

Modeling dam-break flooding using scalable, adaptive quad trees

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David George (USGS), Marsha Berger (NYU) Randall LeVeque (Univ. of

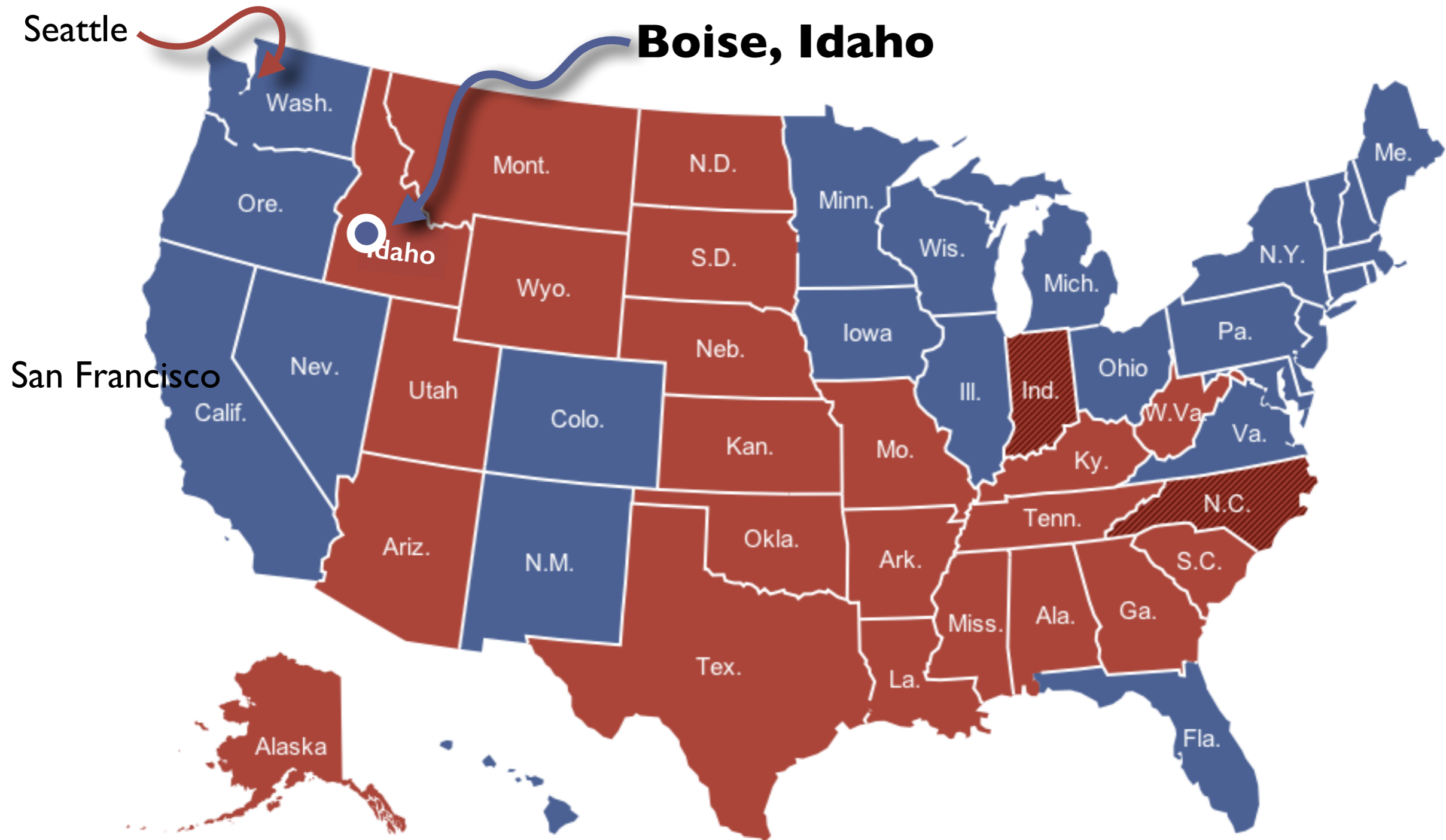
Washington); David Ketcheson (KAUST, Saudi Arabia)

Chiba University

March 6, 2018

Tokyo, Japan

Where is Boise?



*2012 Electoral map (:-((

What is in Idaho?



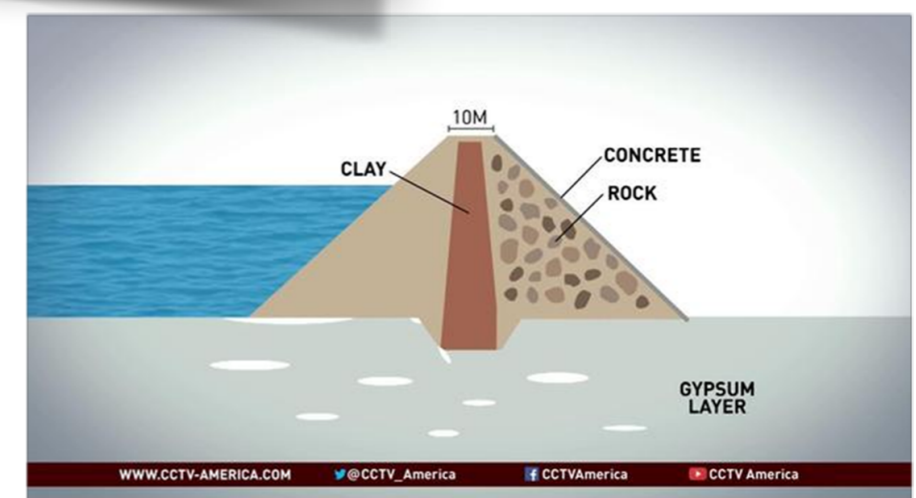
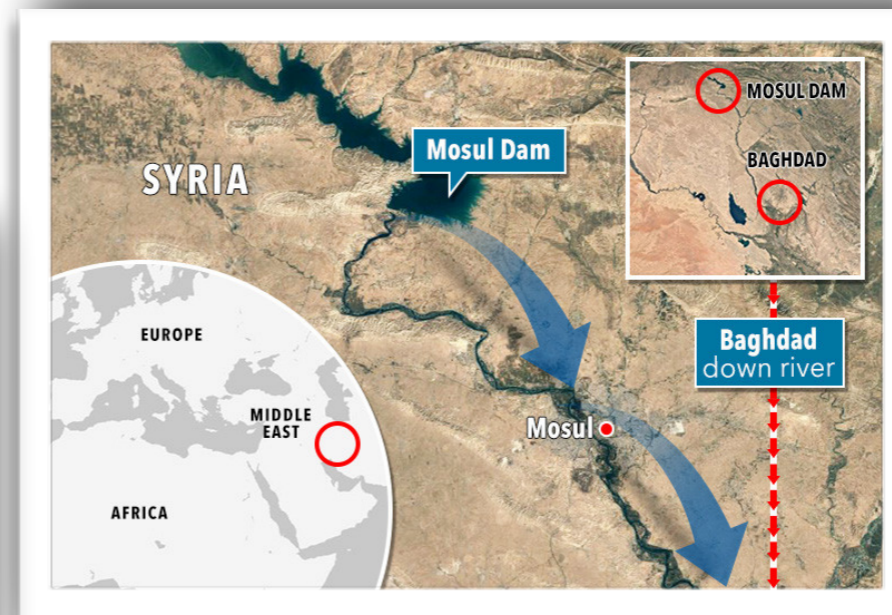
More about Idaho



Threats from dam failures

- According to a U.S. Army Corps of Engineers assessment, “Mosul Dam is the most dangerous dam in the world.” (New Yorker, 1/2/2017)
- Failure could result in million and half people losing their lives or becoming homeless.

If the dam ruptured, it would likely cause a catastrophe of Biblical proportions, loosing **a wave as high as a hundred feet** that would roll down the Tigris, swallowing everything in its path for more than a **hundred miles**. Large parts of Mosul would be **submerged in less than three hours**. Along the river banks, towns and cities containing the heart of Iraq’s population would be flooded; **in four days, a way as high as sixteen feet would crash into Baghdad**, a city of six million people. “If there is a breach in the dam, there will be no warning,” Awash [American-Iraqi civil engineer, advisor on the dam]. “**It’s a nuclear bomb with an predictable fuse**”. -- New Yorker article.

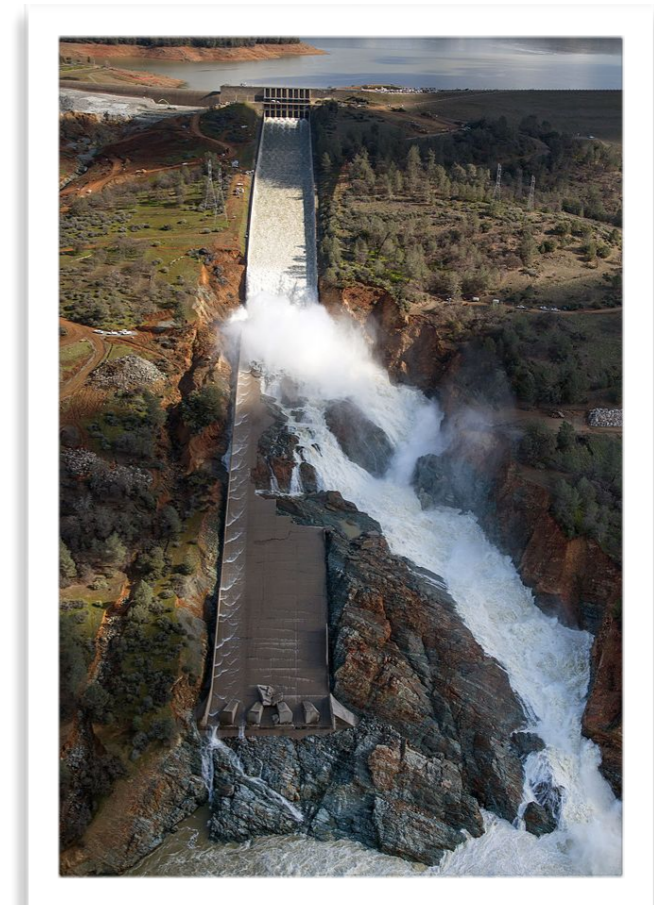


Dam Failures - US

- American Society of Civil Engineers gives the US a grade D for infrastructure -- nearly 20% of US dams have high hazard potential.



Oroville Dam, Oroville, CA. in February 2017, 188,000. Residents were evacuated downstream



Damage in the Oroville Dam Spillway (Dale Kolke / California Department of Water Resources - California Department of Water Resources)

What can simulations do?

- Used to create flood maps for local communities
- Used to communicate threats to lawmakers
- Potentially aid in design and location of future dams

But, we need to model 3d equations, complete with evolving free boundary and free surface?

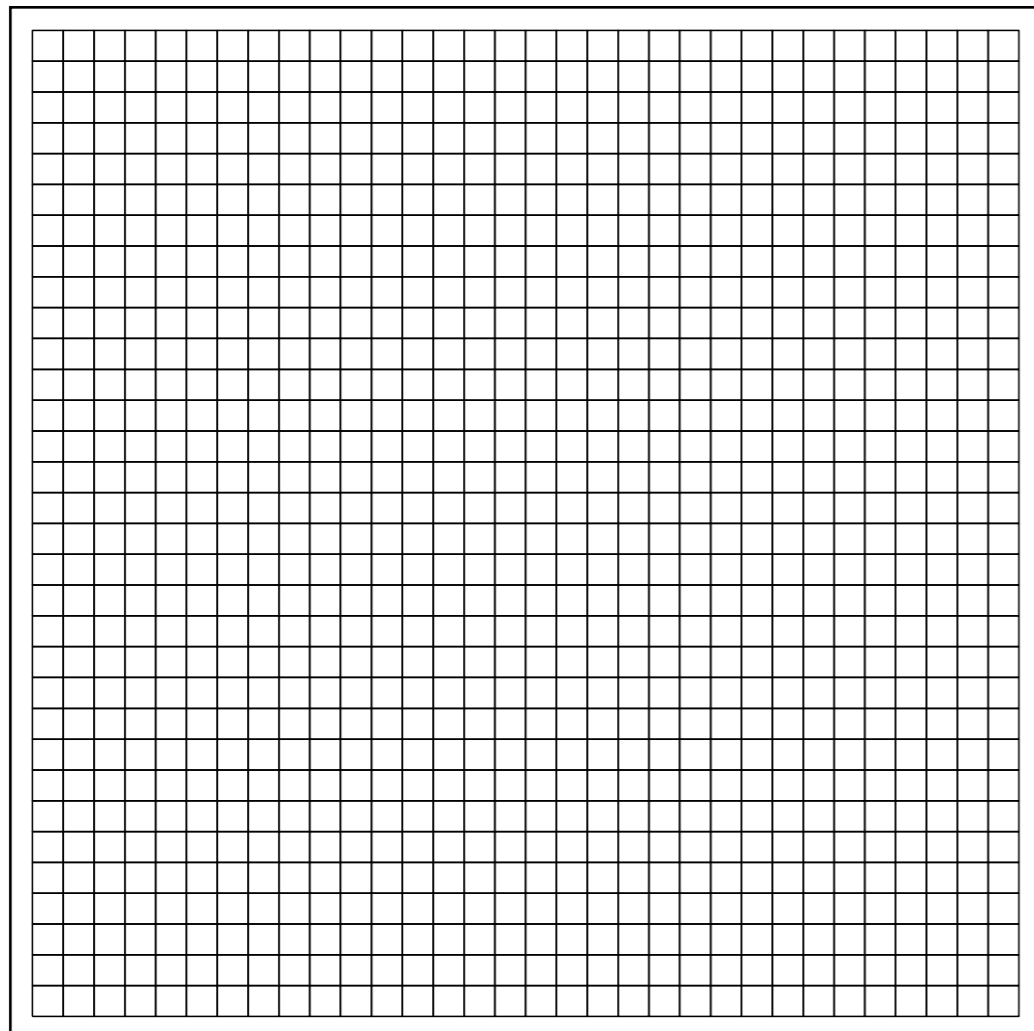
How carefully do we need to model the modes of dam failure?



Basic idea

Embed the evolving flood into a background Cartesian mesh.

