PARALLEM: massively Parallel Landscape Evolution Modelling

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Outline

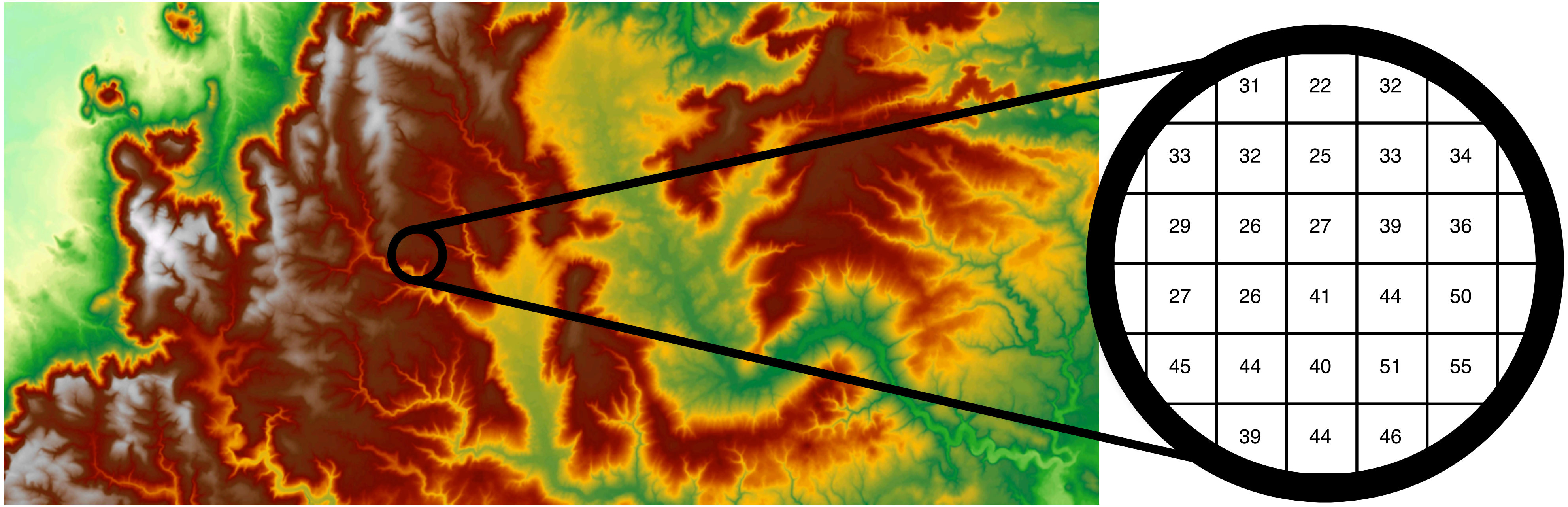
- **What is Landscape Evolution Modelling (LEM)**
- Parallelization of LEM
- Preliminary Results
- The Current Situation
- Future Directions

Landscape Evolution Modeling

- Landscapes change over time due to water/weathering
  - Physical and Chemical Weathering require water to break down material
  - Higher energy flowing water both Erodes and Transports material until decreasing energy conditions result in Deposition of material
- These processes take a long time
  - Many glacial-Interglacial Cycles
    - Cycles are ~100ka for last 800ka, prior to 800ka cycles were ~40ka in length
- We want to use retrodiction to work out how the landscape has changed

Landscape Evolution Modeling

- Use a simulation to model how the landscape changes
  - 3D Landscape is discretized as a regular 2D grid (x, y) with cell values representing surface heights (z) derived from a digital elevation model (DEM)
    - Cells can be 10m x 10m or larger



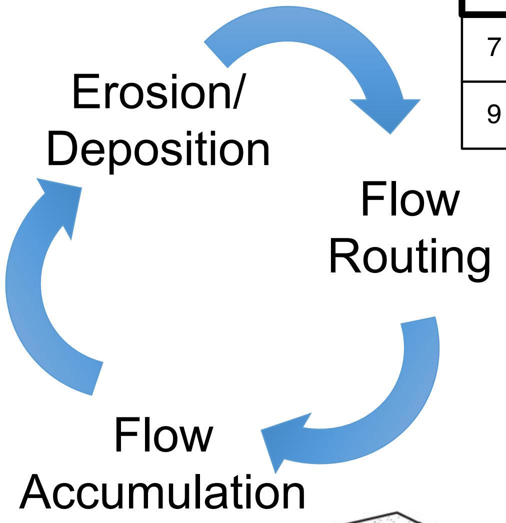
Landscape Evolution Modeling (simplified)

Each iteration of the simulation:

How much material will be removed?
How much material will be deposited?

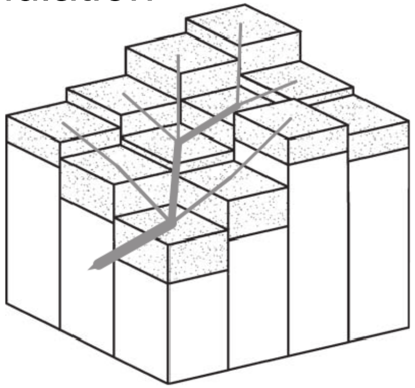
7	8	5	9	6
4	6	7	8	4
5	8	9	10	9
7	10	7	8	7
9	8	4	6	5

- Each step is ‘fairly’ fast…
- But we want to do lots of them 120K to 1M years
- On landscapes of 6-56M cells
- If we could simulate 1 year in 1 minute this would take 83 – 694 days!
  - assuming 1 year = 1 iteration
  - may need more



