ForestClaw/Geo : Modeling dam-break flooding using scalable, adaptive quad trees

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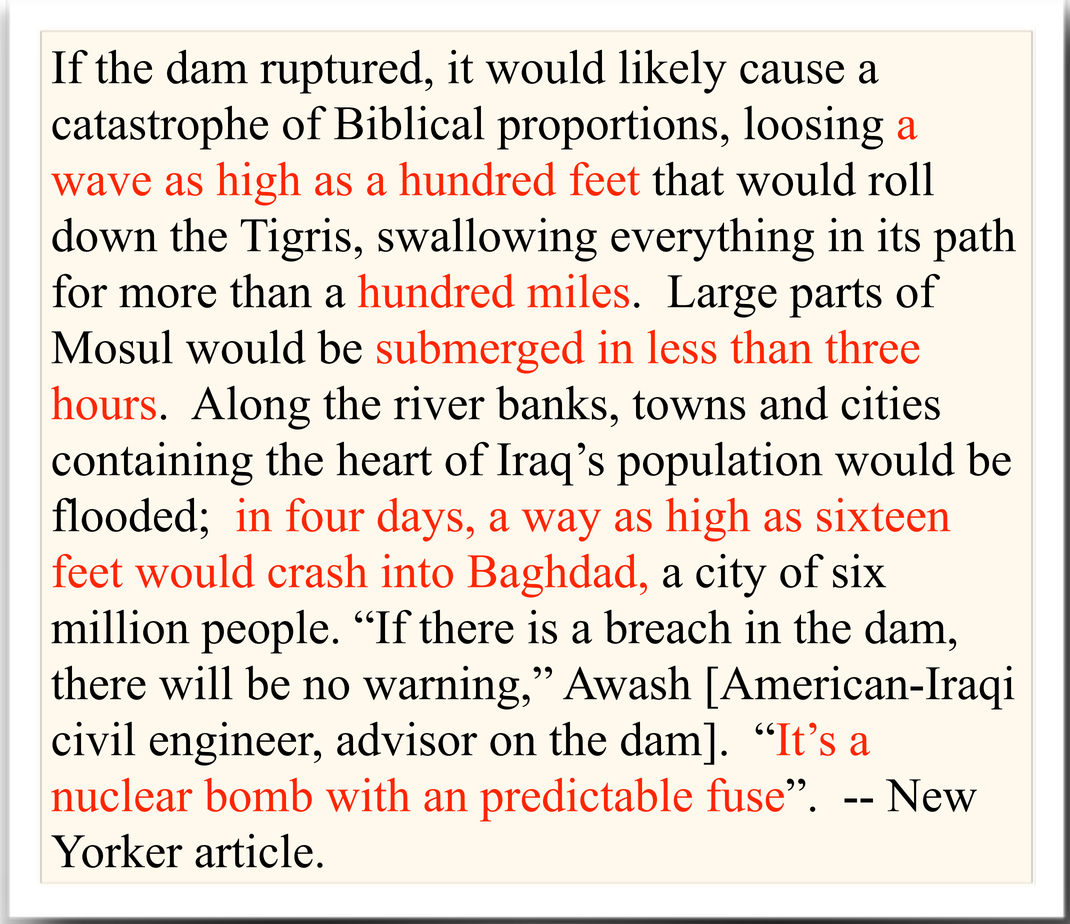
David George (USGS), Marsha Berger (NYU) Randall LeVeque (Univ. of Washington); David Ketcheson (KAUST, Saudi Arabia)