- “capture” rather than “track” the evolving flooding front

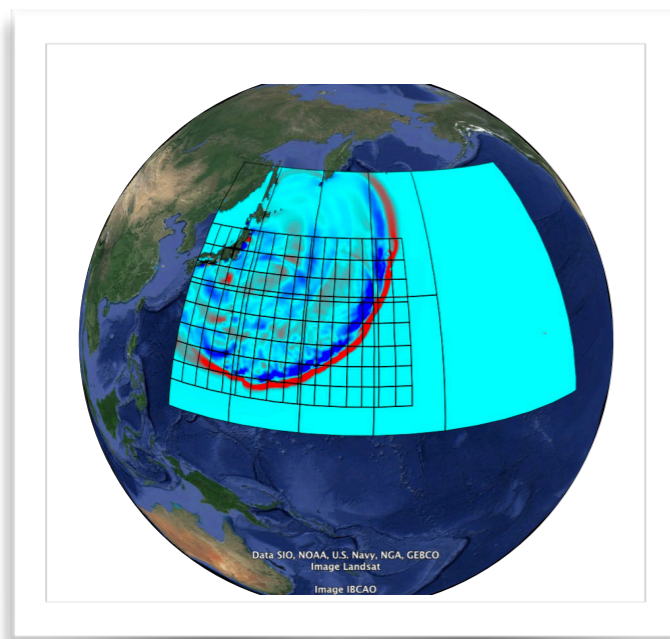


- Use finite volume scheme with suitable Riemann solver that can handle the wet/dry states.
- Handle topography to model realistic flow situations.
- Two dimensional flow makes calculations reasonably inexpensive

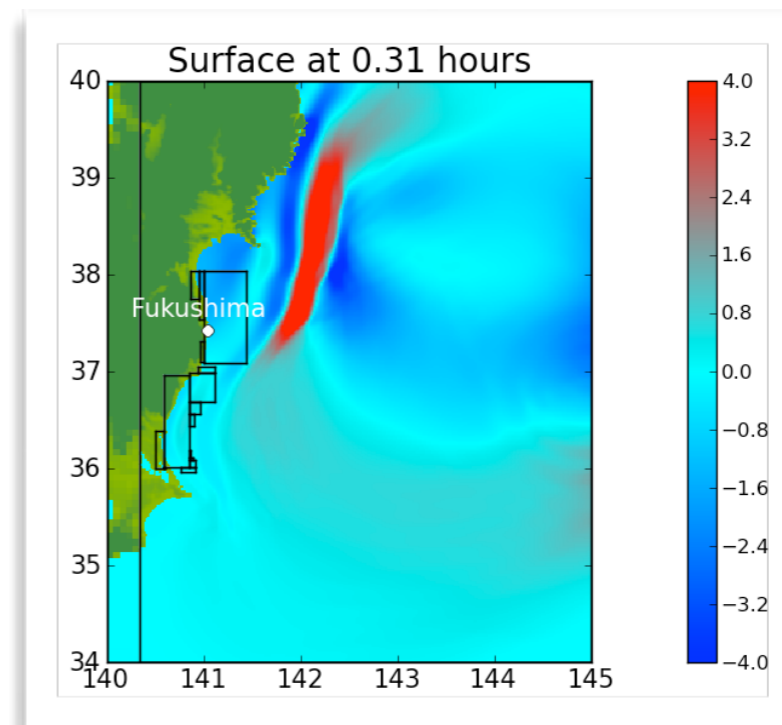
GeoClaw

GeoClaw is a depth-averaged (shallow water wave equations) code based on the finite volume, second order Cartesian grid methods in Clawpack

- Jointly developed by USGS, Univ. of Washington, NYU and Columbia researchers (D. George, R. J. LeVeque, M. Berger, K. Mandli)
- Based on the wave propagation algorithms in Clawpack (R. J. LeVeque)



Fukushima, Japan 2010



<http://www.geoclaw.org>

Depth-averaged models

Alternative to fully 3d flow simulations are the two-dimensional **shallow water wave equations** (SWE).

- The wave length of the flow is long relative to the depth of the flow
- Commonly used in **modeling tsunamis**
- More recently being widely used in modeling landslides, debris flows, avalanches, storm surges, and so on

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) = 0$$
$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) = -ghb_x$$

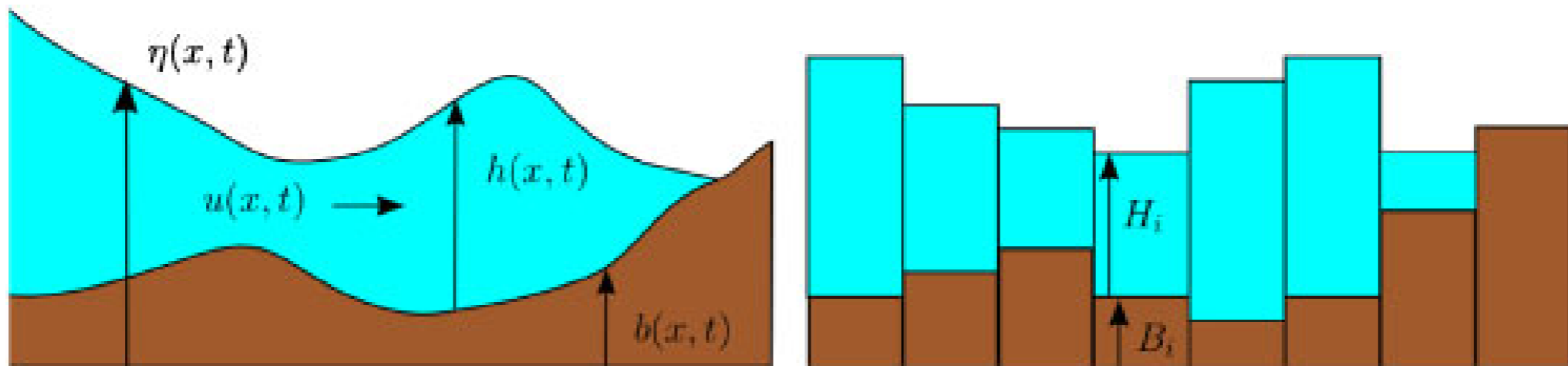
$h(\mathbf{x}, t)$	depth-averaged <i>height</i>
$u(\mathbf{x}, t)$	horizontal velocity
$b(\mathbf{x}, t)$	bathymetry (depth of ocean floor)
g	acceleration due to gravity (9.81 m/s)

2d SWE (GeoClaw)

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0,$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) = -gh\frac{\partial b}{\partial x} + S_{fx},$$

$$\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) = -gh\frac{\partial b}{\partial y} + S_{fy},$$



D. L. George, "Adaptive finite volume methods with well-balanced Riemann solvers for modeling floods in rugged terrain: Application to the Malpasset dam-break flood (France, 1959)", *Int. J. Numer. Methods. Fluids*, 66 (2011), pp. 1000–1018.

GeoClaw

GeoClaw overcomes several technical challenges

- Riemann solver robustly handles **wet and dry states** and discontinuities in topography - *no need to track the evolving flood boundary.*
- Seamlessly handles reading and interpolation of multiple, possibly overlapping, **topography files** for given computational domain
- Numerical gauges allow for easy comparison with observational data
- Uses **adaptive mesh refinement** (AMR)

Clawpack-5

[Docs](#) [Install](#) [Gallery](#) [Community](#) [Source](#) [Develop](#)

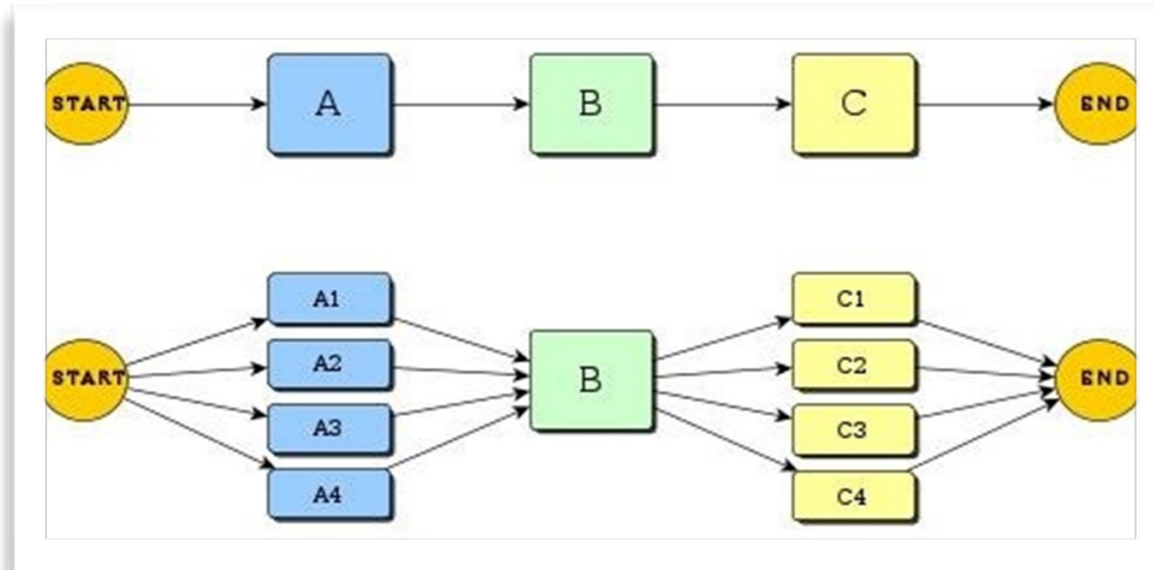
GeoClaw

See www.geoclaw.org for more overview of the GeoClaw software and links to references and uses.

www.clawpack.org

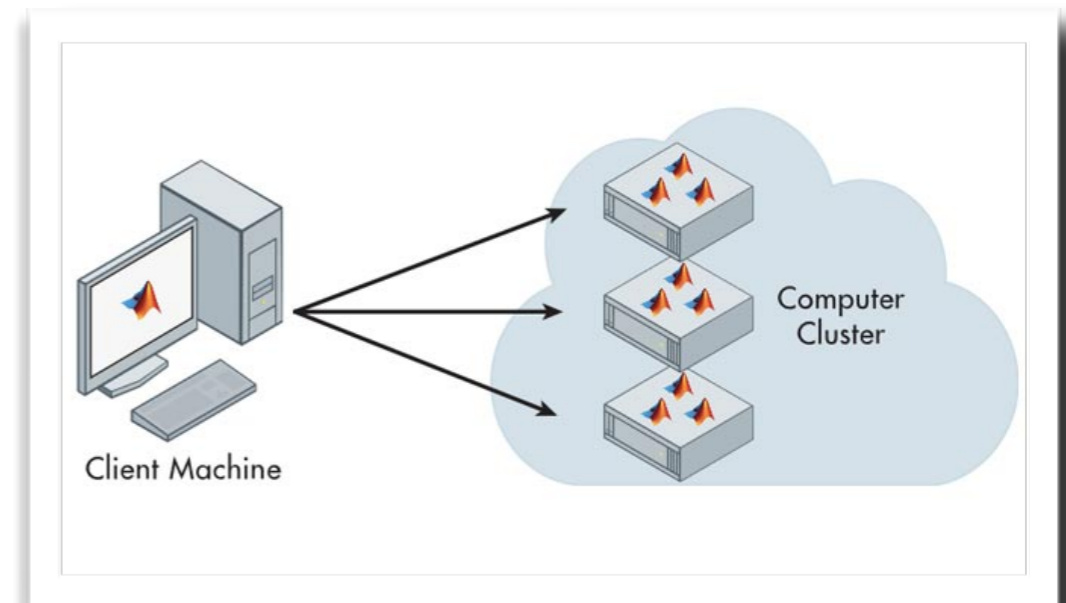
GeoClaw

However, GeoClaw only uses “threaded parallelism”



OpenMP - shared memory

Distributed memory



Our goal is to develop a “distributed” version of GeoClaw.

- Use as much of existing GeoClaw framework as possible and take advantage of the expertise built into the code,
- Provide an **octree-based** adaptive mesh infra-structure,
- Introduce **distributed parallelism** to **replace OpenMP parallelism**

ForestClaw Project

A parallel, adaptive library for logically Cartesian, mapped, multi-block domains

Features of ForestClaw include :

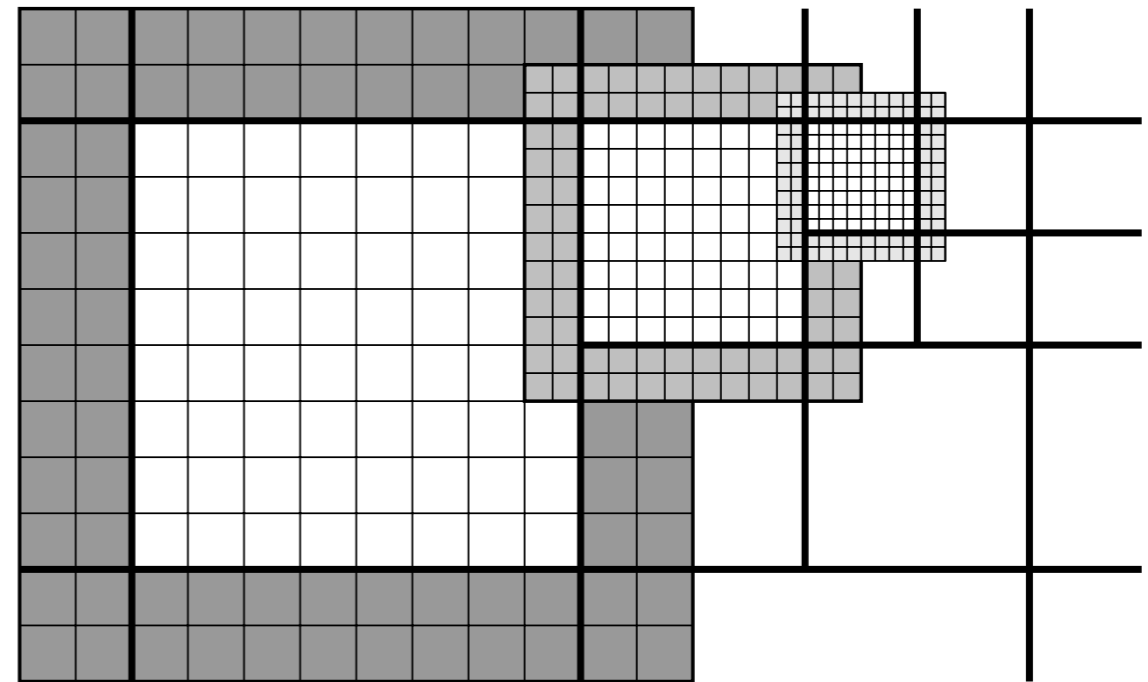
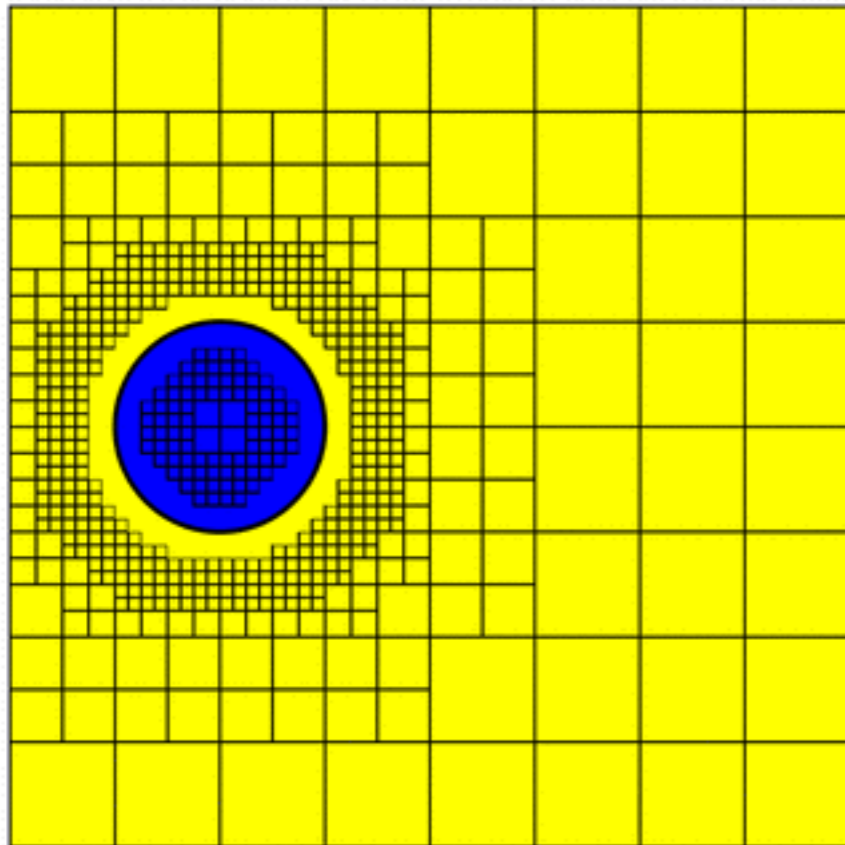
- Uses the **highly scalable p4est** dynamic grid management library (C. Burstedde, Univ. of Bonn, Germany) *Gordon Bell Finalist, 2013; used in 2015 Gordon Bell prize.*
- Each leaf of the quadtree contains a fixed, uniform grid,
- Optional multi-rate time stepping strategy,
- Has **mapped, multi-block** capabilities, (cubed-sphere, for example) to allow for flexibility in physical domains,
- Modular design gives user flexibility in extending ForestClaw with Cartesian grid based solvers and packages.
- Uses essentially the same algorithmic components as patch-based AMR