Sequential version is much slower than this…

1	1	3	1	1
8	2	1	1	5
1	1	1	1	1
2	1	1	1	1
1	1	6	1	2

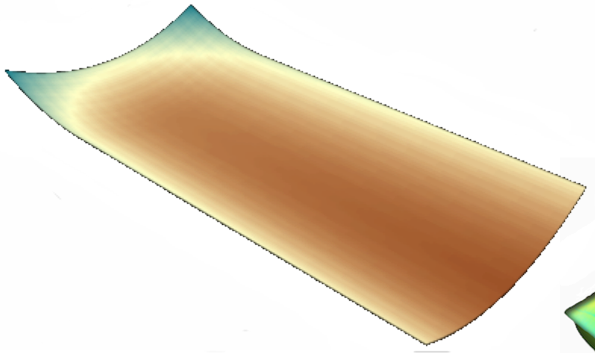


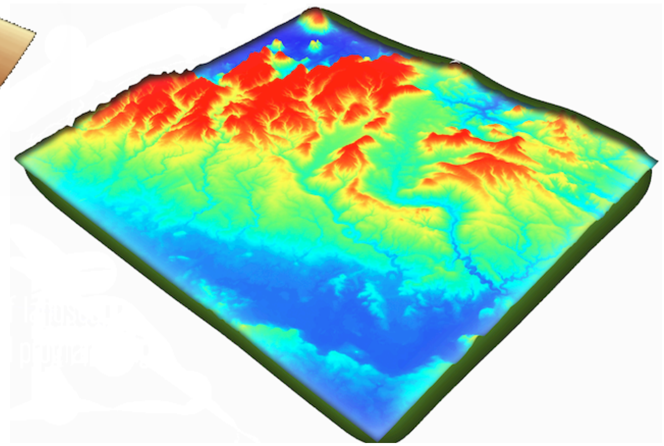
Execution analysis of Sequential LEM

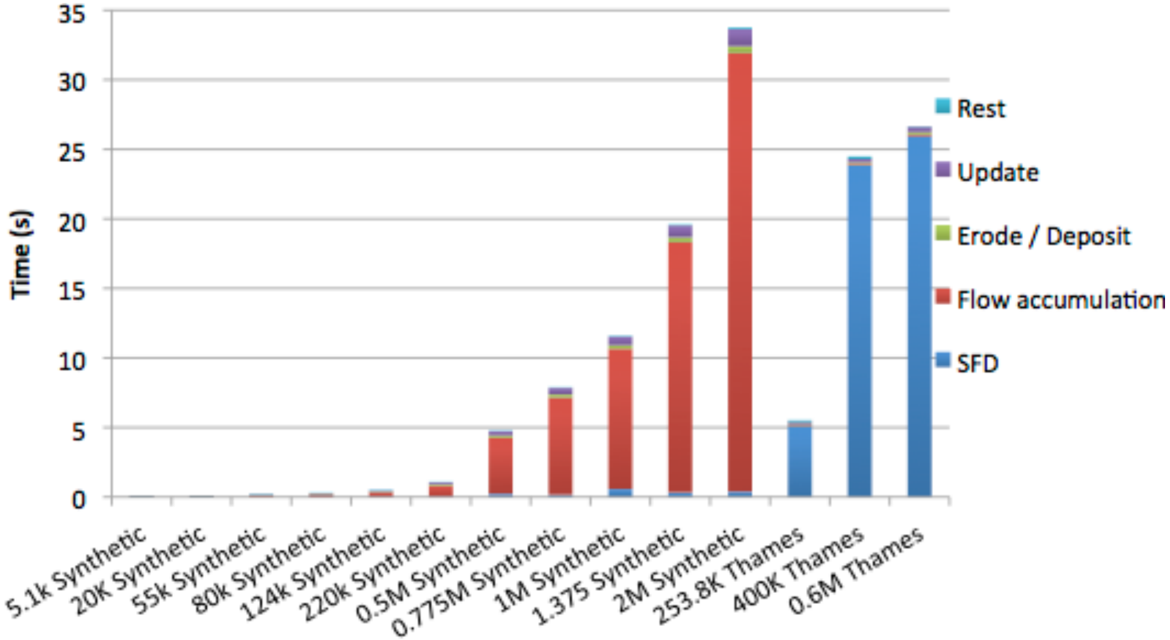
- We started from an existing sequential LEM
  - 51x100 cells for just 120K years took 72 hours
    - estimate for 25M cells 64,000 years
  - This was non-optimal code
    - Reduced execution time from 72 to 4.7 hours
    - 64,000 years down to 300 years
- But this is still not enough for our needs

Execution analysis of Sequential LEM

- Performance Analysis:
- ~74% of time spent routing and accumulating
- Need orders of magnitude speedup
  - So focus was on flow routing / accumulation







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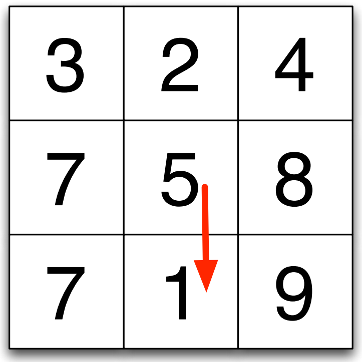
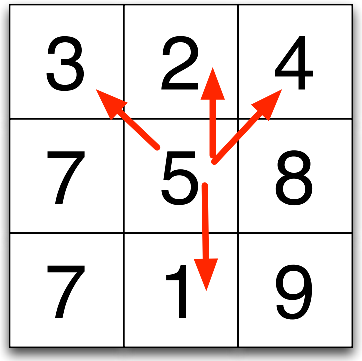
Parallel Flow Routing

- Each cell can be done independently of all others
  - SFD
    - 100% flow in the direction of steepest decent (normally lowest neighbour)



  - MFD
    - Flow is proportioned between all lower neighbours
    - Proportional to slope to each neighbours



- Almost linear speed-up
  - Problems with code divergence
    - CUDA Warps split when code contains a fork

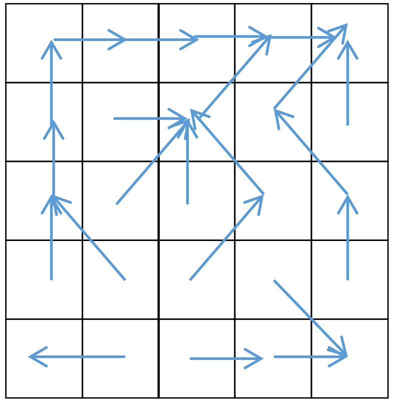
Single flow direction vs multiple flow direction

MFD is 'better' but much more computationally demanding

Parallel Accumulation: Correct Flow

- Iterate:
  - Do not compute a cell until it has no incorrect cells flowing into it
  - Sum all inputs and add self
  - All cells can work independently of each other
    - Some restriction on updates not happening immediately

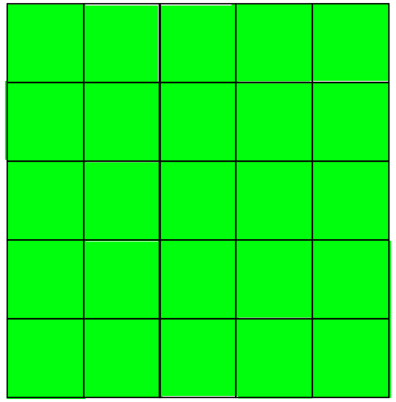
Flow Routing



Accumulation

5	6	7	14	19
4	1	6	3	1
3	1	1	2	2
1	1	1	1	1
2	1	1	2	4

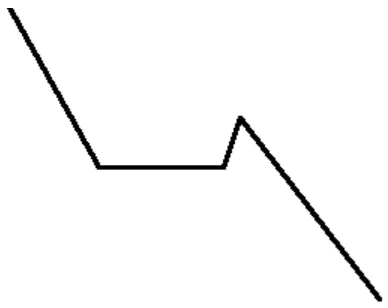
Correct

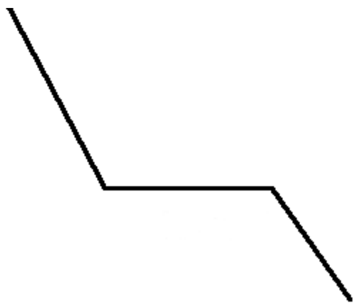


Cell values are not normally 1, but the initial rainfall on the cell

Not the whole story…

- Sinks and Plateaus

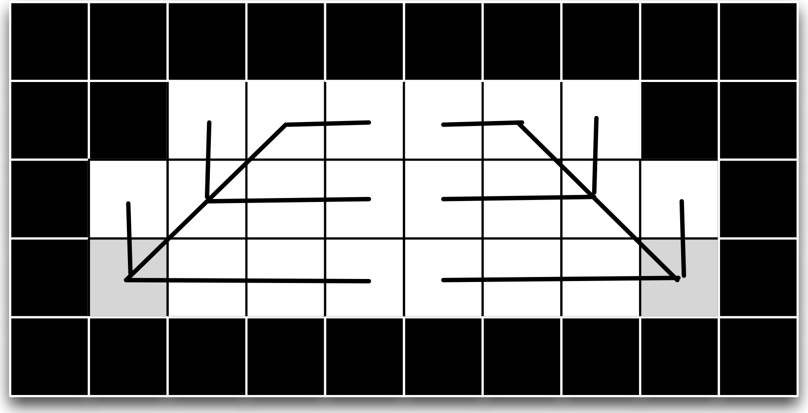


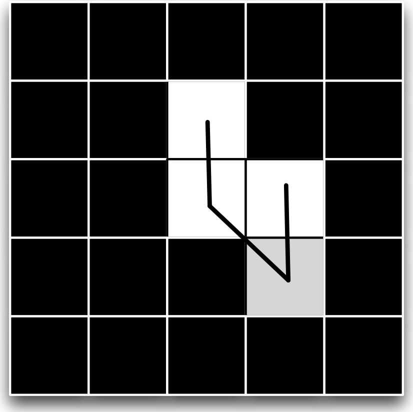


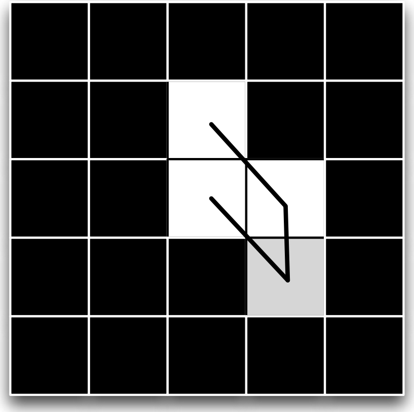
- Can’t work out flow routing on sinks and plateaus
- Need to ‘fake’ a flow routing
  - Fill a sink until it can flow out
    - Turn it into a plateau
  - Fake flow directions on a plateau to the outlet

