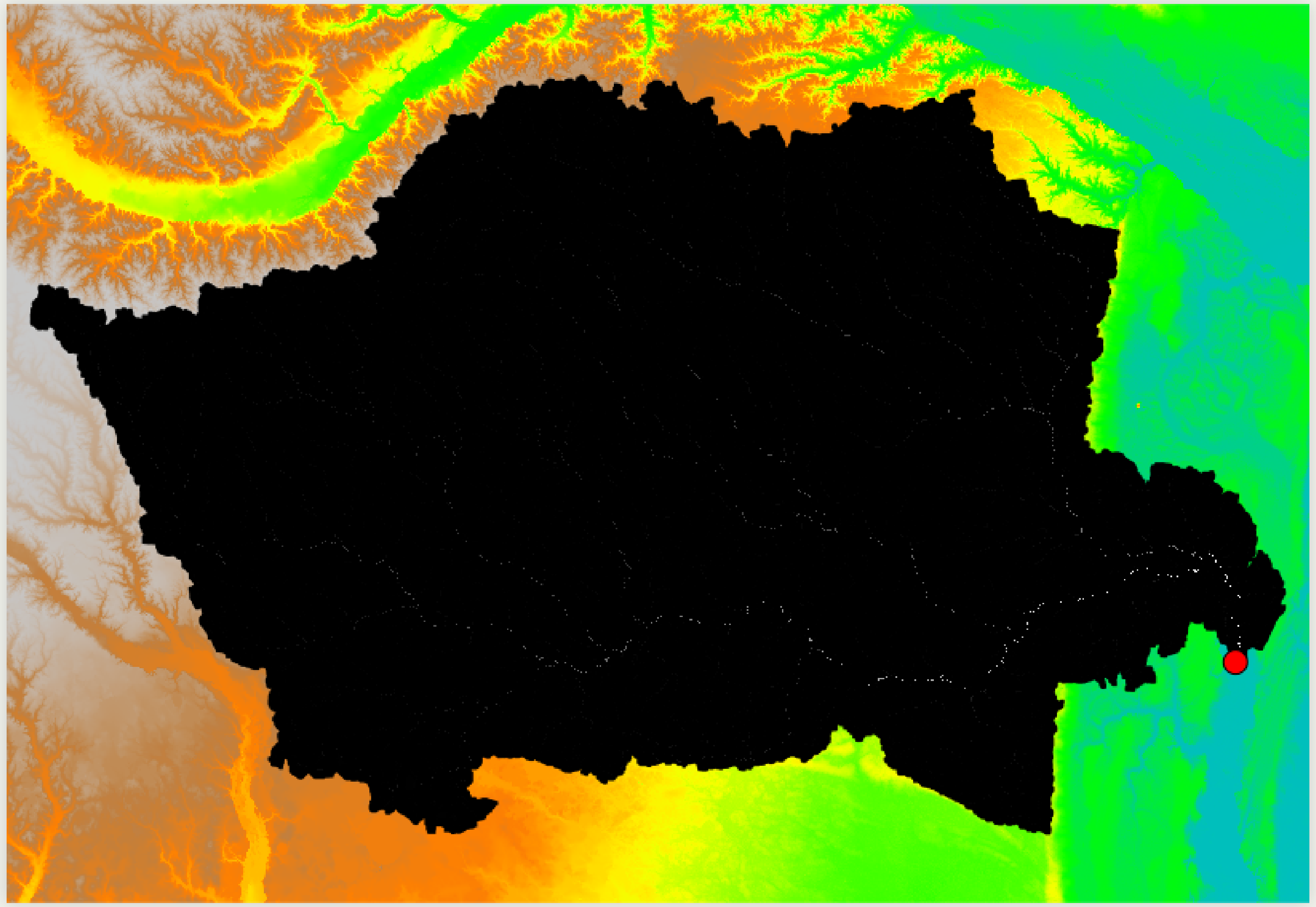
- 0 at the outlet
- high at a headwater



Upstream flow length

Flow length starting from a headwater