Thanks to NSF for supporting this work

www.forestclaw.org

ForestClaw adaptivity

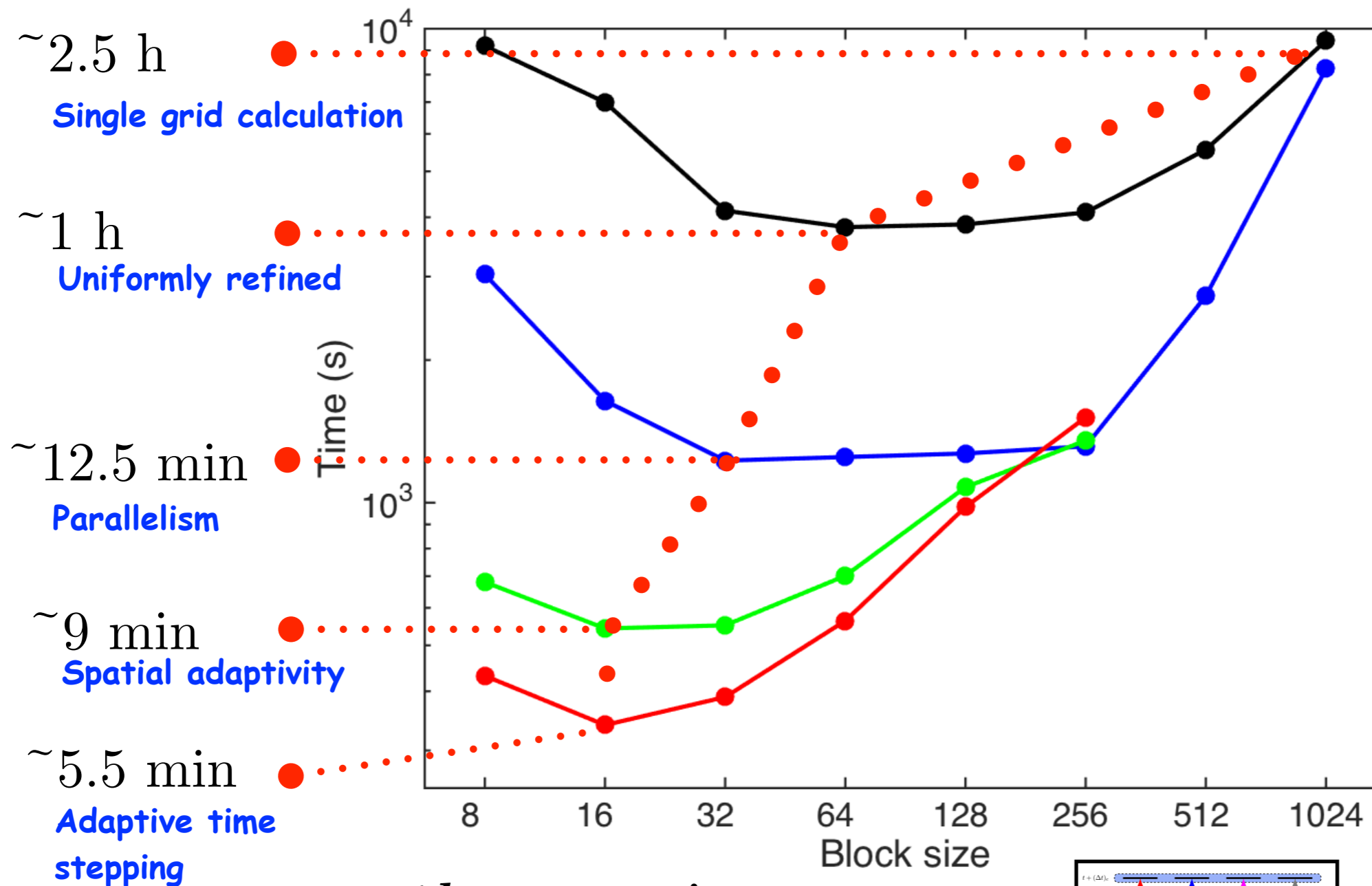
q(1) at time 0.0000



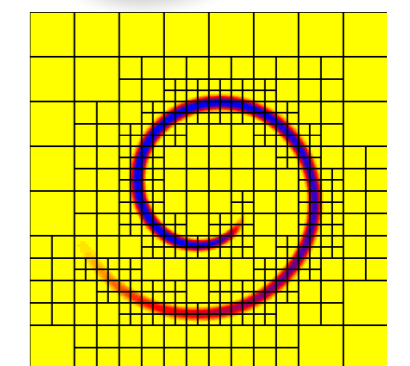
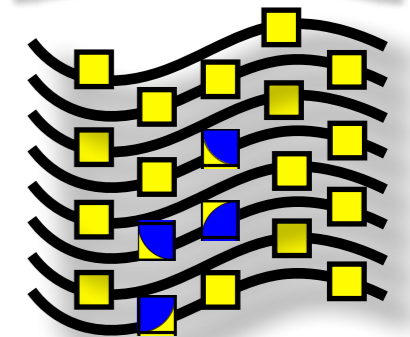
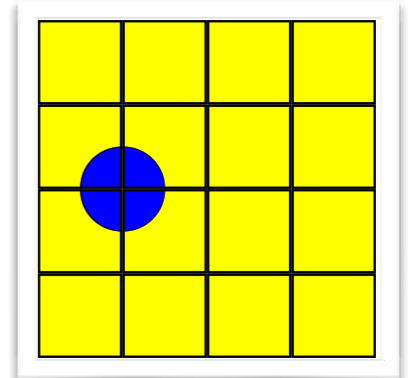
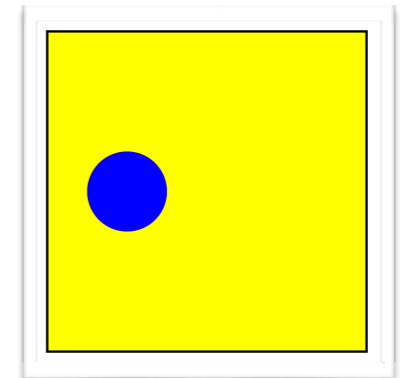
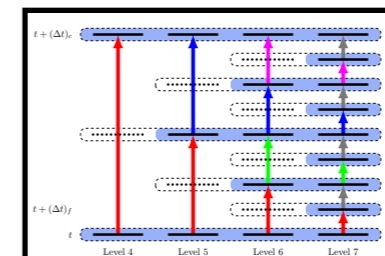
Each quadrant is a single logically grid, designed for finite volume or finite difference solvers.

Regridding, connectivity done using p4est (www.p4est.org)

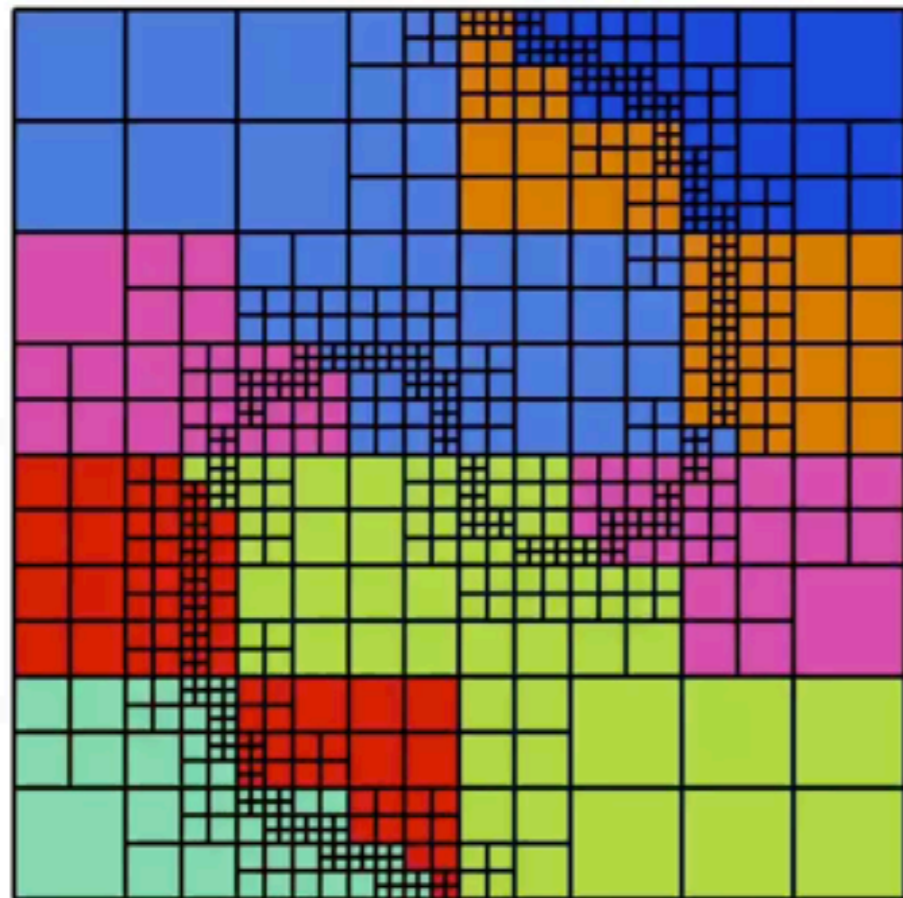
Computational performance



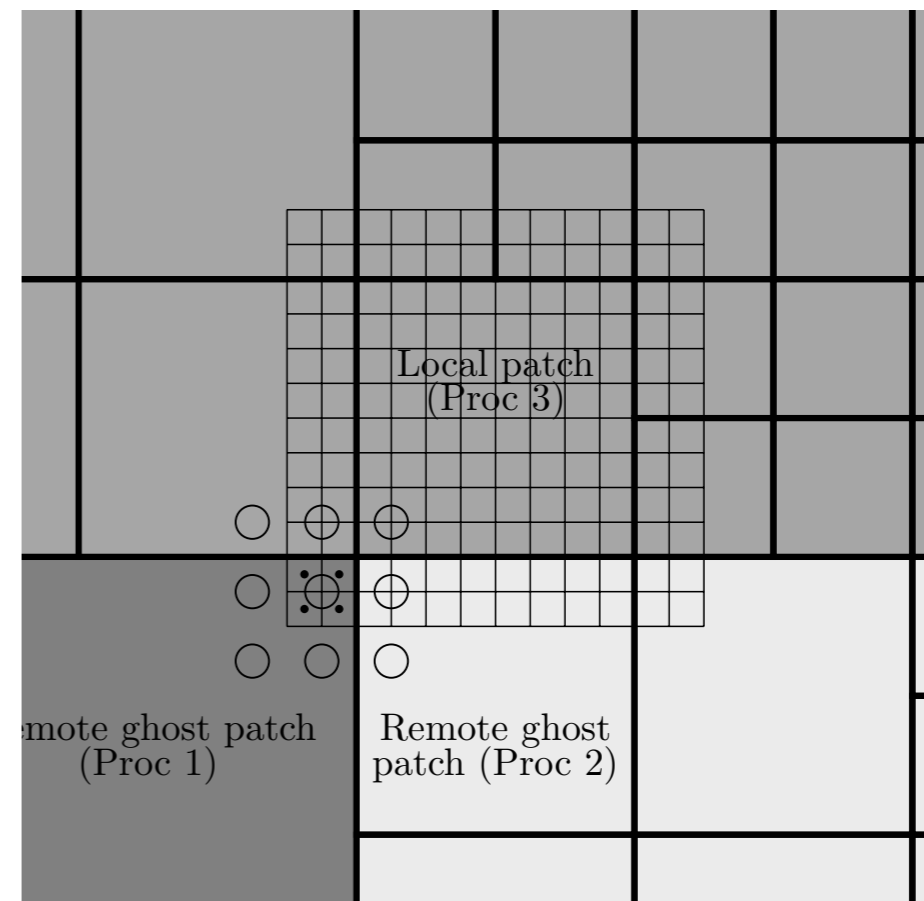
Almost 30 times improvement



ForestClaw - Parallelism



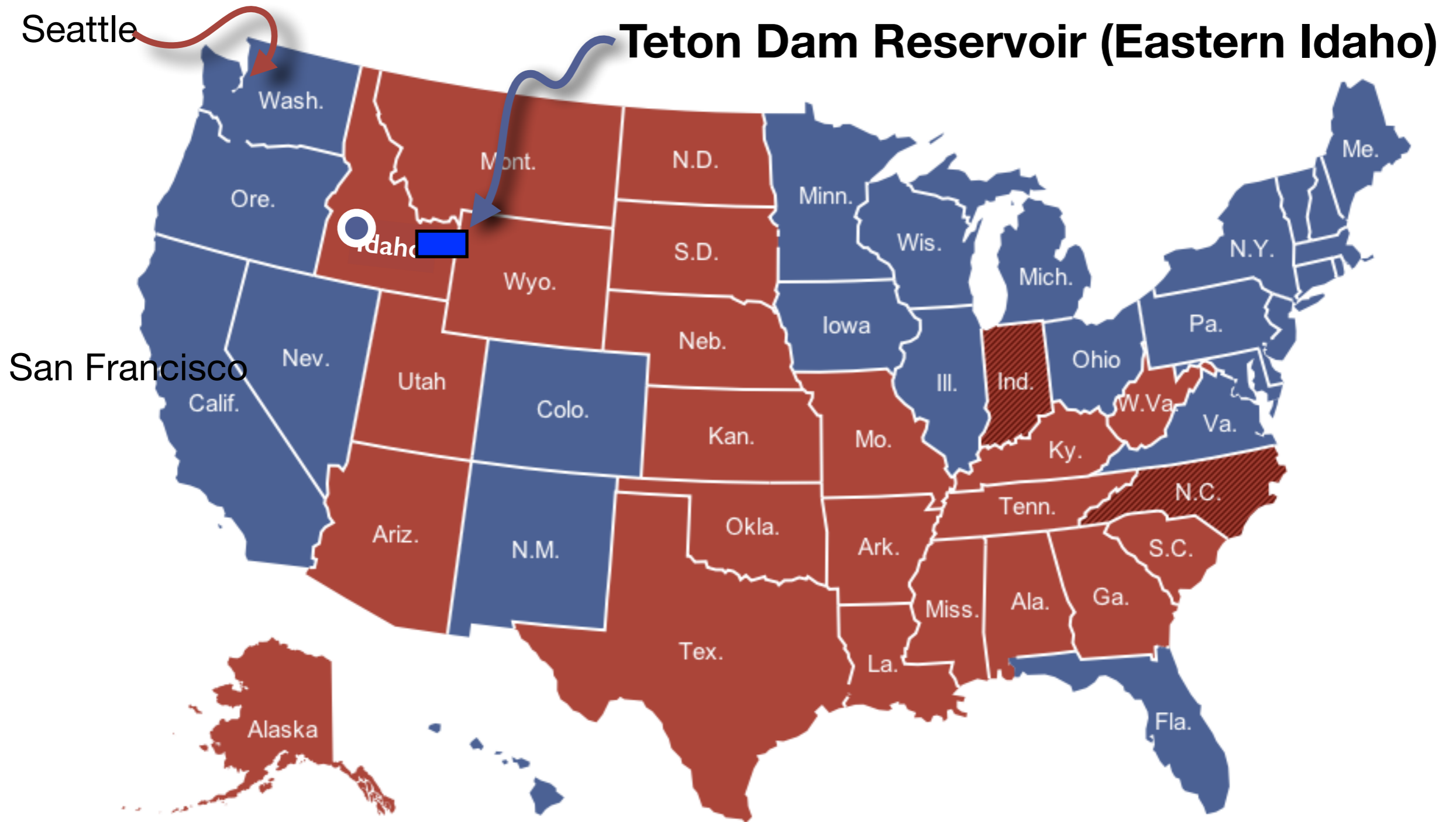
p4est : Load balancing using a space filling curve