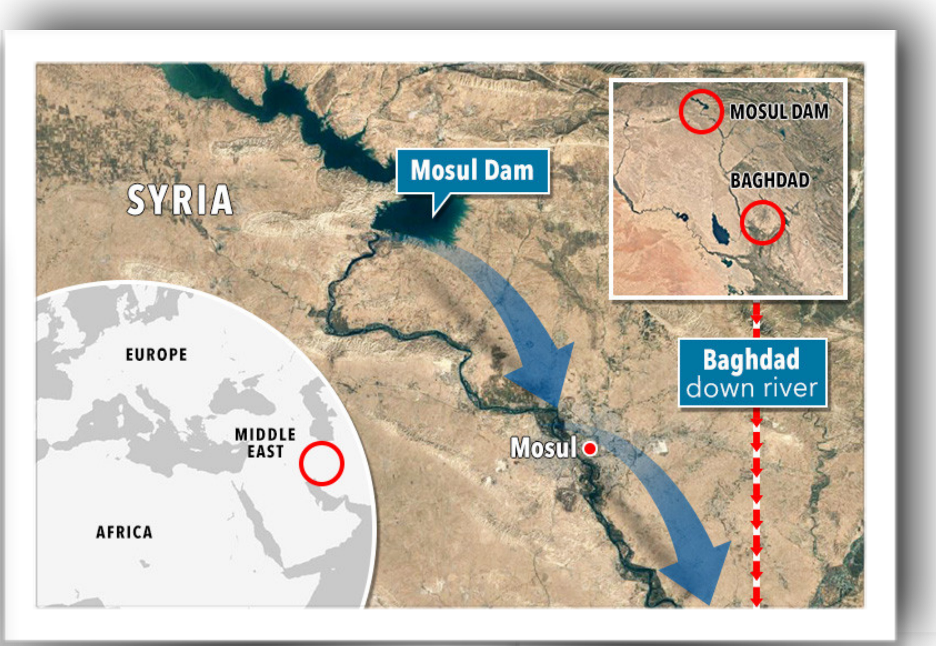
KAUST workshop on predictive complex computational fluid dynamics
May 22-24, 2017
KAUST, Saudi Arabia

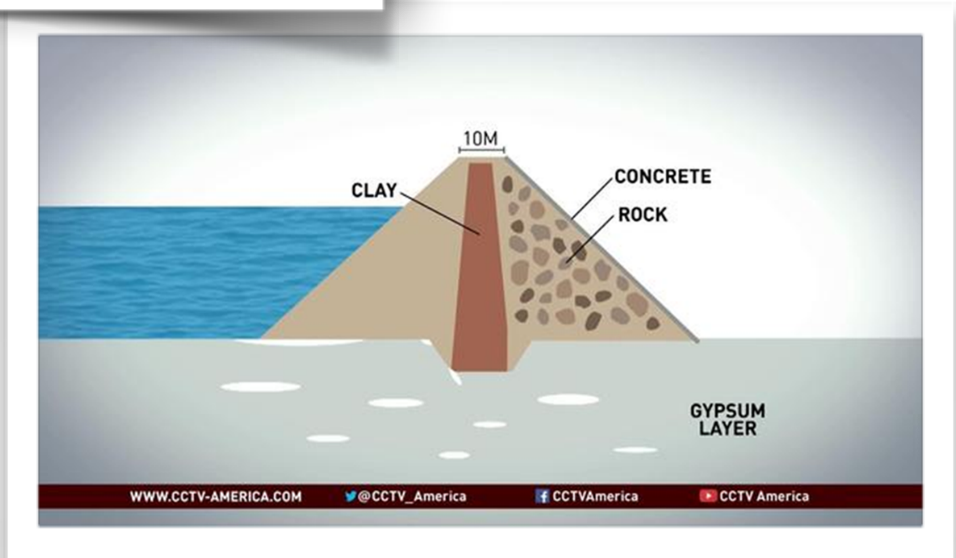
Threats from dam failures

- 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 results 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.

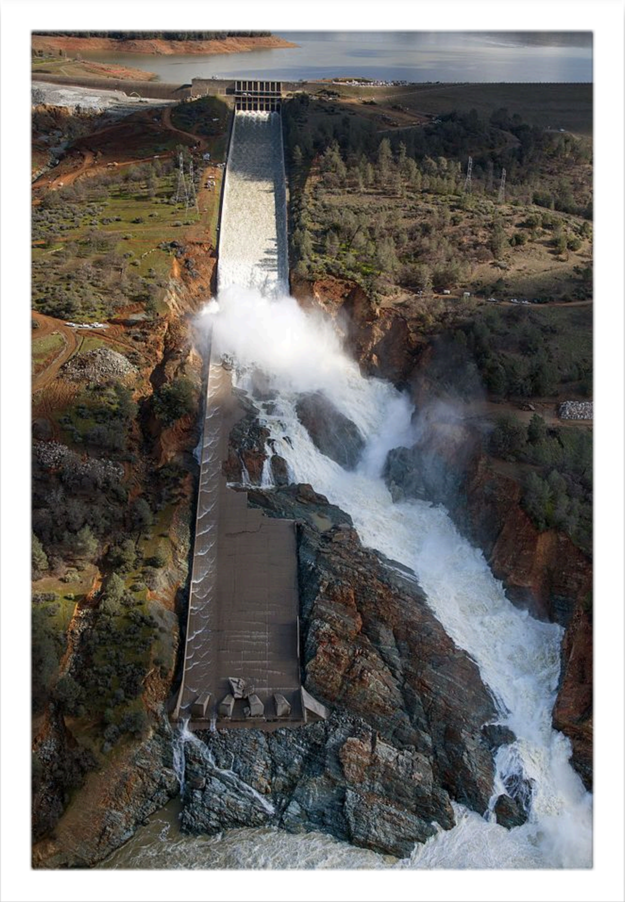




Dam Failures - US

- 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?