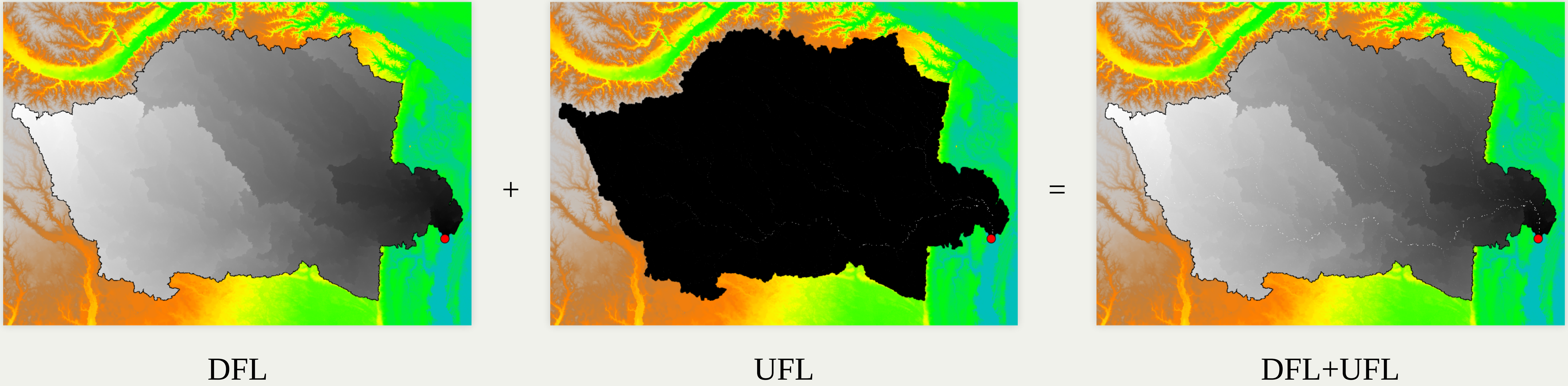
$$\text{UFL}_i = \begin{cases} 0 & i = 0 \text{ at a headwater} \\ \text{FL}_{i-1,i} + \max(\text{UFL}_{i-1}) & i \geq 1 \end{cases}$$