Parallel Plateau routing

- Need to find the outflow of a plateau and flow all water to it
- A common solution is to use a breadth first search algorithm
  - Parallel implementation
  - Though result does look ‘unnatural’
  - Alternative patterns are possible – but acceptable
- We are investigating alternative solutions

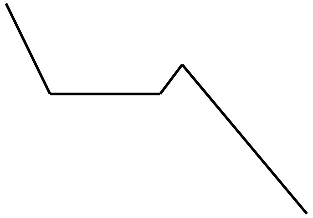


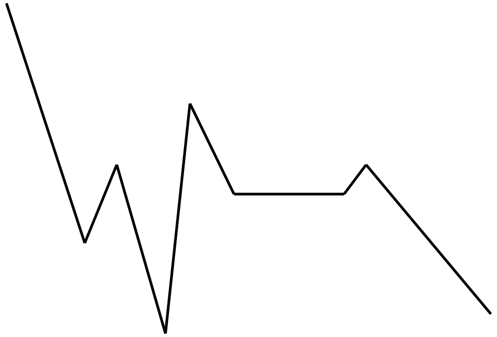




Sink filling

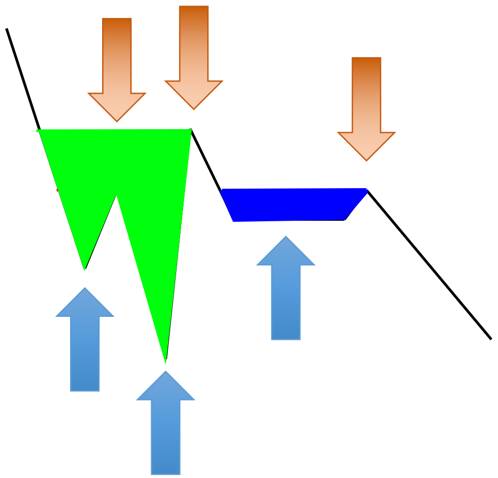
- Dealing with a single sink is (relatively) simple
  - Fill sink until we end up with a plateau (lake)
- But what if we have multiple nested sinks?





Nested Sink filling

- Implemented parallel version of the sink filling algorithm proposed by Arger et al [2003]
  - Identify each sink (parallel)
  - Determine which cells flow into this sink - watershed (parallel)
  - Determine the lowest cell joining each pair of sinks (parallel/sequential)
  - Work out how high cells in each sink need to be raised to to allow all cells to flow out of the DEM (sequential)
  - Fill all sink cells to this height (parallel)



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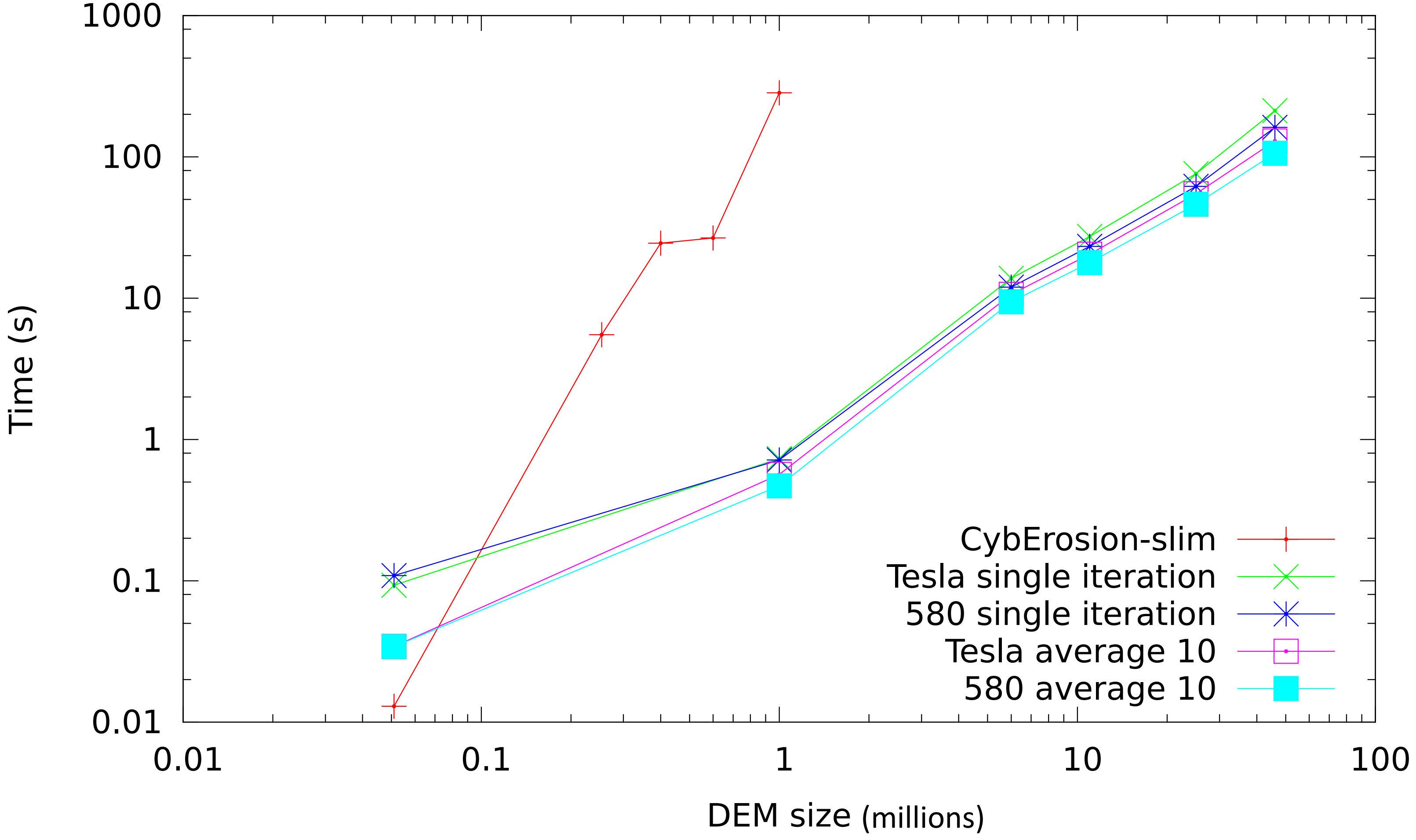
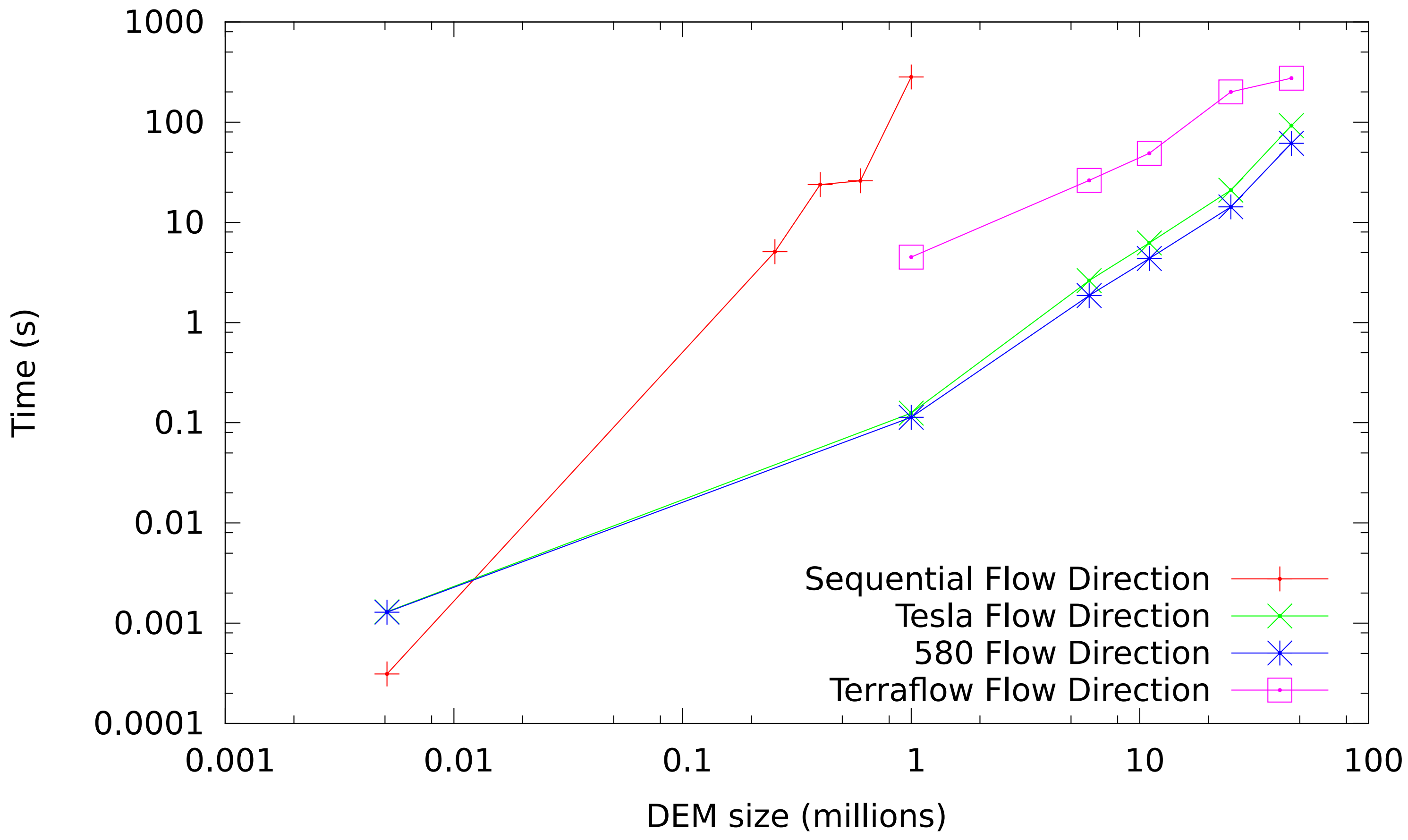
Results : Performance