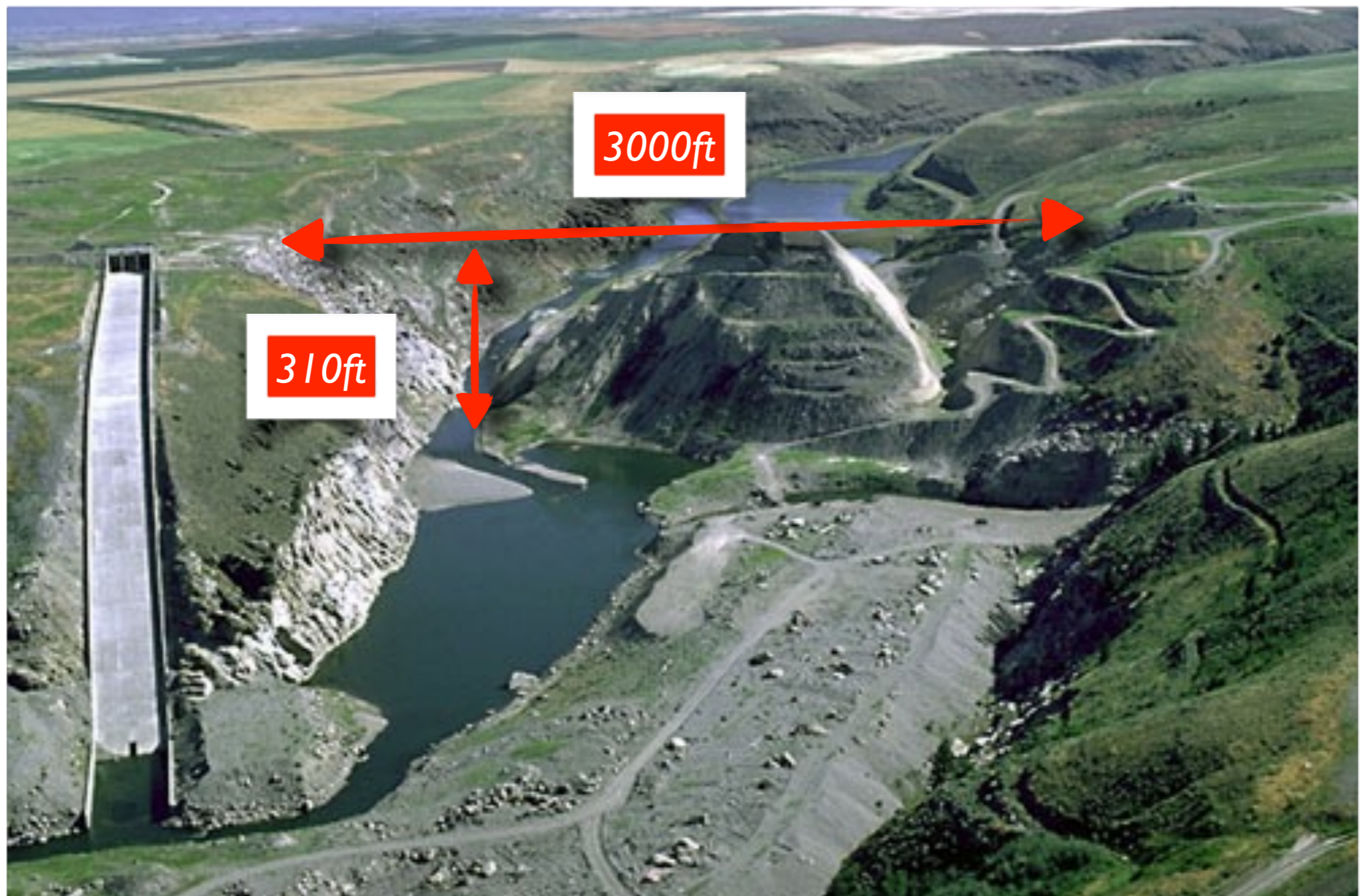
Fine grid corner ghost cells at corners where 3 or more processors meet

D. Calhoun and C. Burstedde, "ForestClaw : A parallel algorithm for patch-based adaptive mesh refinement on a forest of quadtrees", (submitted), 2017. ([arXiv:1703.03116](https://arxiv.org/abs/1703.03116))

Teton Dam



Teton Dam Failure, June 5, 1976



11 people died; \$2bn in damage

Teton Dam Failure, June 5, 1976



8 minutes before dam failure

Teton Dam Failure, June 5, 1976



~11:52 AM, June 5, 1976

Teton Dam Failure, June 5, 1976



By WaterArchives.org from Sacramento, California, USA - [IDAHO-L-0010] Teton Dam Flood - Newdale, CC BY-SA 2.0,

Historical Data

Location	Miles from Dam	Flood Arrival Time	Flood Arrival Travel Time (time from embankment breach)	Peak Flow (cubic feet per second)	Flood Description
Teton Canyon	2.5	12:05 p.m. June 5	8 minutes	2,300,000	50 to 75 ft wall-of-water
Near mouth of Teton Canyon	5.0	12:20 p.m.	23 minutes		
Wilford	8.4				120 of the 154 homes "completely swept away"
Town of Teton	8.8	12:30 p.m.	33 minutes	1,060,000	Only tiny fraction flooded
Sugar City	12.3	About 1:30 p.m.	1.5 hours		15-foot wall-of-water
Rexburg	15.3	About 2:30 p.m.	2.5 hours		6 to 8 feet in a few minutes
Roberts	43.1	9:00 p.m.	9 hours		
Idaho Falls	63.0	1 a.m. June 6	13 hours	90,500	
Shelley	71.2	2 a.m.	14 hours	67,300	Peak 21 hours after arrival. 0.5 feet per hour average rate of rise.

W. Graham, "Reclamation : Managing water in the west, The Teton Dam Failure - An effective warning and evacuation", U.S. Department of the Interior, Bureau of Reclamation, Denver Colorado

Inundation map

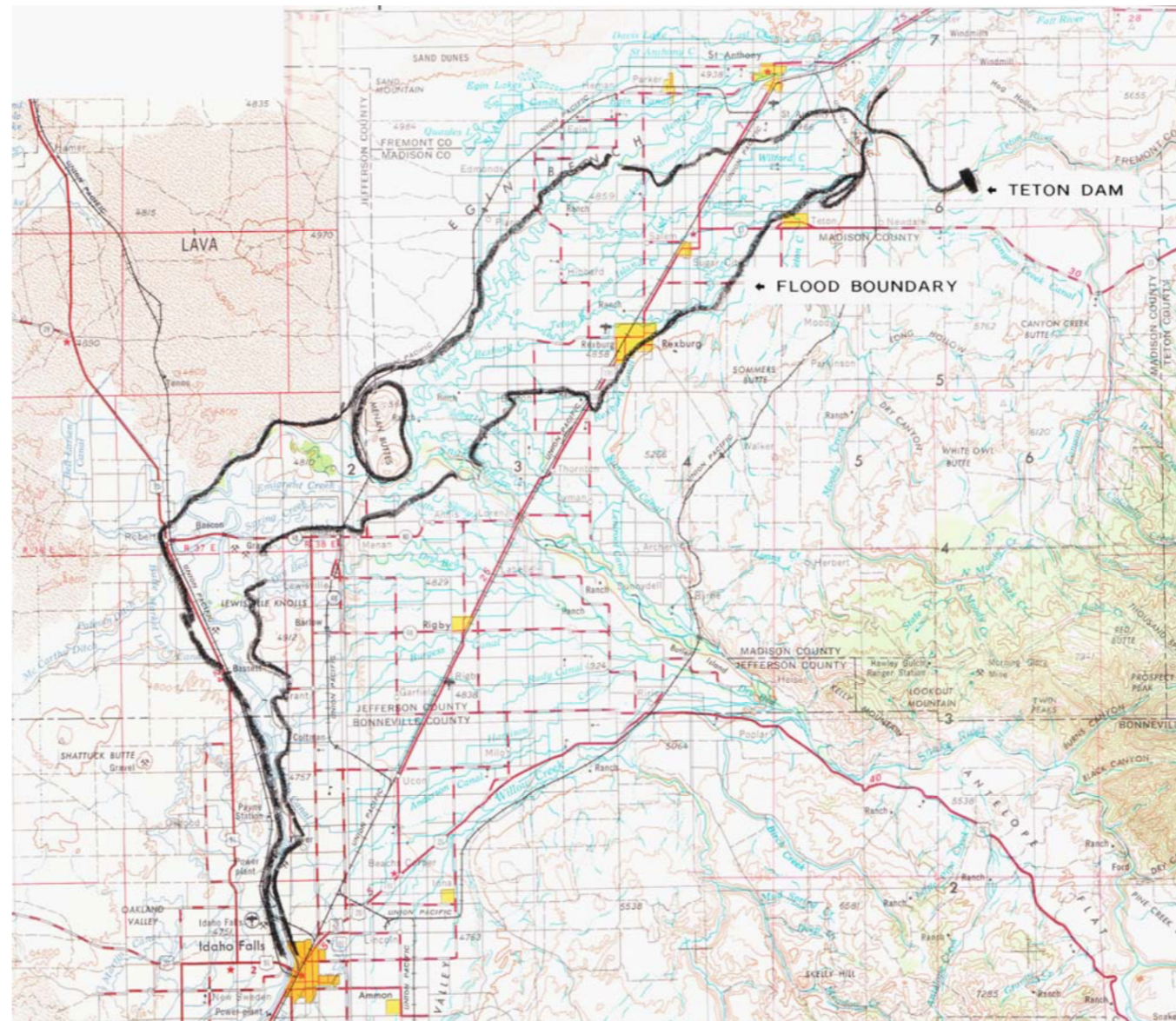


Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

W. Graham, "Reclamation : Managing water in the west, The Teton Dam Failure - An effective warning and evacuation", U.S. Department of the Interior, Bureau of Reclamation, Denver Colorado

Simulations using ForestClaw/Geo

Simulation details :

- Run at 10m effective resolution (8192 x 4096)
- 12 hours of simulation time
- Manning coefficient set to 0.025
- Results compared with historical flood boundaries and arrival times
- No detailed modeling of the dam failure itself

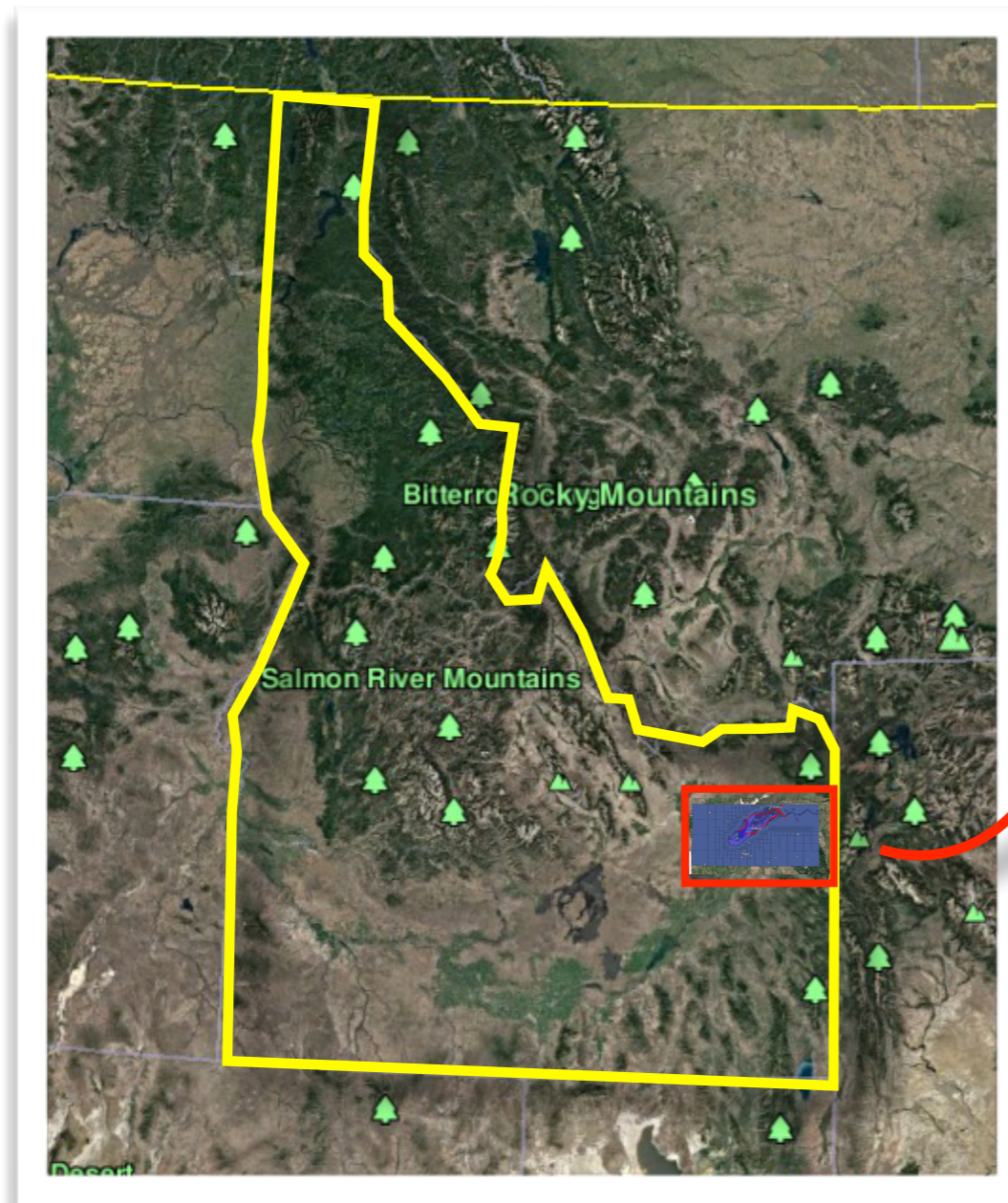
Numerical parameters

- 7 levels of refinement
- standard 'feature-based' refinement based on wave speeds and depth
- 2 blocks or quad-trees used to grid the domain