Note

- 0 at a headwater
- high at the outlet
- taking the maximum at a confluence

DFL+UFL



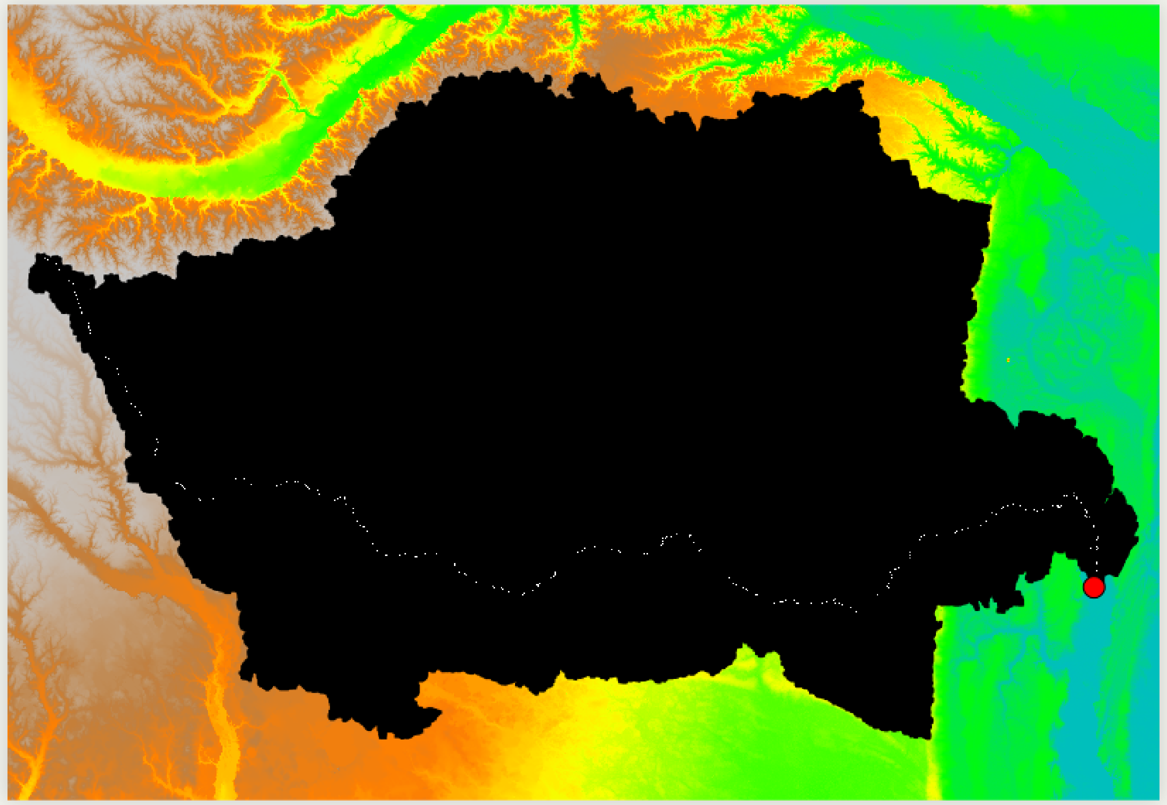
Note

- maximum DFL at the headwater on the LFP
- maximum UFL at the outlet
- both maximums are the same $\rightarrow$ LFL (longest flow length)
- any DFL+UFL cells on the LFP have this maximum value