- Overall performance



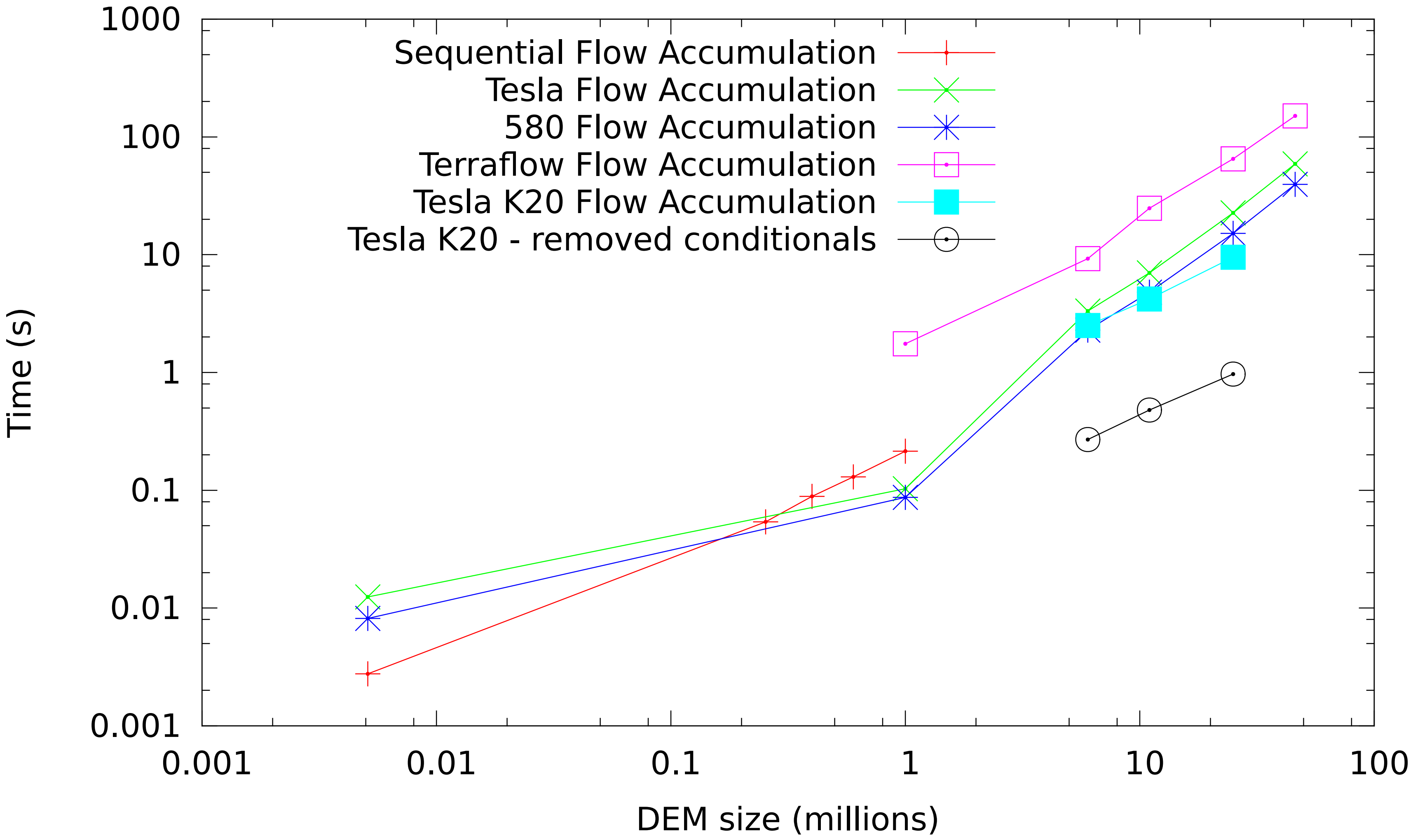
Results : Performance

- Flow Direction
  - Including sink & plateau solution



Results : Performance

- Flow Accumulation



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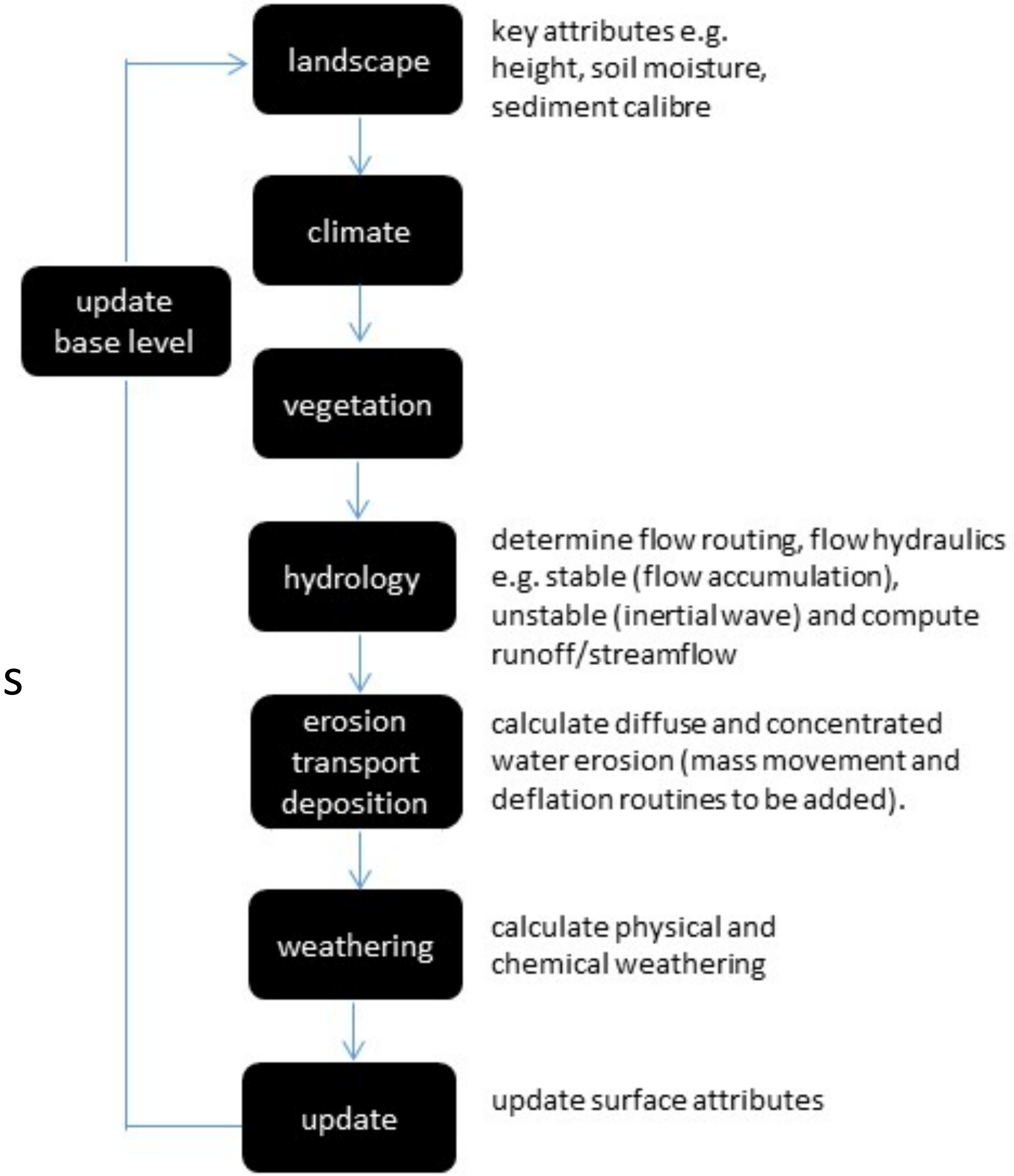
The Current Simulation

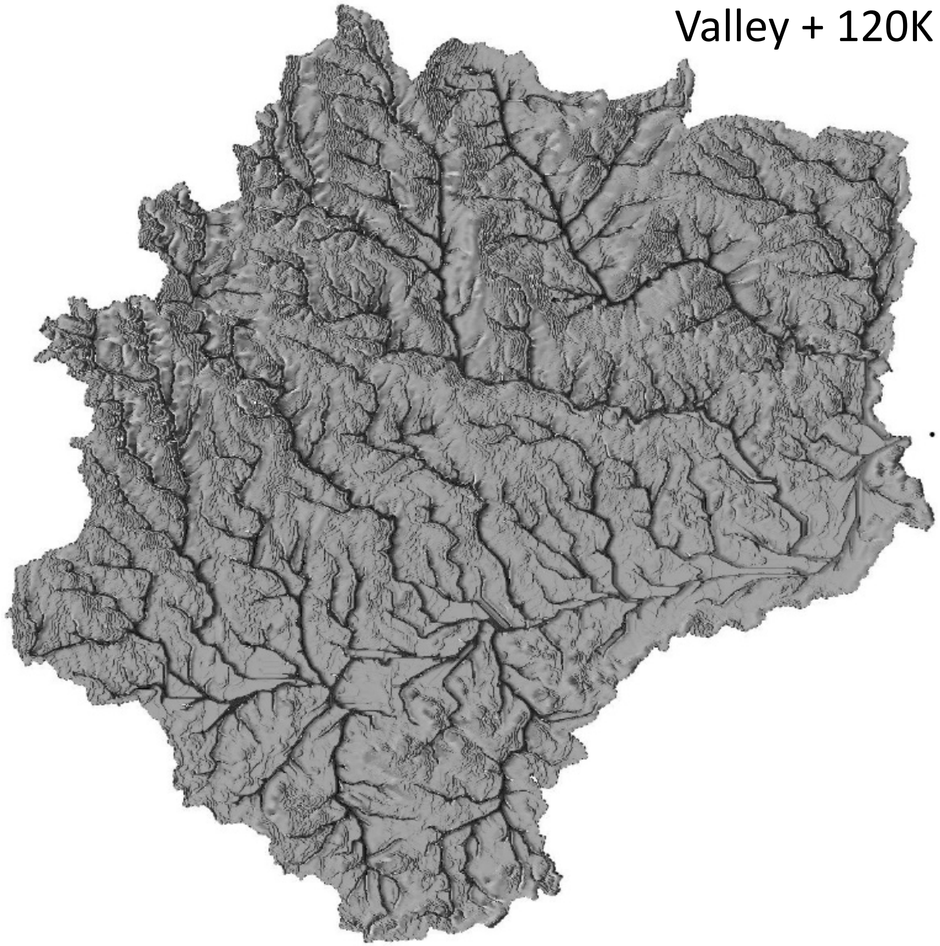
- Core Model now extended with processes
  - Most only affect individual cells (weathering, vegetation)
  - Some have cross DEM effects (mass movement) but can use same process as before