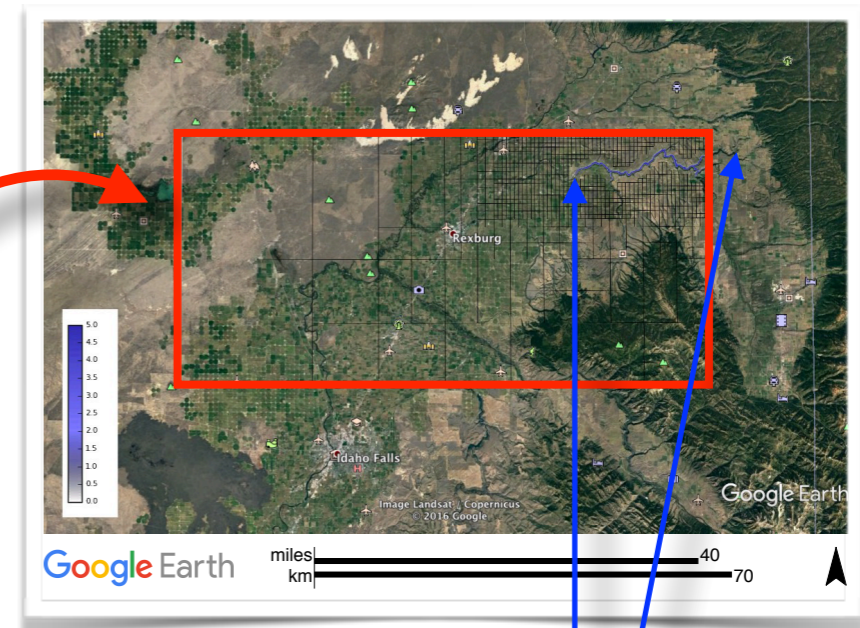
Platform

- 22 Broadwell nodes : Dual Intel Xeon E5-2680 v4 14 core 2.4GHz

Teton Dam Failure, June 5, 1976



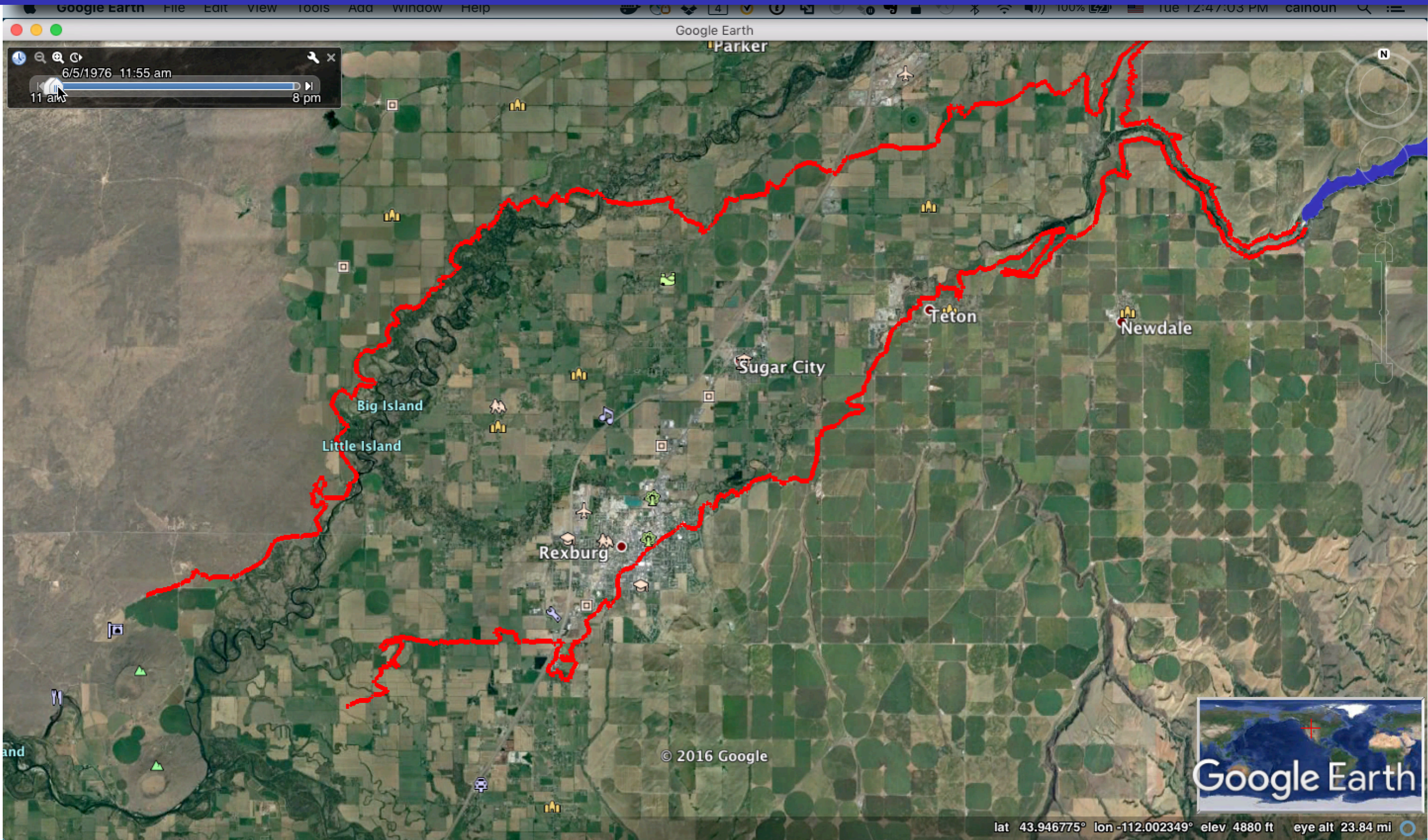
Computational Area : 88km x 42km



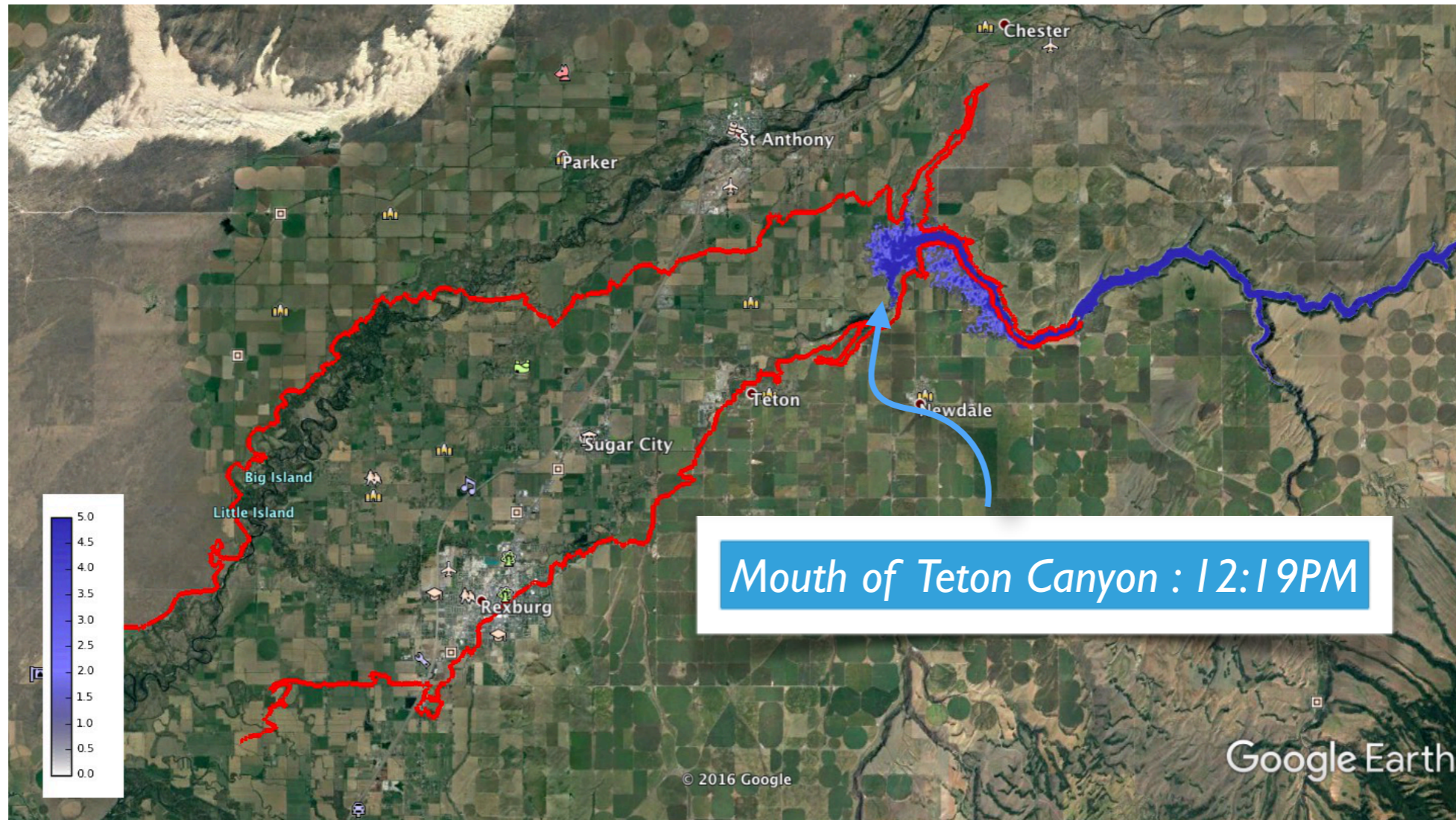
Reservoir

~10m resolution : ~8192 x 4096
effective resolution

Simulation results



Simulation results

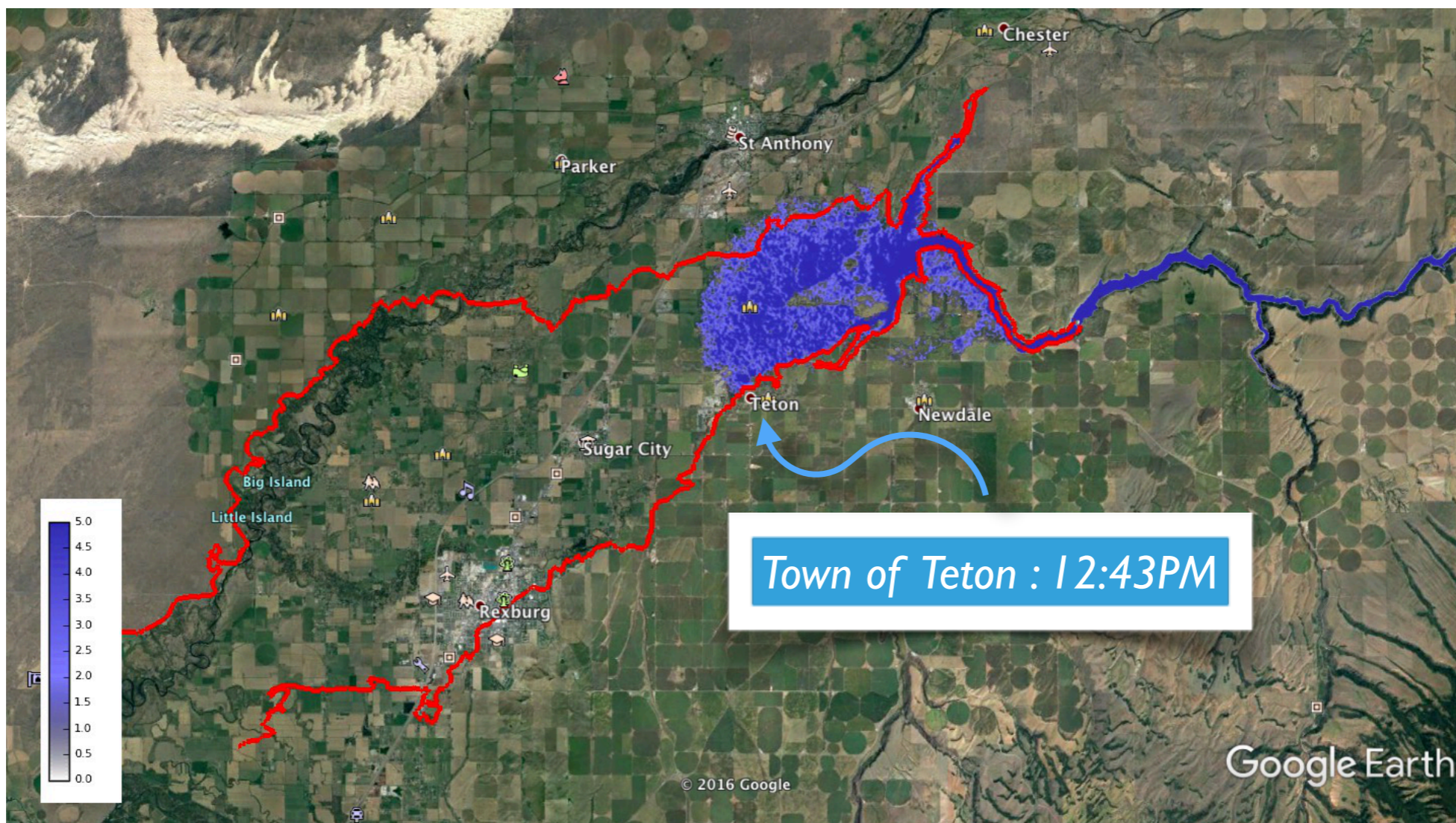


Google Earth



Near mouth of Teton Canyon	5.0	12:20 p.m.	23 minutes			
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Simulation results