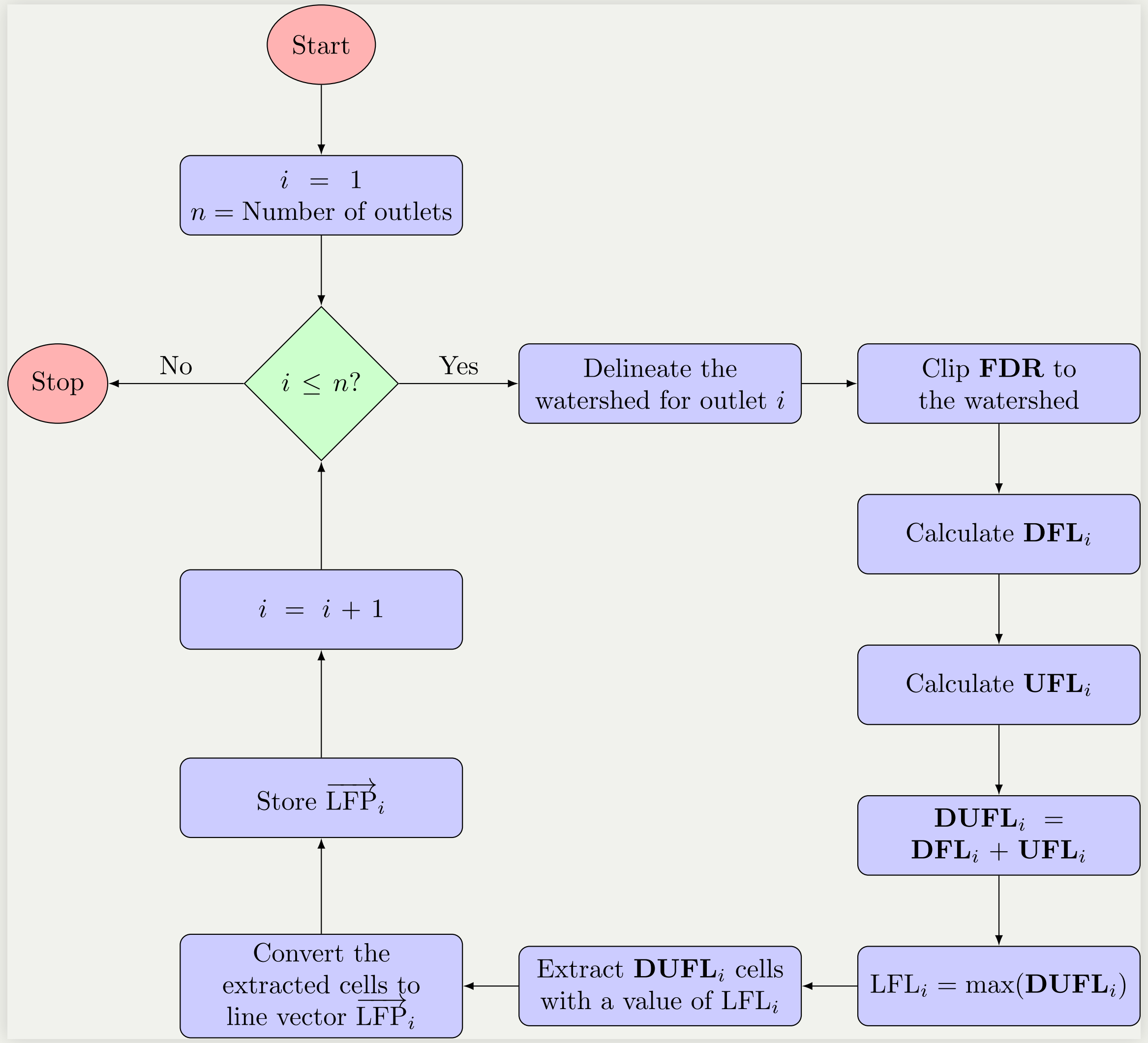
LFP

$\overrightarrow{\text{LFP}}$ defined by all the cells with a value of LFL

$$\text{LFL} = \max(\mathbf{DFL} + \mathbf{UFL})$$

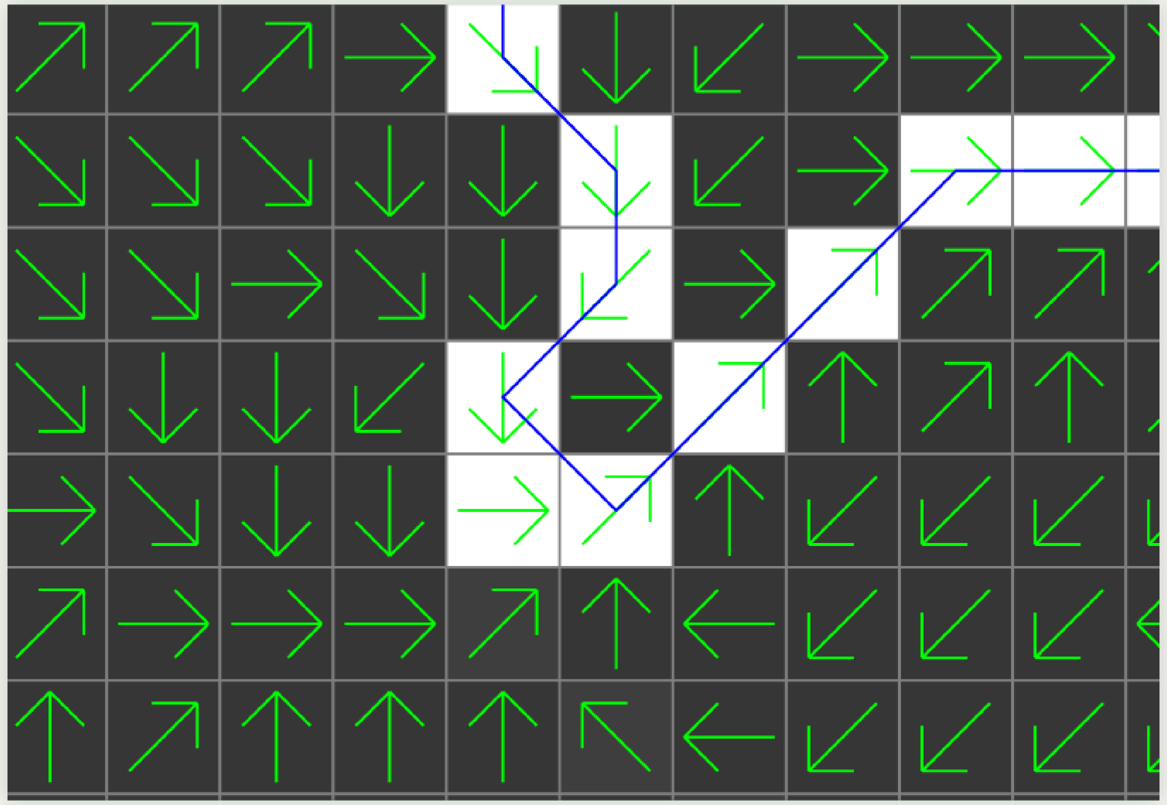


Typical procedure for multiple outlets



Critical problem

Green arrows: flow directions, blue line: LFP



Hydrologically **invalid!**

Other problems

Slow!

Esri’s Flow Length tool is limited.

Divide-and-conquor approach

Purely vector-based approach

r.accumulate GRASS GIS addon

Divide

Divide the problem into smaller pieces in a recursive way.

$$\overrightarrow{\text{LFP}}_i \in \left\{ \overrightarrow{\text{LFP}}_j + \overrightarrow{\text{FP}}_{ji} \ \forall j \in \mathbf{UP} \right\}$$

where

- $\mathbf{UP} = \{\text{Upstream neighbors of cell } i\}$
- $0 \le \|\mathbf{UP}\| \le 8$

Define a function of j that returns the length of the longest flow path at cell i.

$$f(j) = \begin{cases} \left\|\overrightarrow{\text{LFP}}_j\right\| + \left\|\overrightarrow{\text{FP}}_{ji}\right\| = \left\|\overrightarrow{\text{LFP}}_i\right\| & \text{if } \mathbf{UP} \neq \emptyset \\ 0 & \text{otherwise} \end{cases}$$

Now, the problem becomes finding all $\arg\max_{j \in \mathbf{UP}} f(j)$ by traversing upstream cells starting from the outlet. The search stops when $\mathbf{UP} = \emptyset$.

Conquor

Intuitively, the longest longest flow length

$$\mathrm{LFL}_{\max} = s \cdot \mathrm{FAC}\sqrt{2}$$

where s and FAC are the cell size and flow accumulation, respectively

Based on Hack's law, the shorted longest flow length

$$\mathrm{LFL}_{\min} = s\sqrt{\mathrm{FAC}}$$

Between upstream neighbor cells i and j, cell i is on the $\overrightarrow{\mathrm{LFP}}$ if $\mathrm{LFL}_{\min,i} > \mathrm{LFL}_{\max,j}$.