The Current Simulation

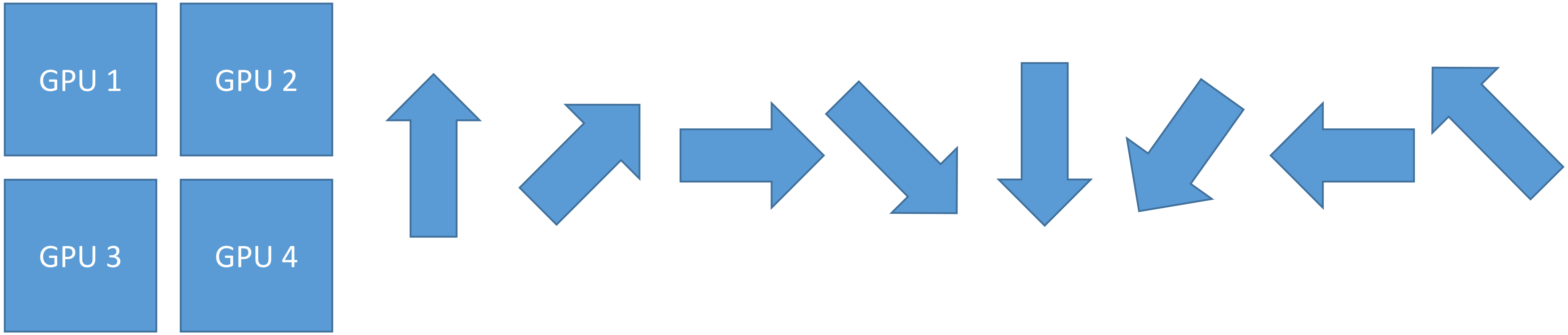
- Actively running landscape models on K40/K80 GPGPUs
- Taking ~7 weeks to run our model (MFD)
  - Leading to interesting results
  - Not seen as models have traditionally been much smaller
  - Taking ~4 weeks for SFD
- Currently running on just 1 GPGPU
  - Running multiple models simultaneously
  - Now have a multi-GPGPU code for running flow accumulation
    - Designed to ‘sweep’ over the landscape