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)
- Widely used for modeling inundation and flooding from tsunamis, storm surges, landslides and debris flows (See http://www.geoclaw.org)

GeoClaw overcomes several technical challenges

- Seamlessly handles reading and interpolation of multiple, possibly overlapping, bathymetry files for given computational domain
- Riemann solver robustly handles wet and dry states and discontinuities in bathymetry
- Well-balanced scheme maintains steady states in presence of bathymetry
- Use of adaptive mesh refinement (AMR) means that resolution is allocated only where needed (dry land is resolved only at the coarsest levels)
- Numerical gauges allow for easy comparison with observational data

GeoClaw

Some potential downsides to GeoClaw :

- Based on AMRClaw, a legacy code base for adaptive mesh refinement,
- Original developers are close to retirement,
- Relies on shared memory parallelism (i.e. OpenMP) - no distributed memory capabilities.
- Very difficult to extend with new functionality, i.e. dispersive terms

While GeoClaw has attracted many users, it is challenging to get students interested in core development. Even developers have been known to complain about how hard it is to maintain and extend GeoClaw.

ForestClaw Project

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

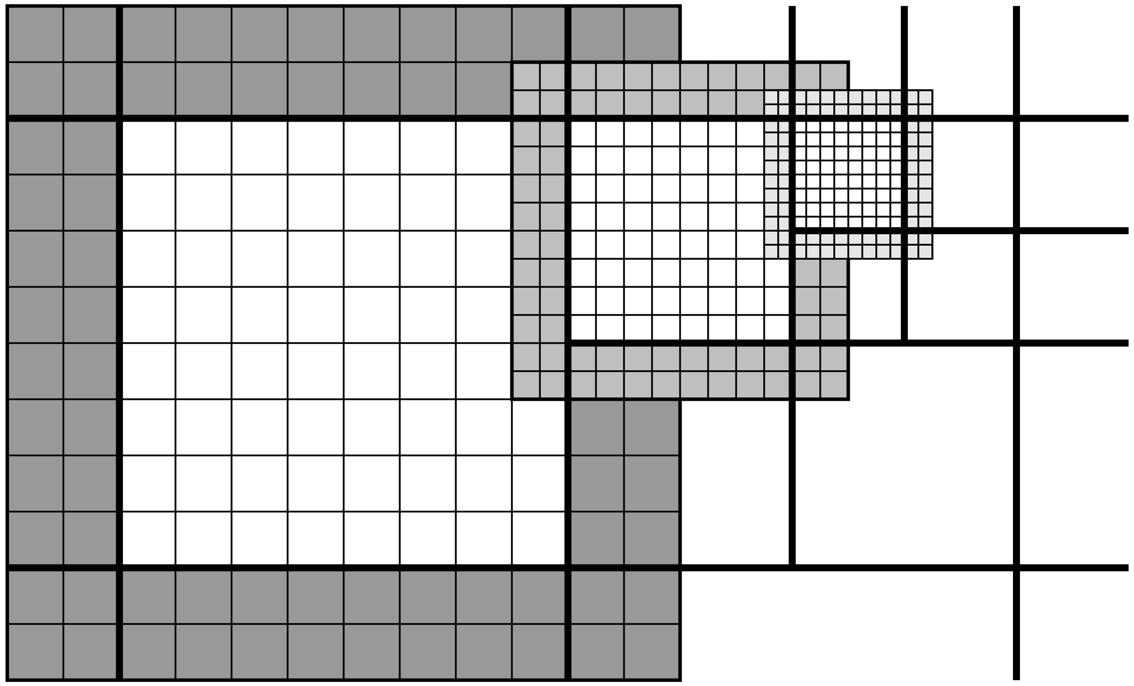
Features of ForestClaw include :