Stack overflow and solution

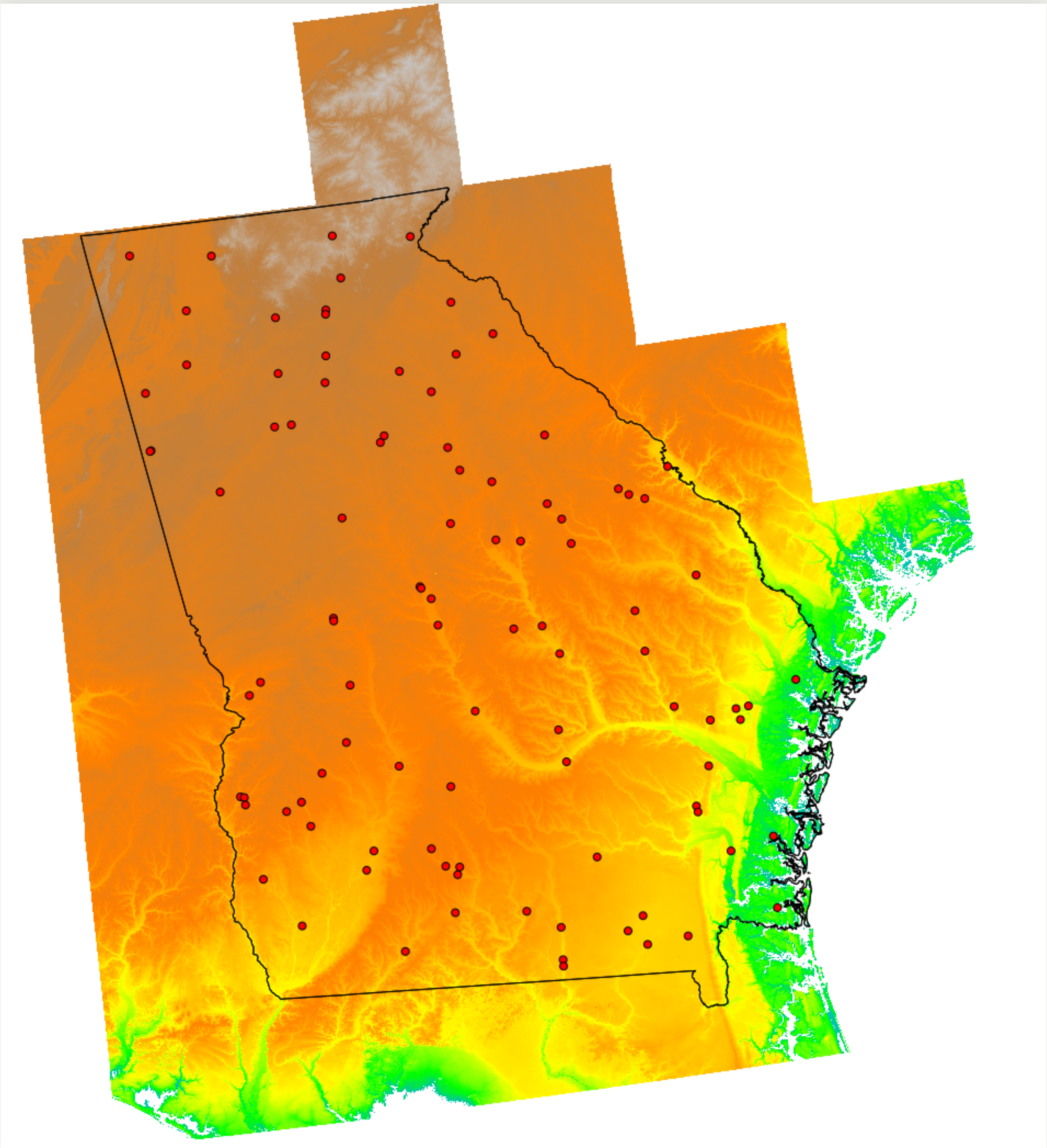
- Depending on the watershed size, recursion can consume all stack memory and cause a stack overflow
- Convert recursion to iteration using a heap-based stack
- A single loop until the stack with upstream cells depletes

Benchmark experiments: r.accumulate vs. Arc Hydro

Is paid software always better than open and free software?

Data

- National Elevation Dataset (NED) 1 arc-second (approximately 30 meters)
- 27 NED maps
- National Atlas of the United State state boundaries for masking
- Generated 100 outlets randomly