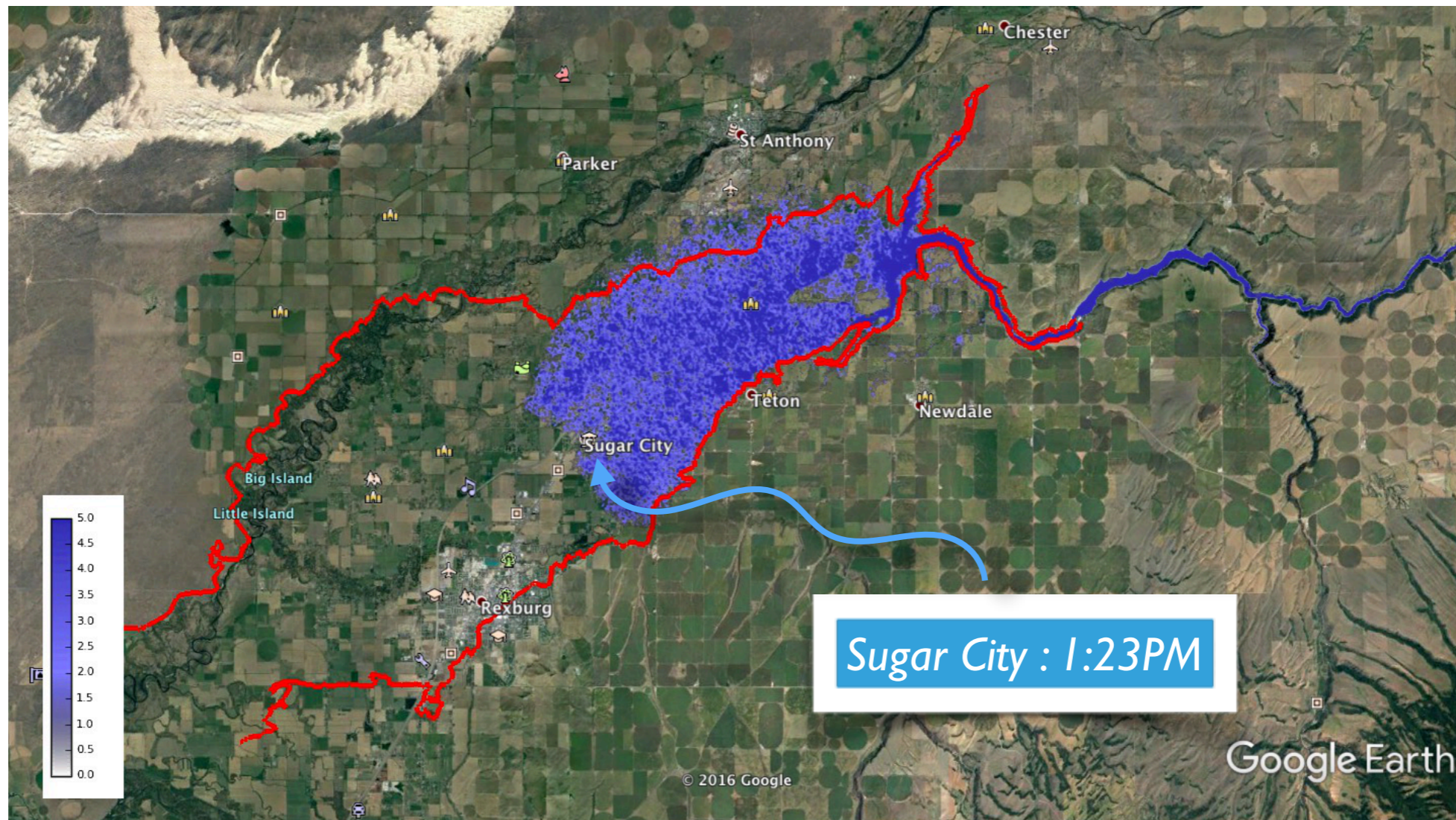


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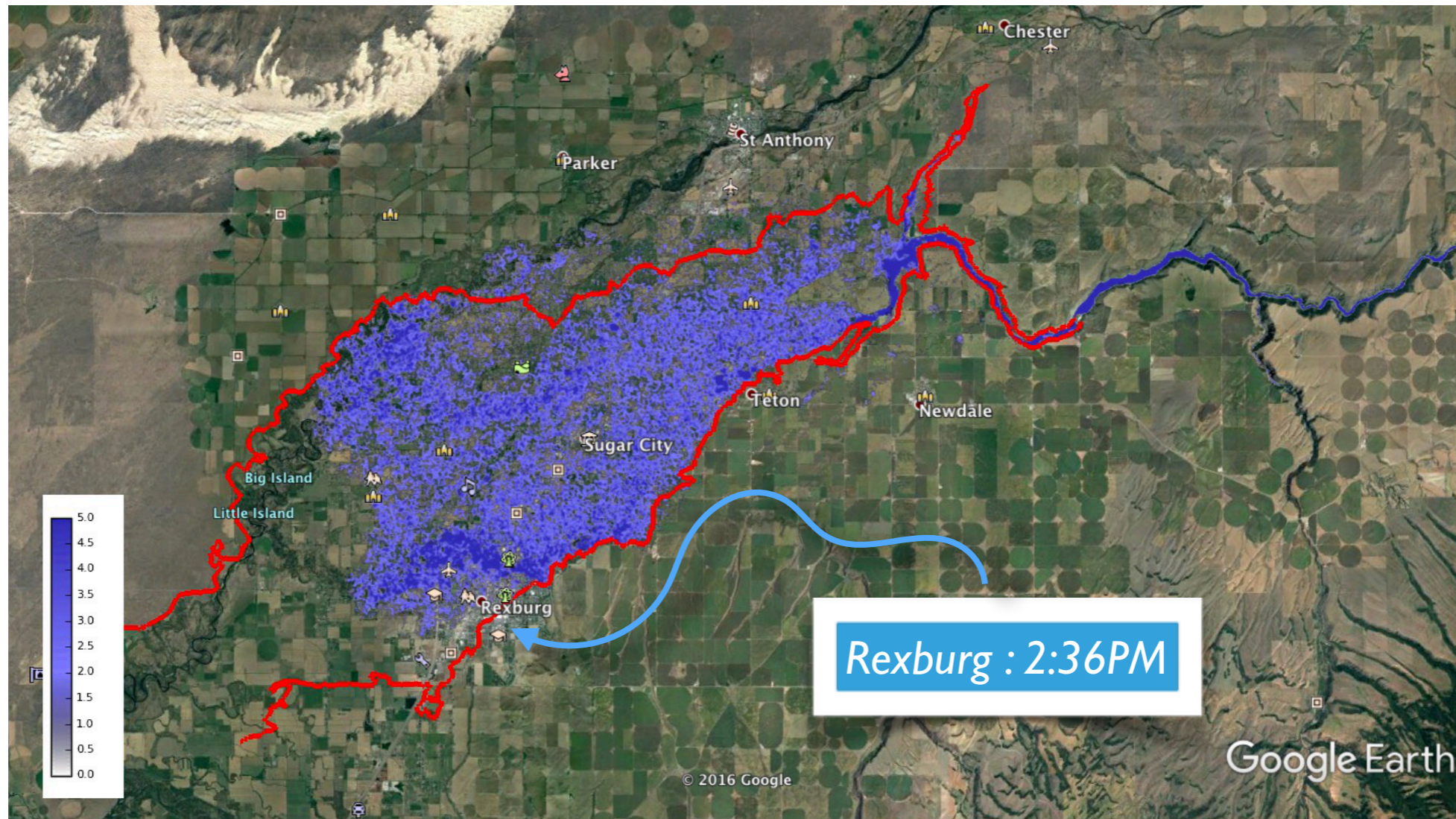


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Simulation results

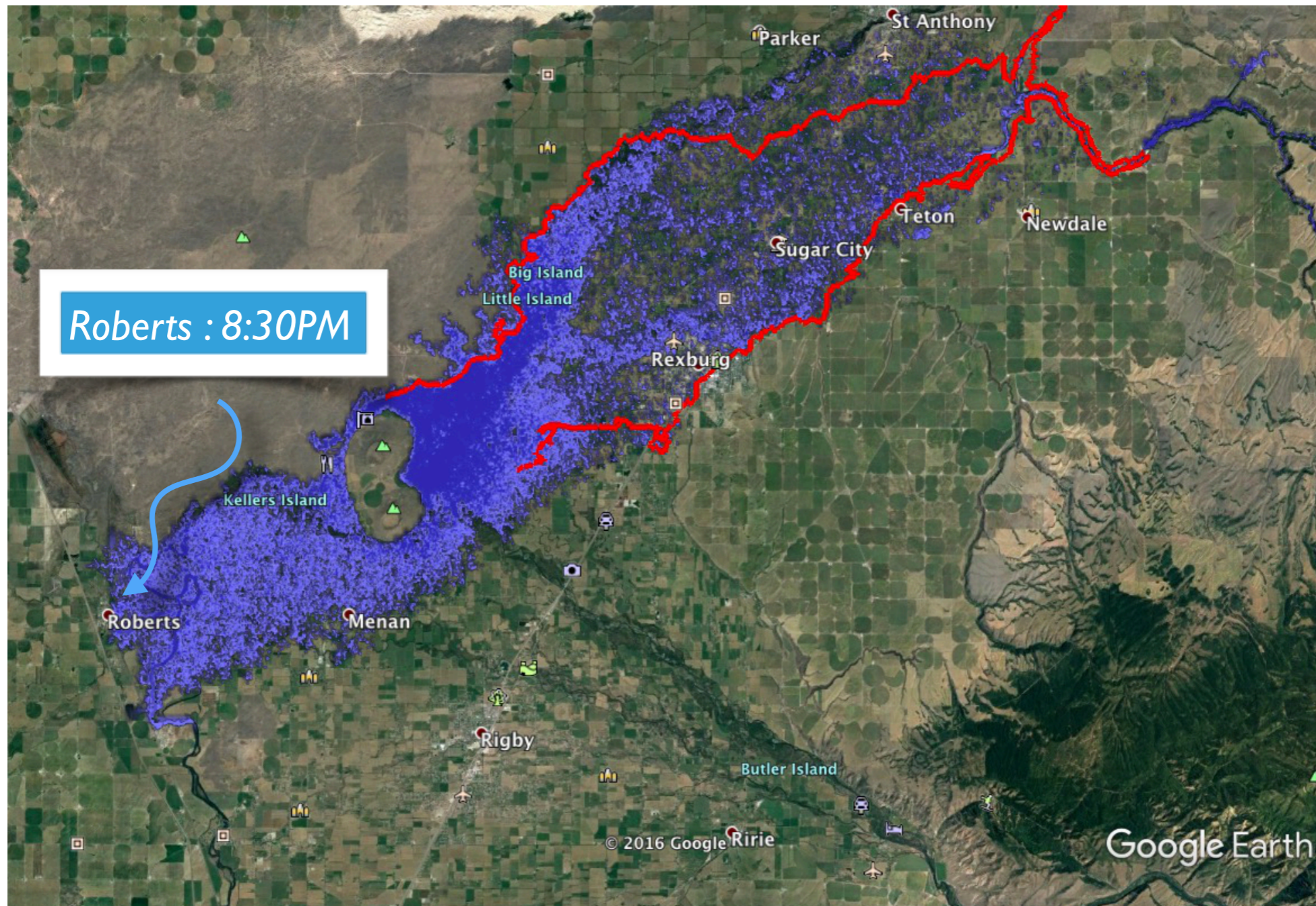


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Rexburg	15.3	About 2:30 p.m.	2.5 hours		6 to 8 feet in a few minutes
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Simulation results



Roberts	43.1	9:00 p.m.	9 hours		
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Simulation results

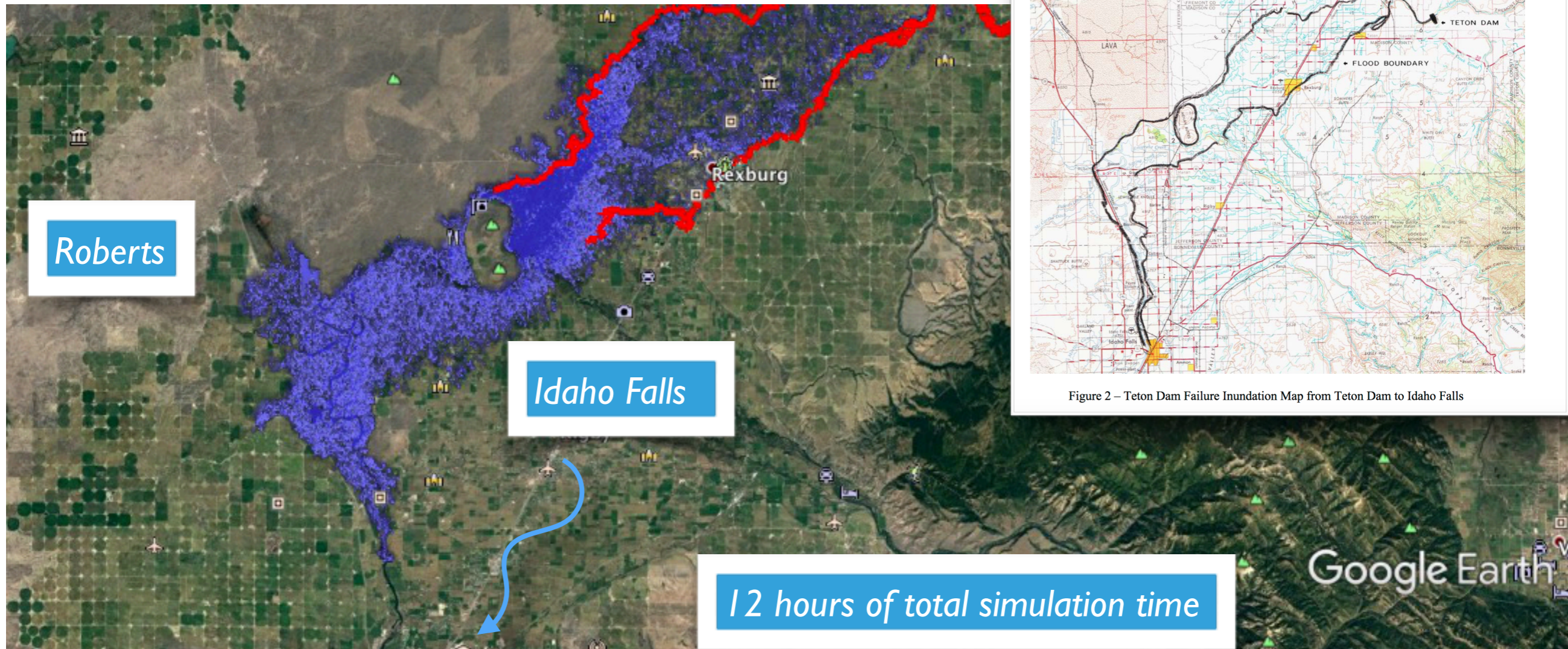
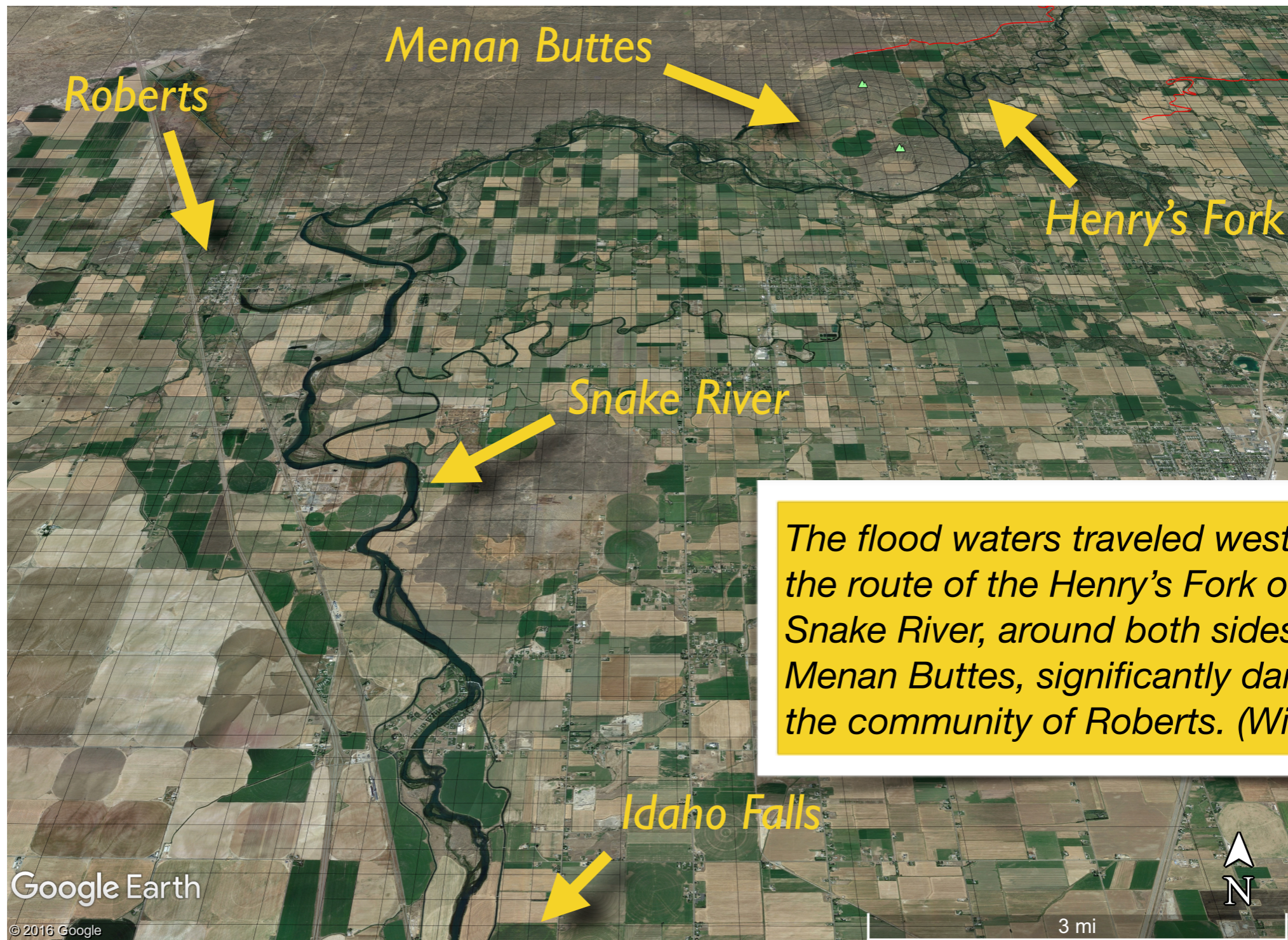


Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

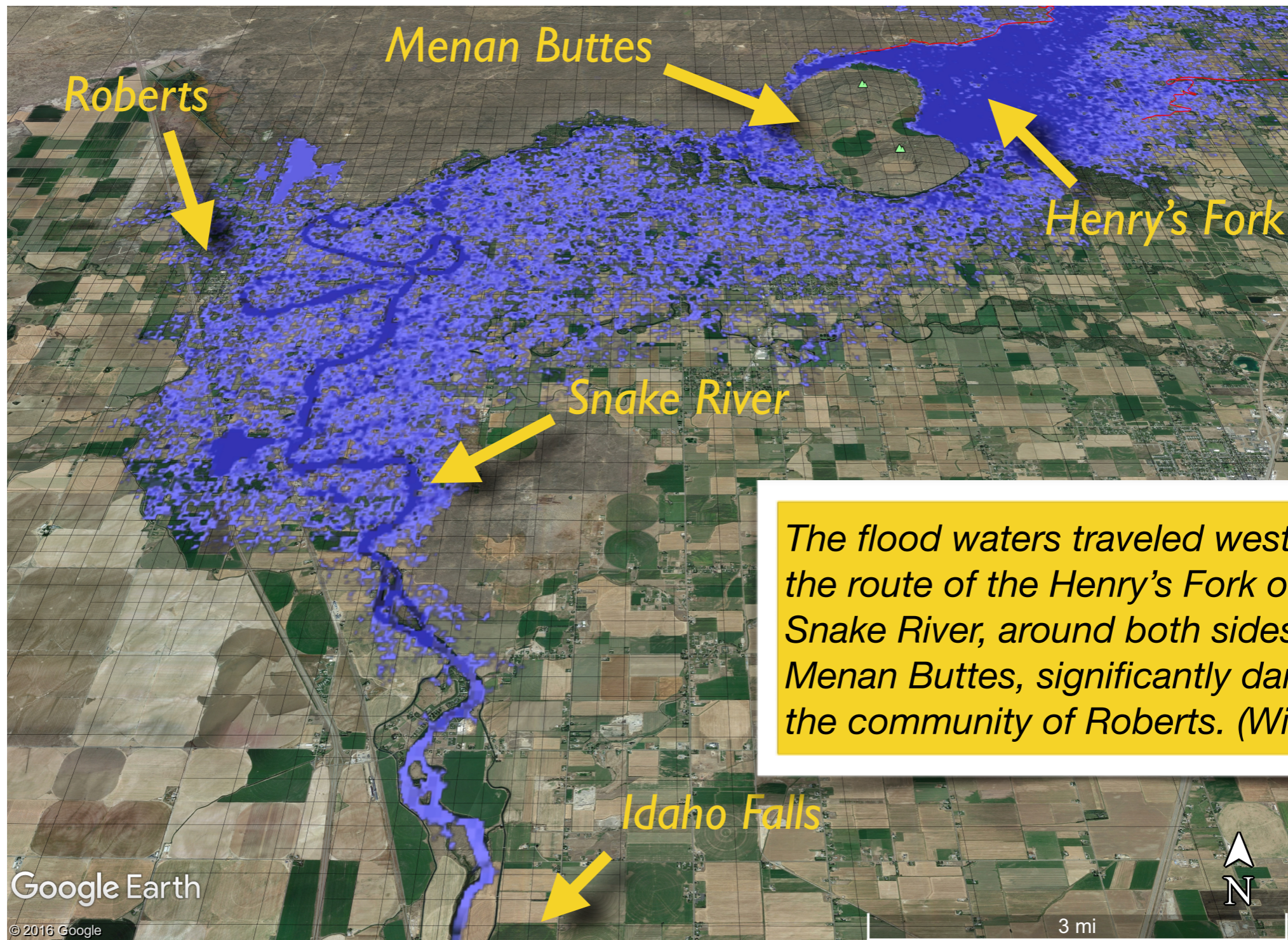
Level 0

Roberts	43.1	9:00 p.m.	9 hours		
Idaho Falls	63.0	1 a.m.	13 hours	90,500	

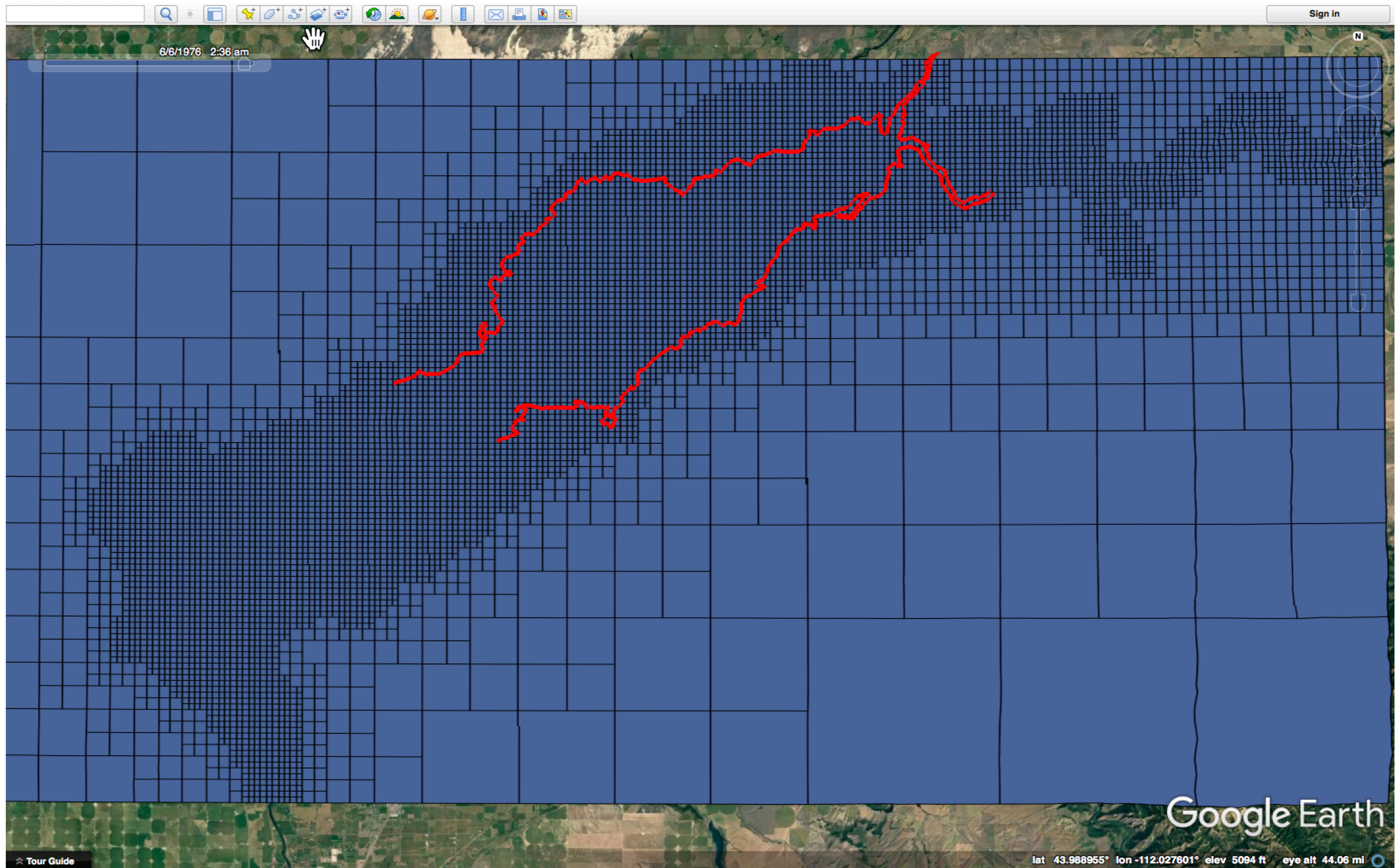
Snake River



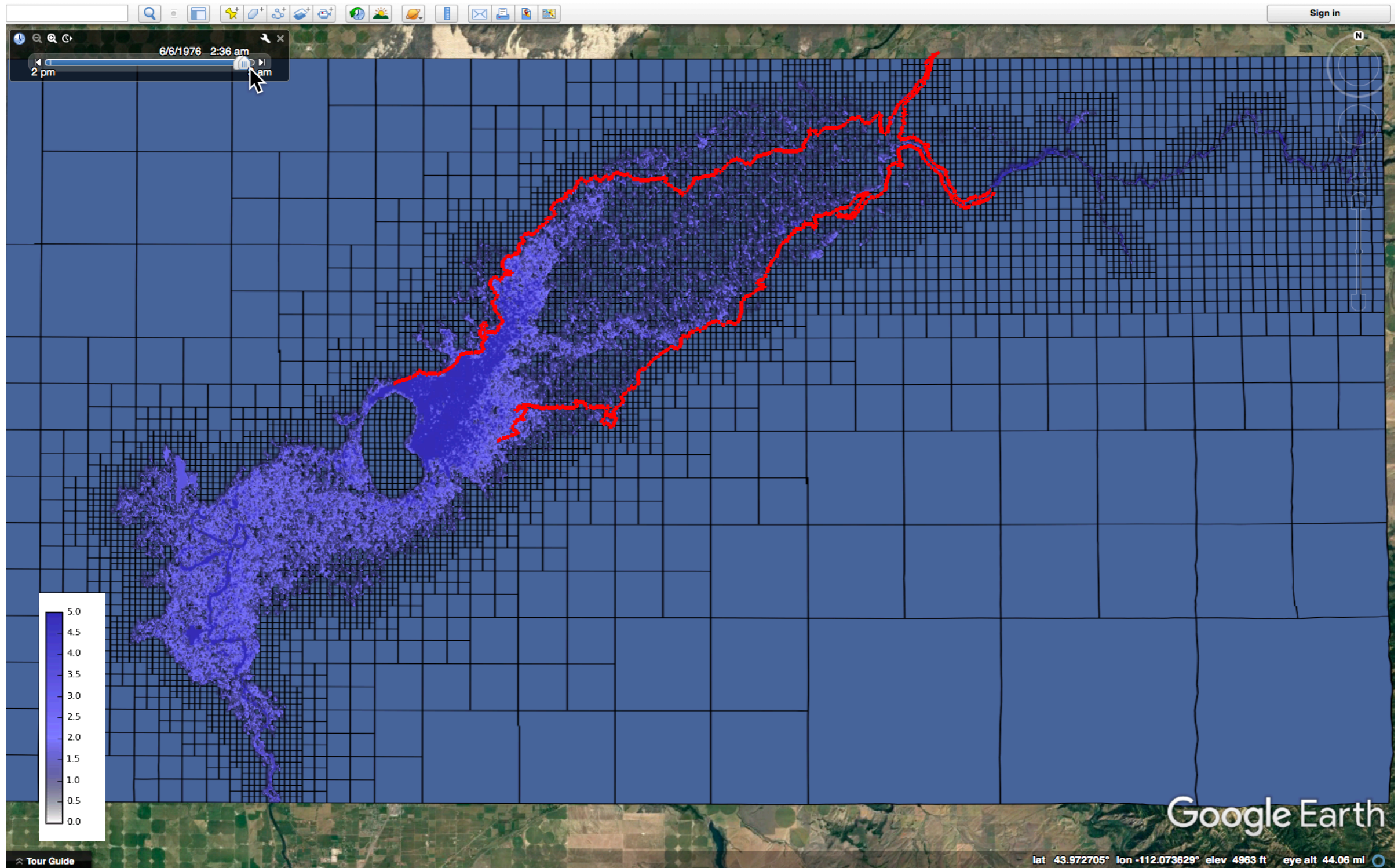
Snake River



Adaptive Mesh



Adaptive Mesh



Parallel/AMR Efficiency

~ 10m resolution (8192 x 4096)

6.5 hours vs.
30 minutes

Procs	14	28	56	112	224
Wall (s)	23601.9	12510.6	6626.7	3499.7	1872.9
Speed-up	1.00	1.89	3.56	6.74	12.60
Efficiency	100%	94%	89%	84%	79%
Grids per processor	670	334	167	83	41

Procs	Wall	Advance	(%)	Ghost Comm	(%)	Ghost fill	(%)	Regrid	(%)	Speed-up	Par. eff.
14	23601.9	17706.4	75%	4500.4	19%	1343.3	6%	28.5	0%	1.0	100%
28	12510.6	8863.0	71%	2838.0	23%	772.4	6%	17.0	0%	1.9	94%
56	6626.7	4453.7	67%	1714.5	26%	432.6	7%	9.1	0%	3.6	89%
112	3499.7	2229.0	64%	1002.8	29%	248.1	7%	5.3	0%	6.7	84%
224	1872.9	1114.1	59%	602.8	32%	138.6	7%	3.3	0%	12.6	79%

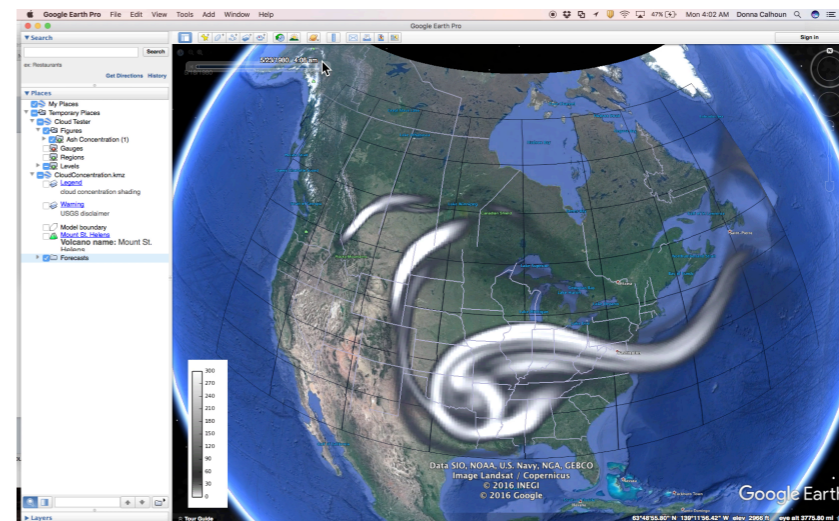
Conclusions and Future plans

Geo/ForestClaw arrival times agree well with historical data.

What is left to do?

- Better modeling of dam failure to get initial outflow correct
- Use numerical “gauges” to compare with historical depth records
- Multi-rate time stepping (tricky with SWE, since wave speed depends on depth)
- Other dam failure scenarios, i.e. Malpassat, France.

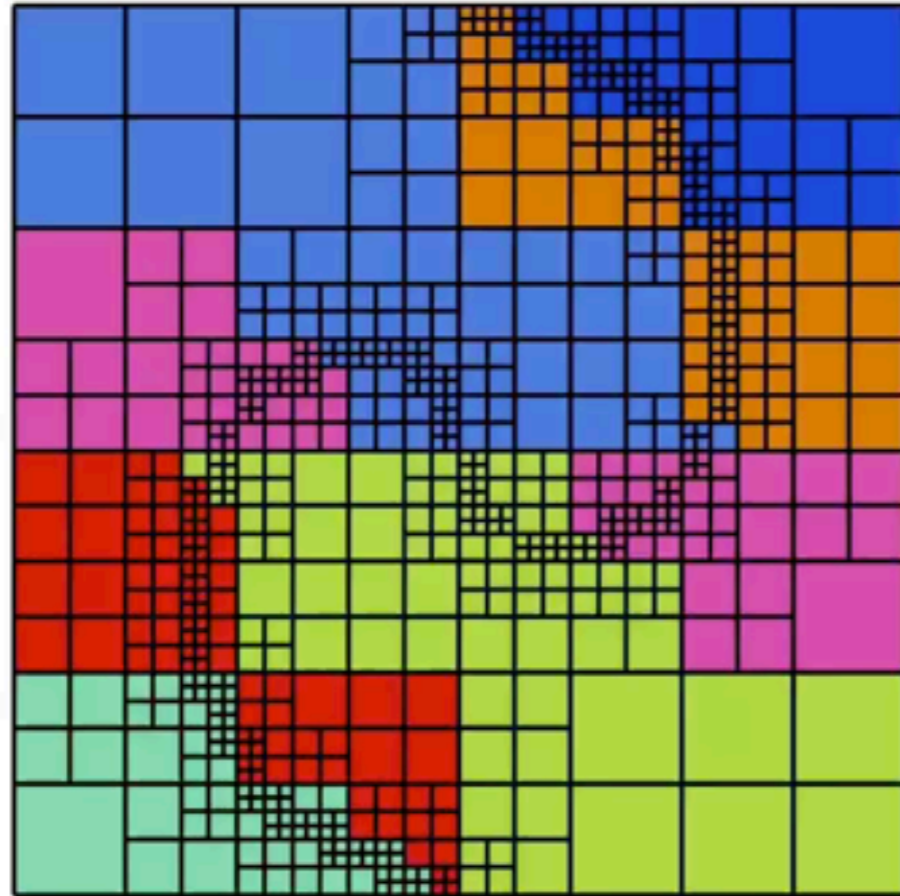
A second project : Volcanic Ash cloud modeling



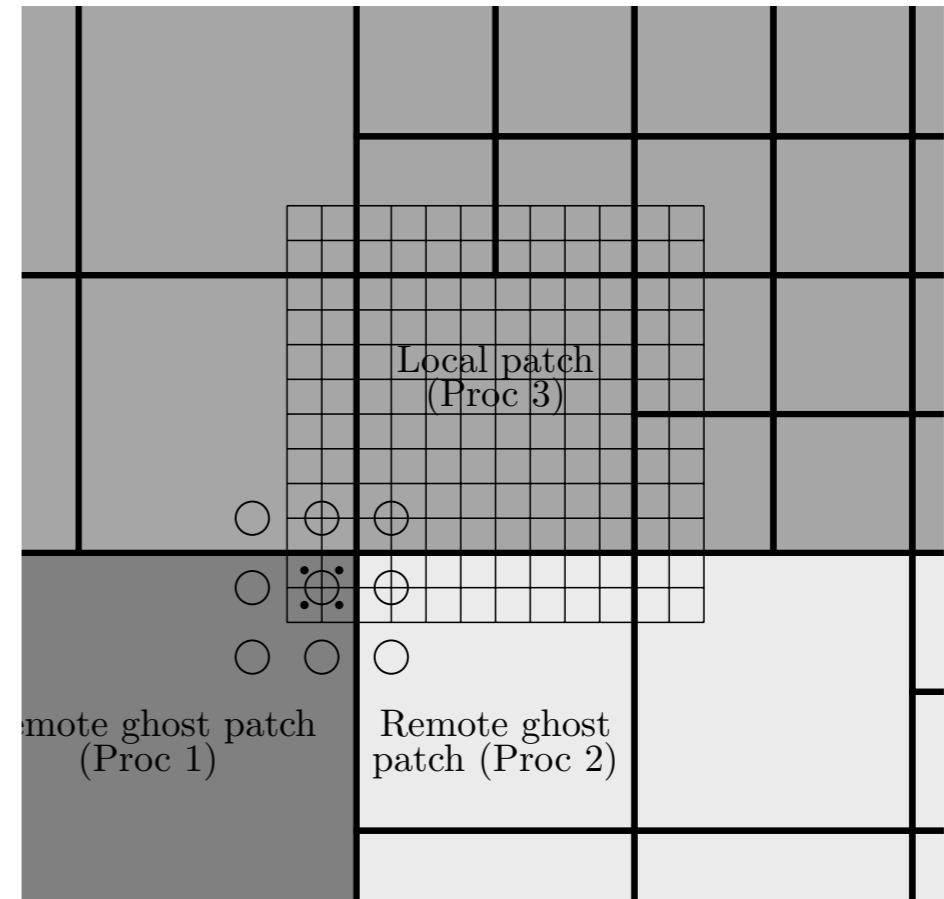
The End

Thank you!