- 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

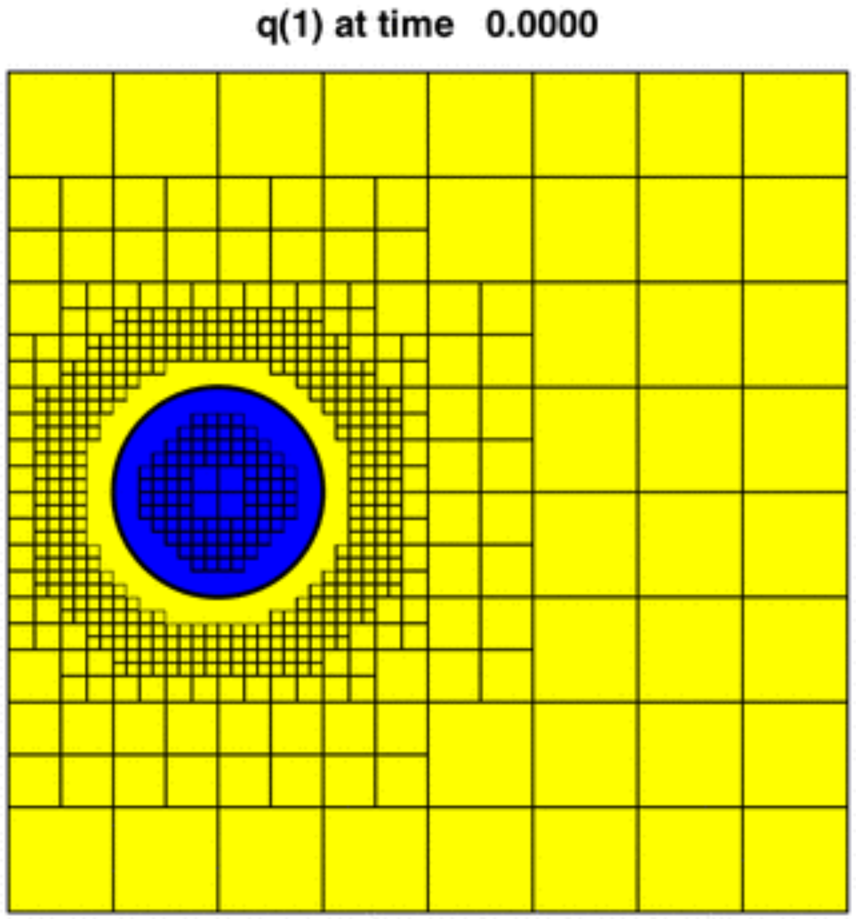
Thanks to NSF for supporting this work

www.forestclaw.org

ForestClaw adaptivity

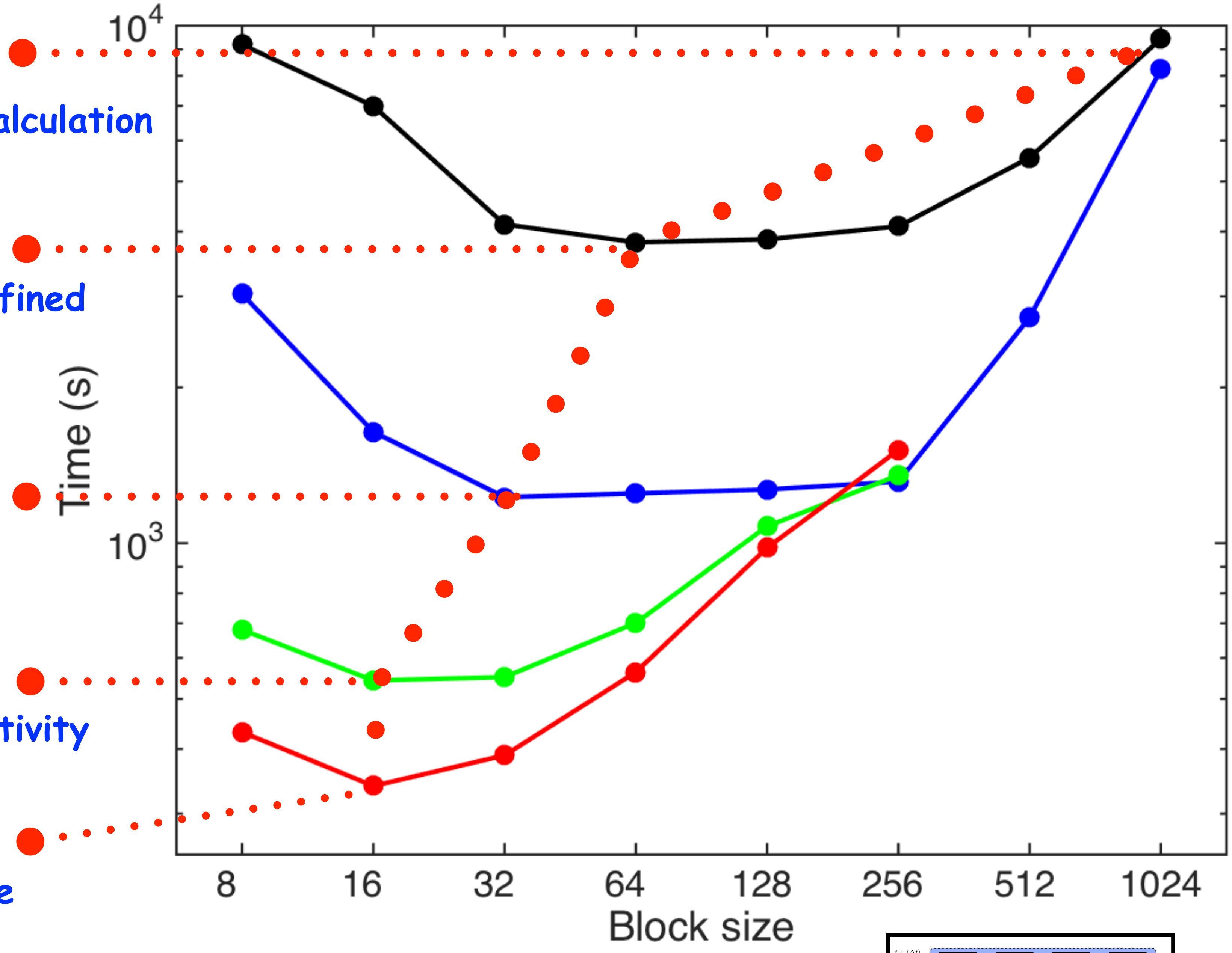


Each quadrant is a single logically grid, designed for finite volume or finite difference solvers.