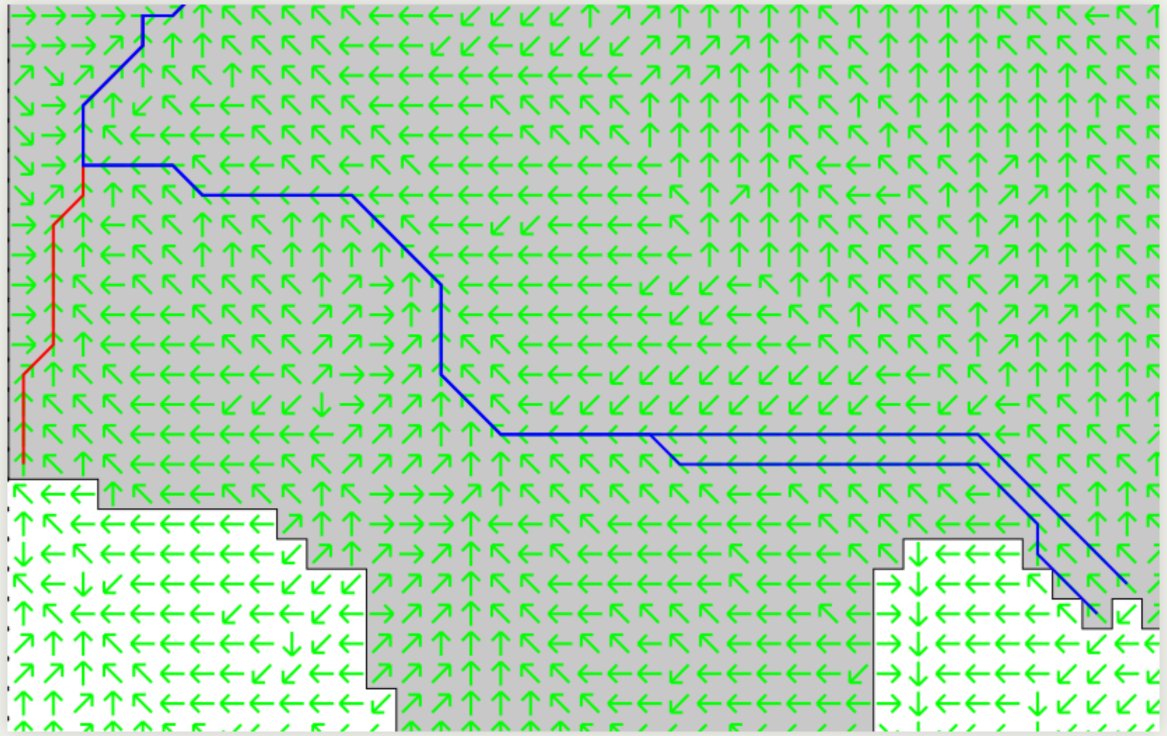
System specifications

- CPU: Intel Xeon E5620 2.40 GHz
- Memory: 48 GB
- OS: Linux kernel version 4.4.14
- GIS: GRASS development version 7.7.svn revision r74124