ForestClaw - Parallelism



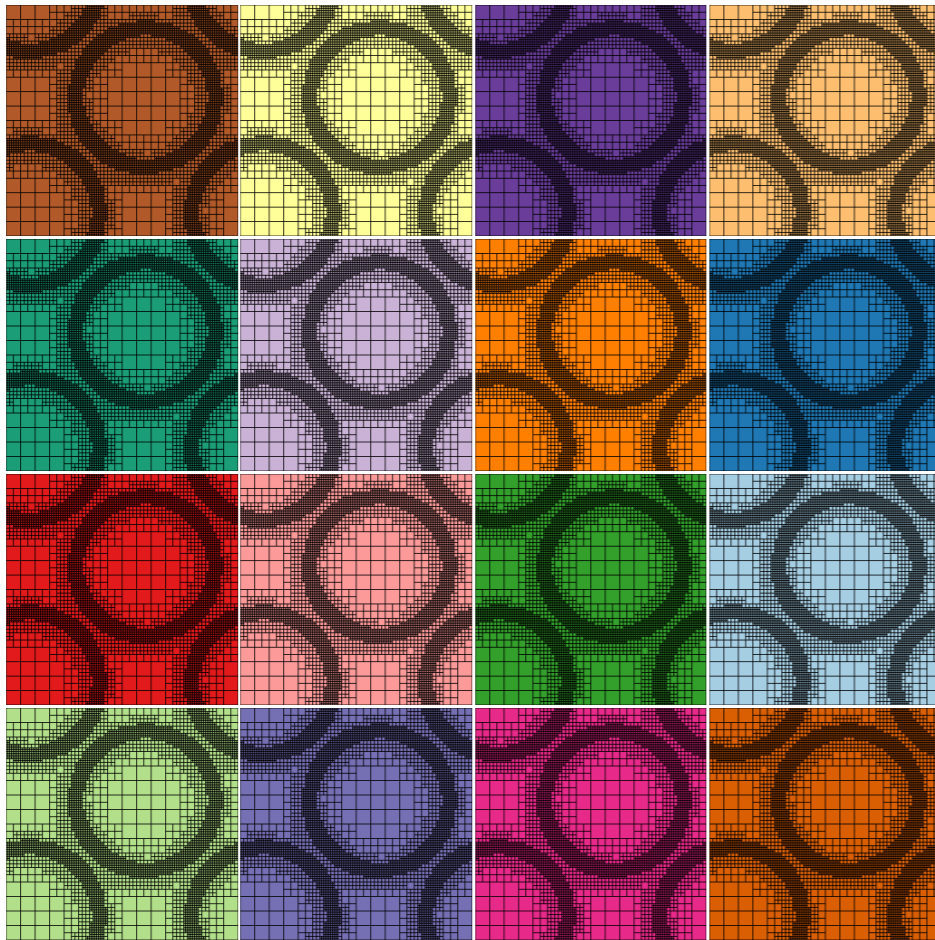
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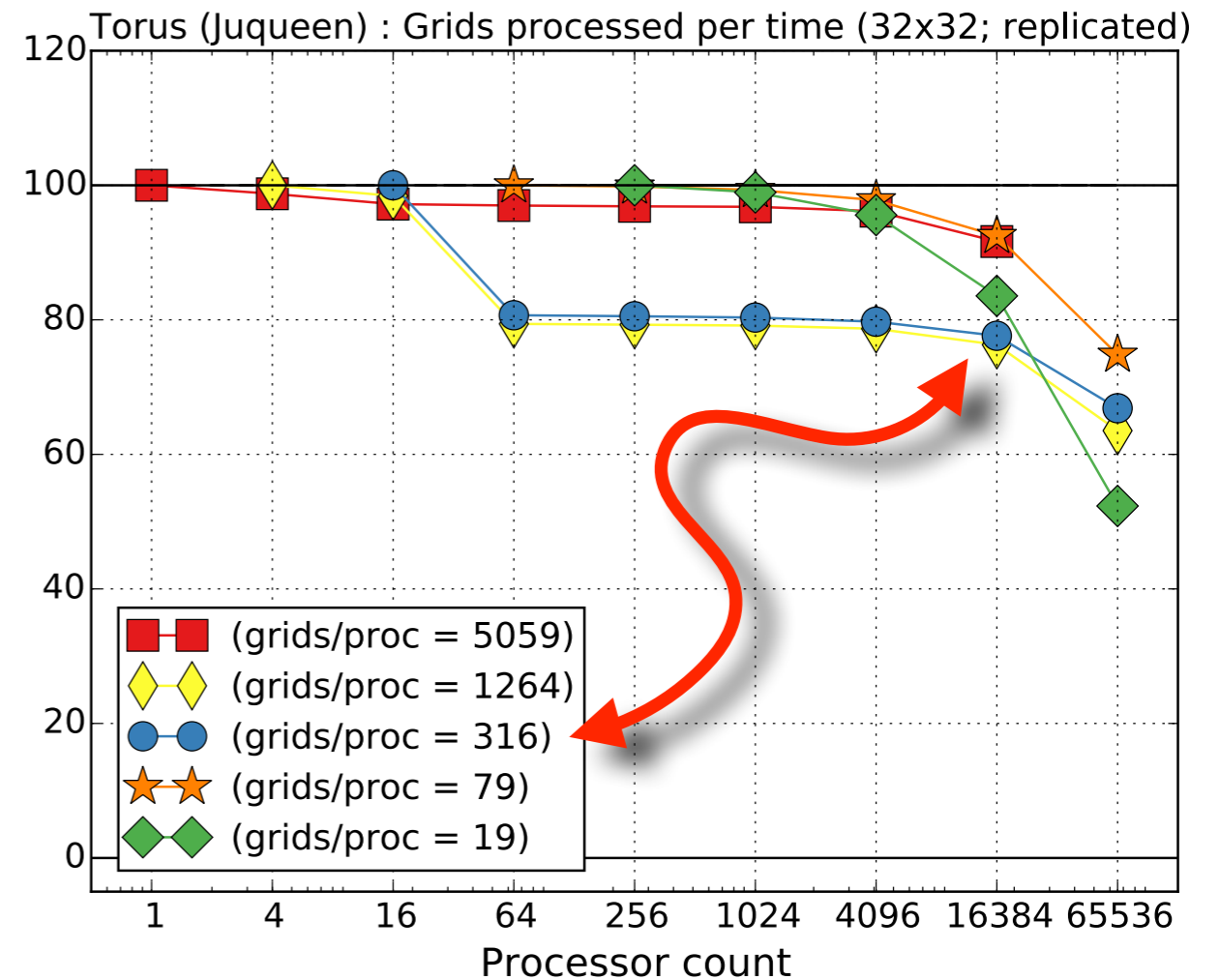
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Parallel scaling (BlueGene/Q)



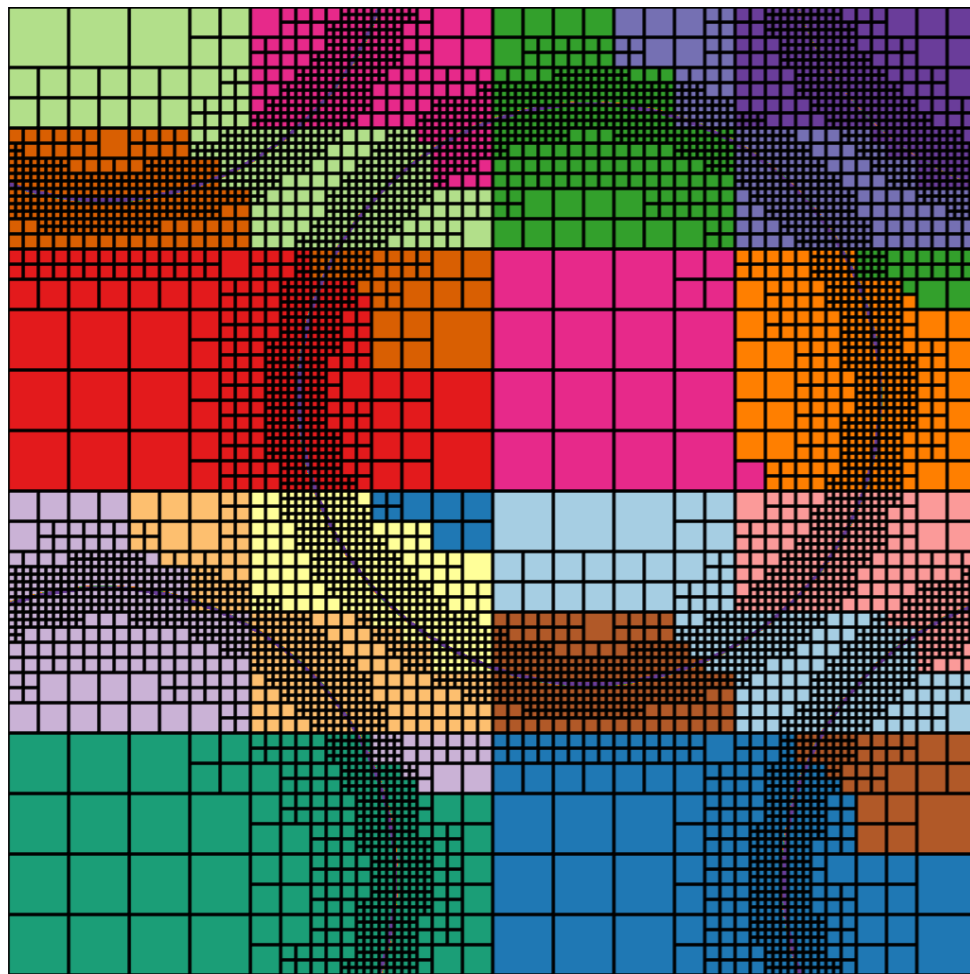
*Scalar advection on replicated domain
using 32x32 patches*



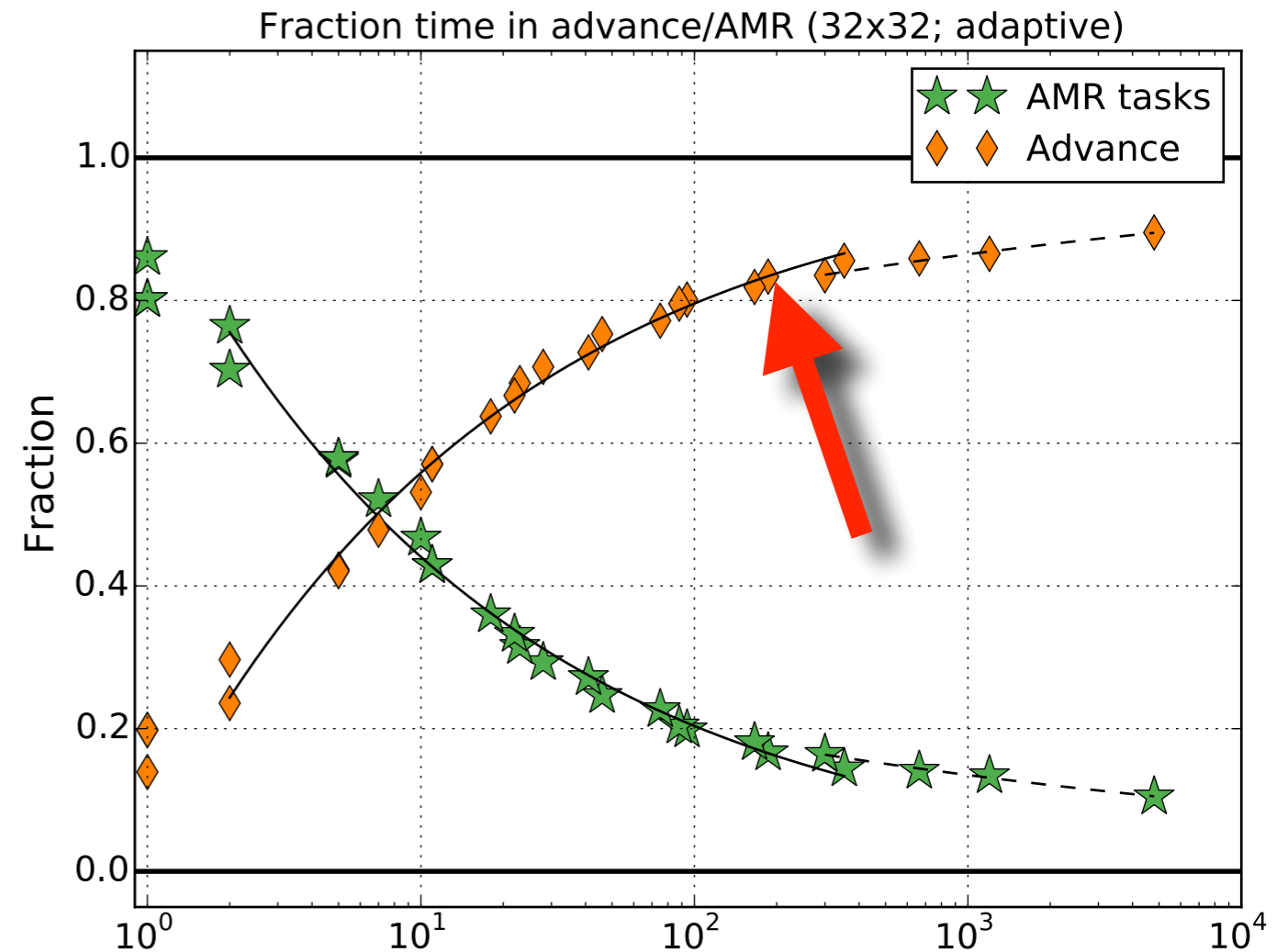
90% (or better) efficiency at 16K cores

Weak scaling

Parallel scaling (BlueGene/Q)



Strong scaling for single grid



80% AMR efficiency at approx. 100 grids per core

D. Duplyakin, J. Brown, D. Calhoun, "Applying Active Learning to Adaptive Mesh Refinement Simulations", (submitted) IEEE (2017)