Upper Thames Valley + 120K



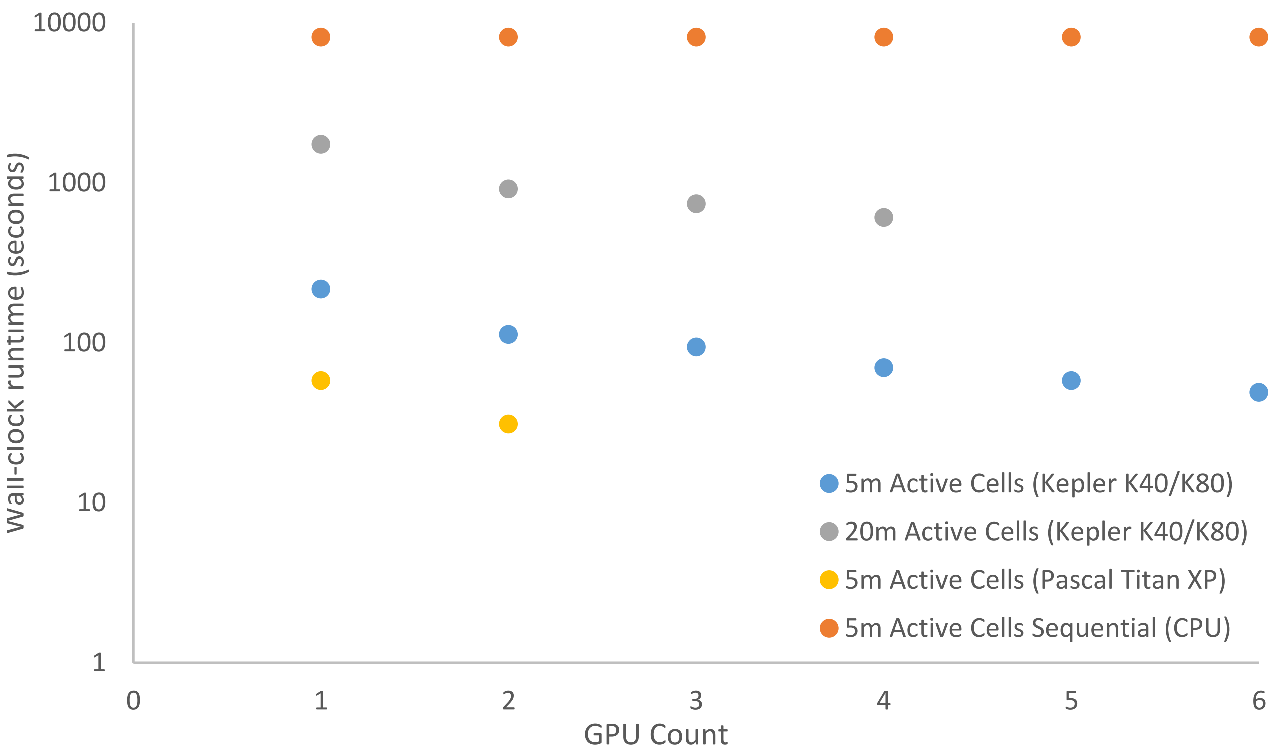
Multi-GPU: Attempt 1

- Flow direction can be done without problems
- Flow accumulation requires communication
- Perform each flow direction as one kernel call
  - No branching
  - Communication easier between cards