Results and discussions

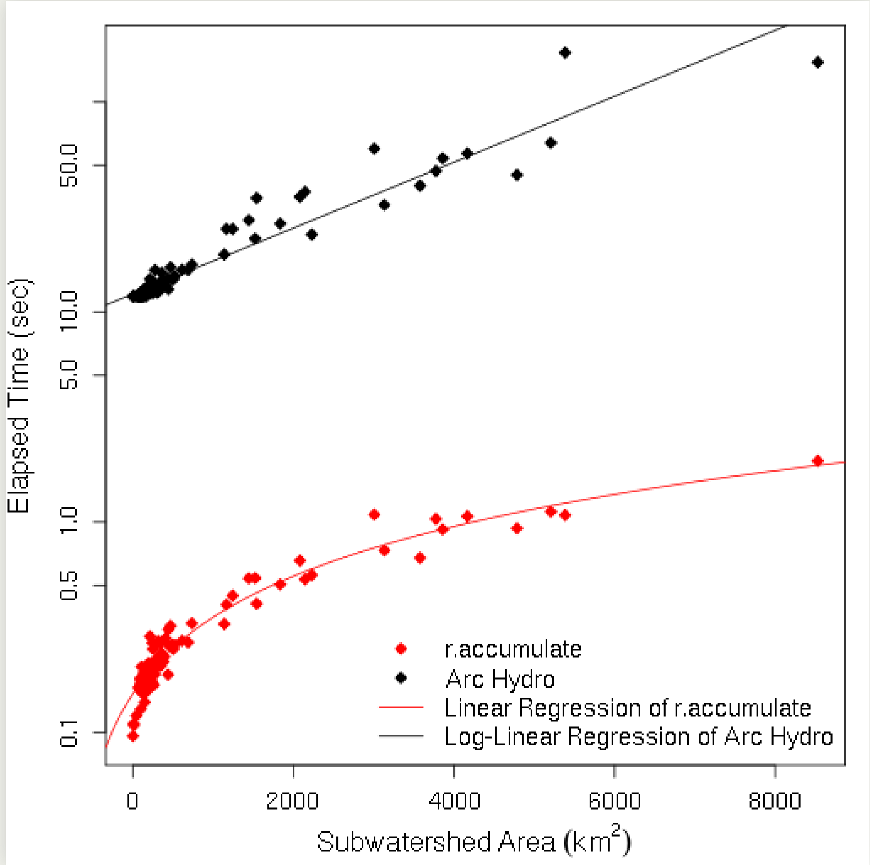
LFP geometries

Both methods produced almost identical LFPs except for some areas

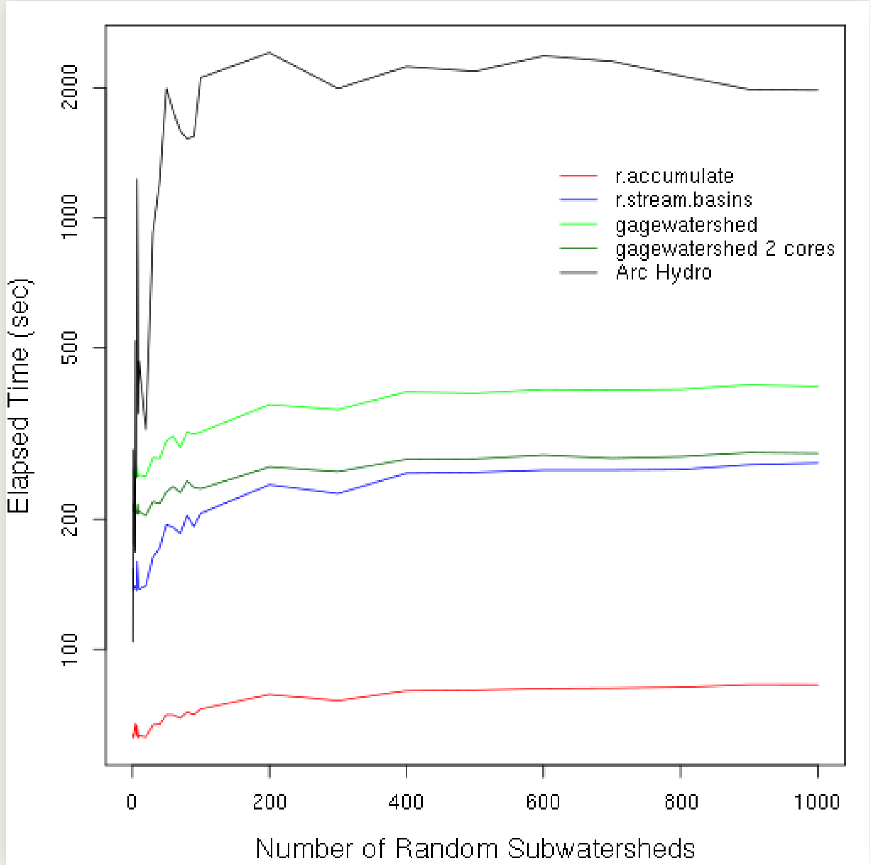


Blue: r.accumulate, Red: Arc Hydro

Performance comparison with Arc Hydro



Efficient delineation of a massive number of subwatersheds



Conclusions

- The fewer raster operations, the faster!
- The performance of r.accumulate is linearly growing with the subwatershed size.
- While that of Arc Hydro exponentially growing.
- The new approach is cost-efficient and can be used for interactive hydrologic modeling (e.g., web).

References

- Cho, H., 2020. *A Recursive Algorithm for Calculating the Longest Flow Path and Its Iterative Implementation.* Environmental Modelling & Software 131, 104774. doi:10.1016/j.envsoft.2020.104774.
- Smith, P. N. H., 1995. *Hydrologic Data Development System.* Transportation Research Record: Journal of the Transportation Research Board 1599, 118–127. doi:10.3141/1599-15.
- Hack, J. T., 1957. *Studies of Longitudinal Stream Profiles in Virginia and Maryland.* Geological Survey Professional Paper 294-B, 45–97. https://pubs.usgs.gov/pp/0294b/report.pdf.