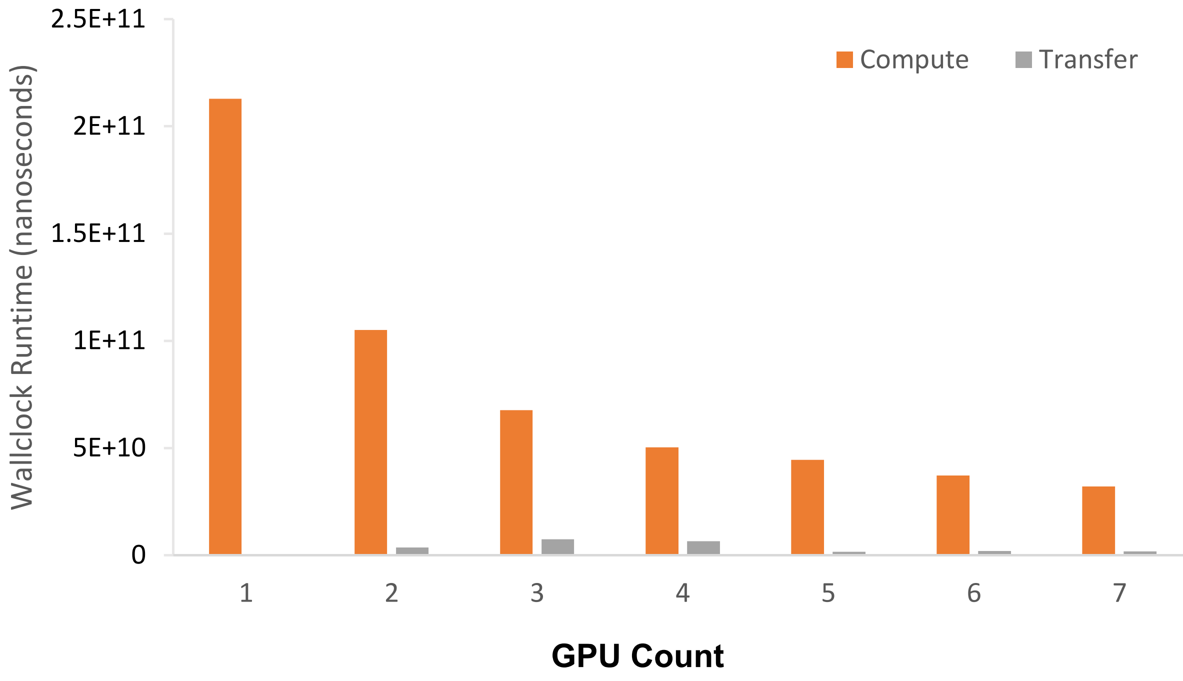


Multi-GPU: Attempt 1

Whole Simulation

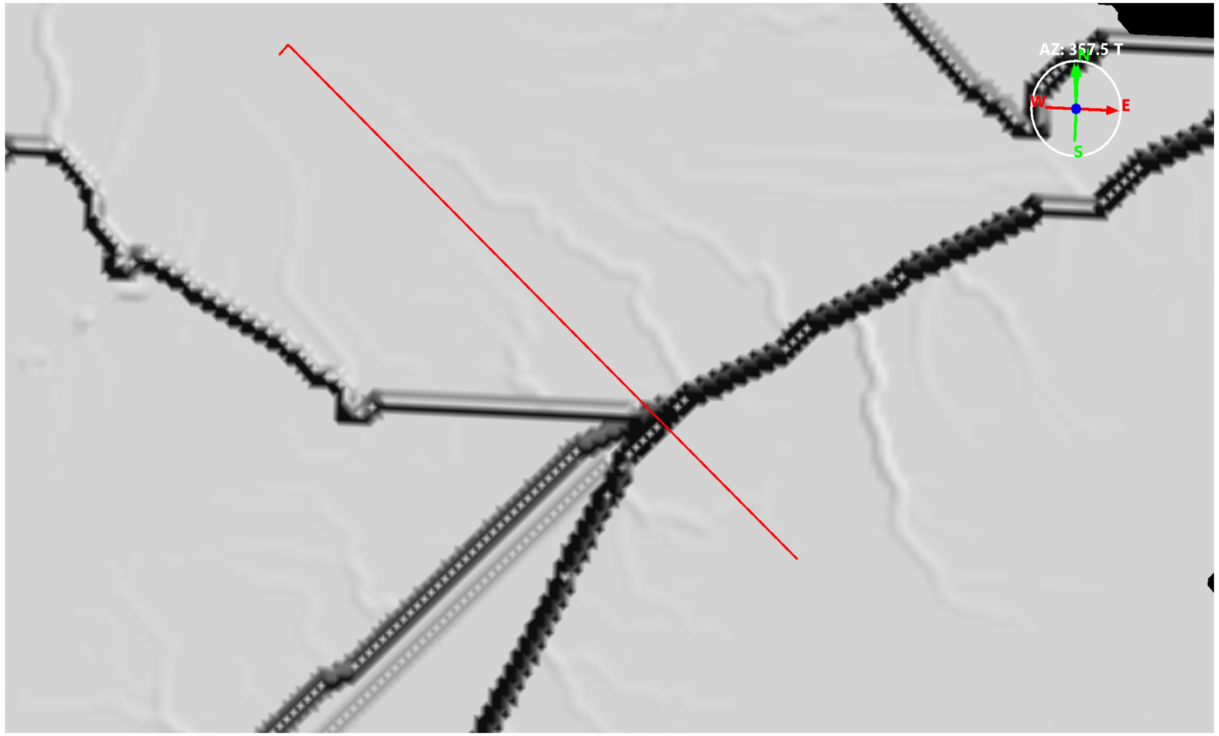


Flow Accumulation

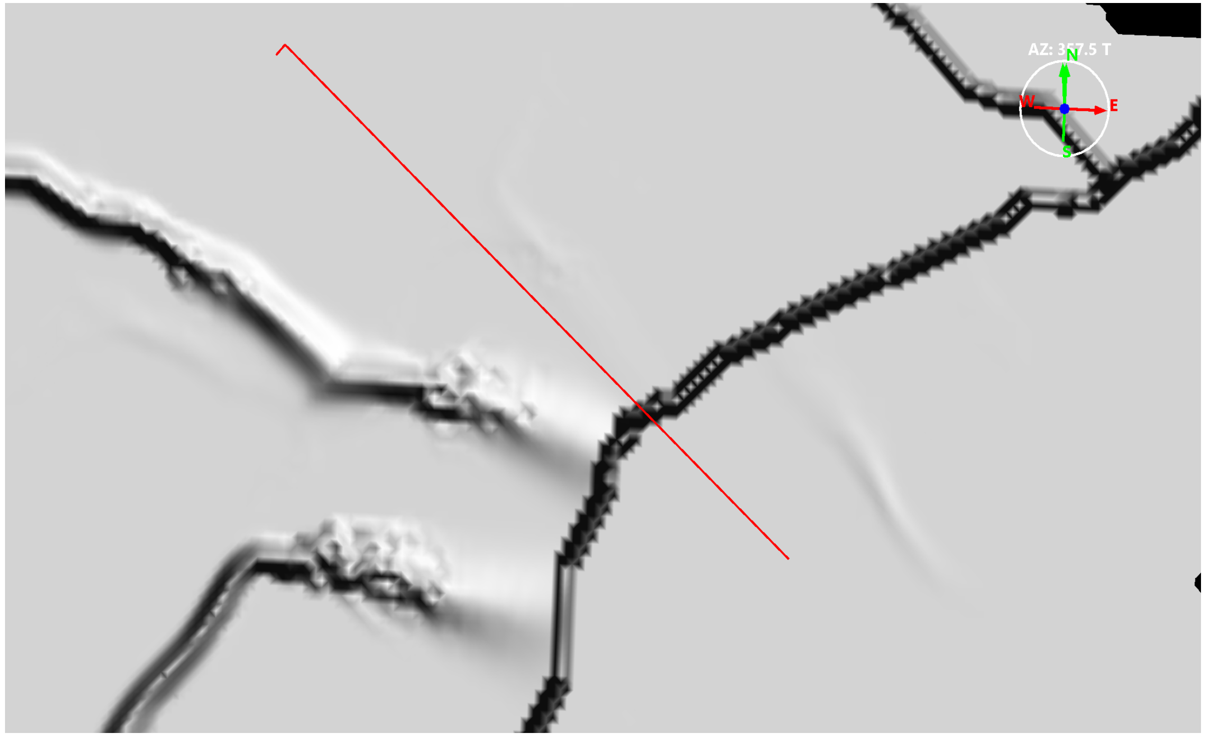


Problem: Landscape Cutting with SFD

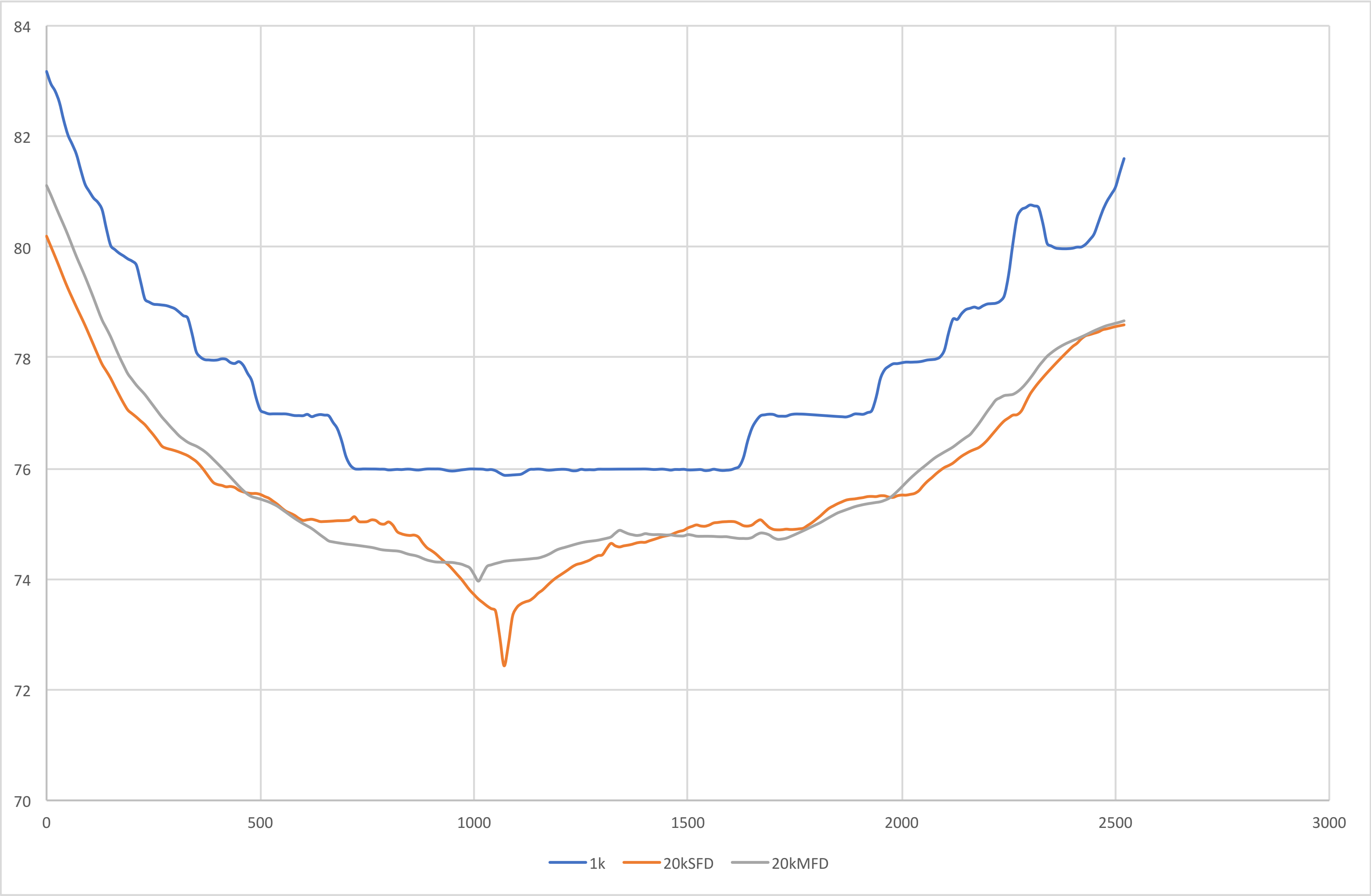
SFD



MFD

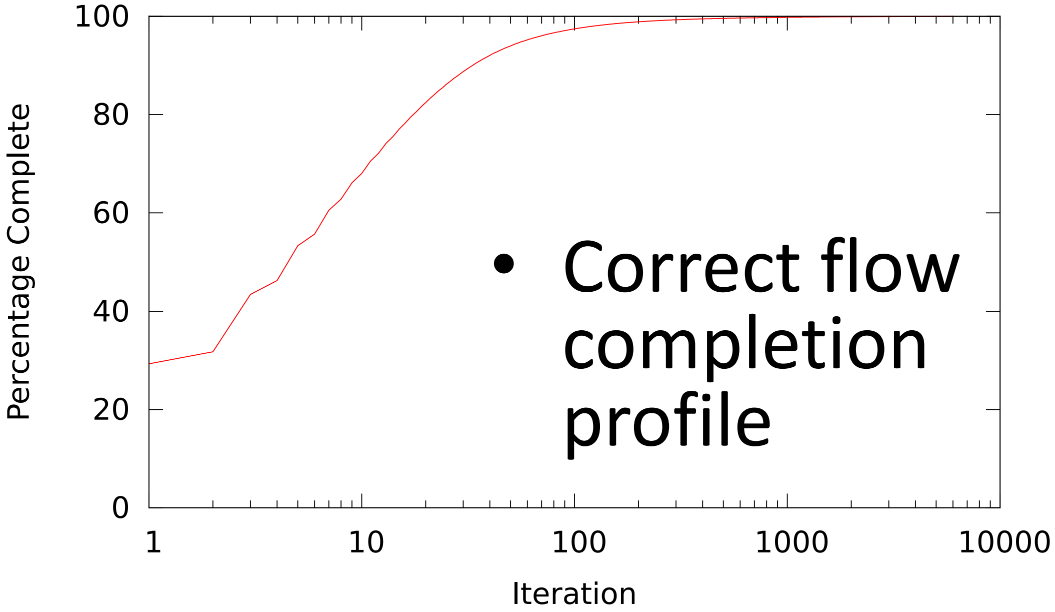


Comparing ‘cut in’ between SFD and MFD

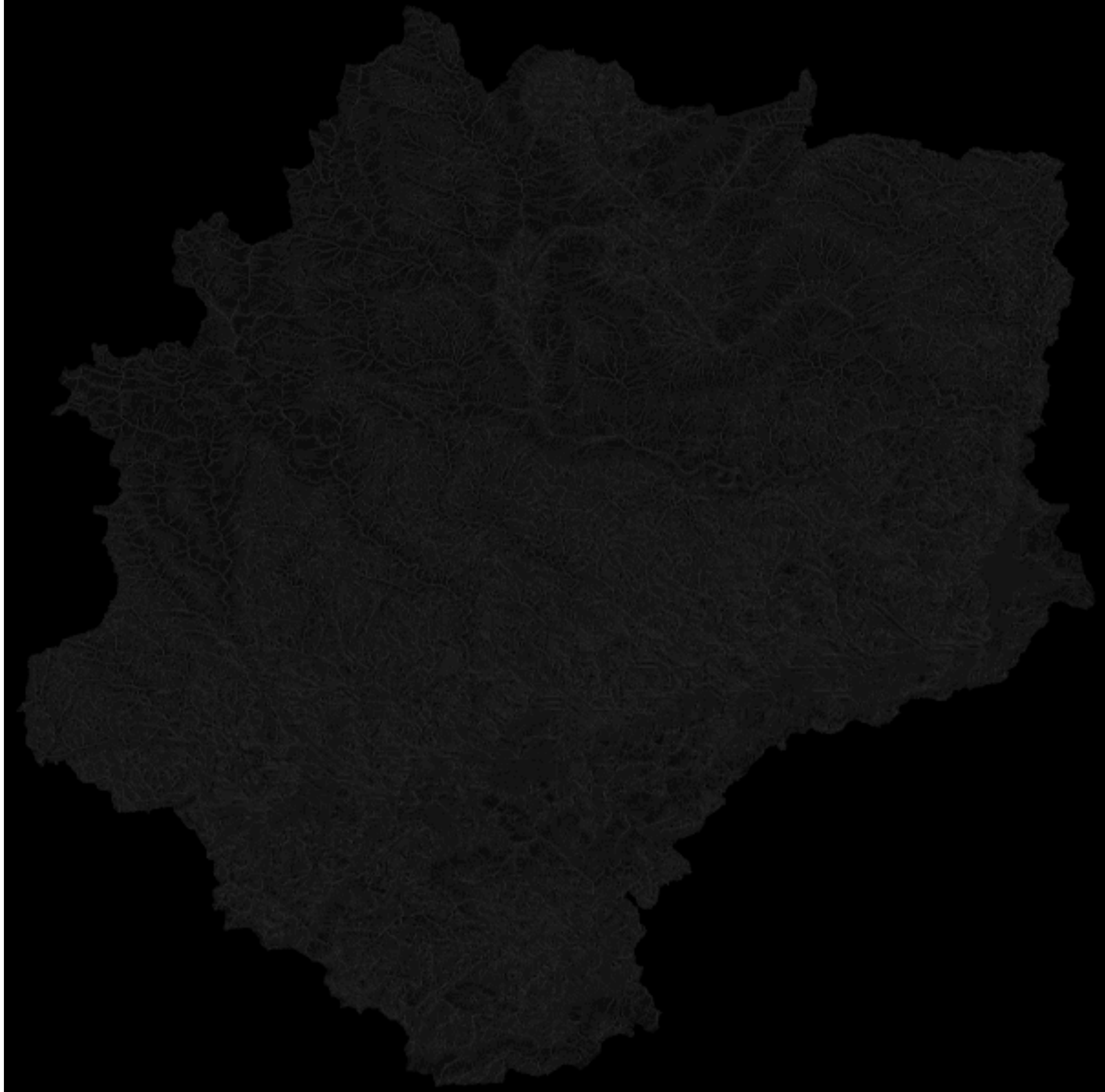


Problem: Algorithm Slow-down

- Correct flow algorithm requires all input cells to be correct before progressing
- Becomes a problem for rivers



- Correct flow completion profile



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Process Improvements

- Smaller cells lead to greater depth of erosion
  - Rivers are currently only one cell wide
  - Make rivers wider (multi-cell)
- Modification of process algorithms to allow for lateral erosion

IAPETUS
Doctoral Training Partnership
One potential PhD position to work on this

Summary

- Able to show 2+ orders of magnitude speedup in PARALLEM
- Significant potential for further speedup
  - Optimization of the processes
  - Remove sequentialization of correct flow
- The use of GPGPUs has allowed us to redress the execution restriction which has prevented us doing MFD – leading to ‘better’ landscapes

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We Are recruiting:
- 2 PostDoc (Machine Learning)
- Always looking for good PhD Candidates

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