Regridding, connectivity done using p4est

Computational performance



~2.5 h
Single grid calculation

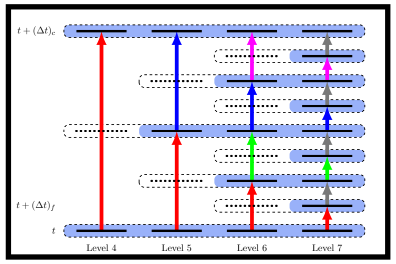
~1 h
Uniformly refined

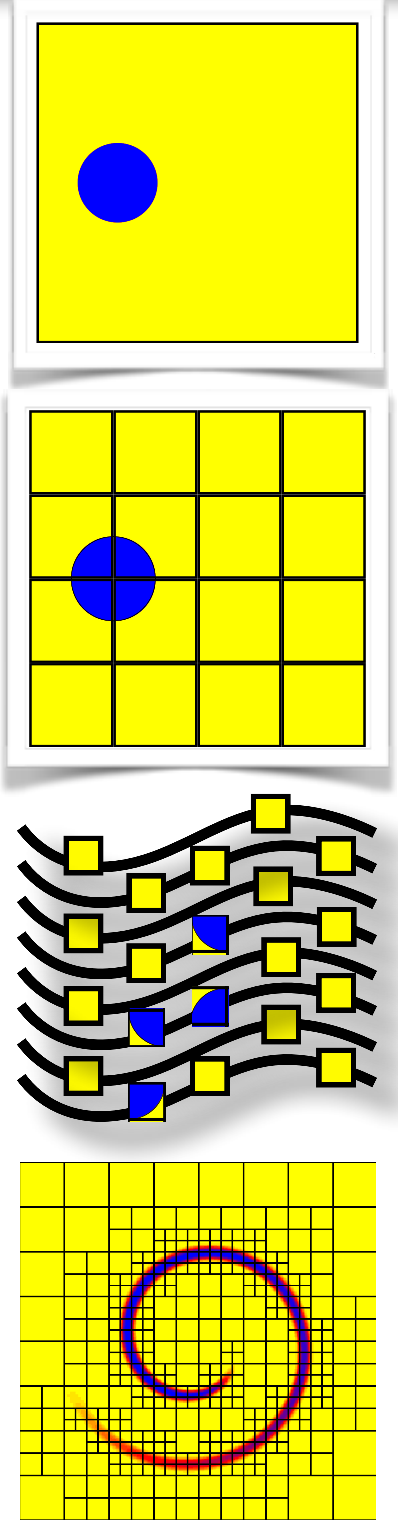
~12.5 min
Parallelism

~9 min
Spatial adaptivity

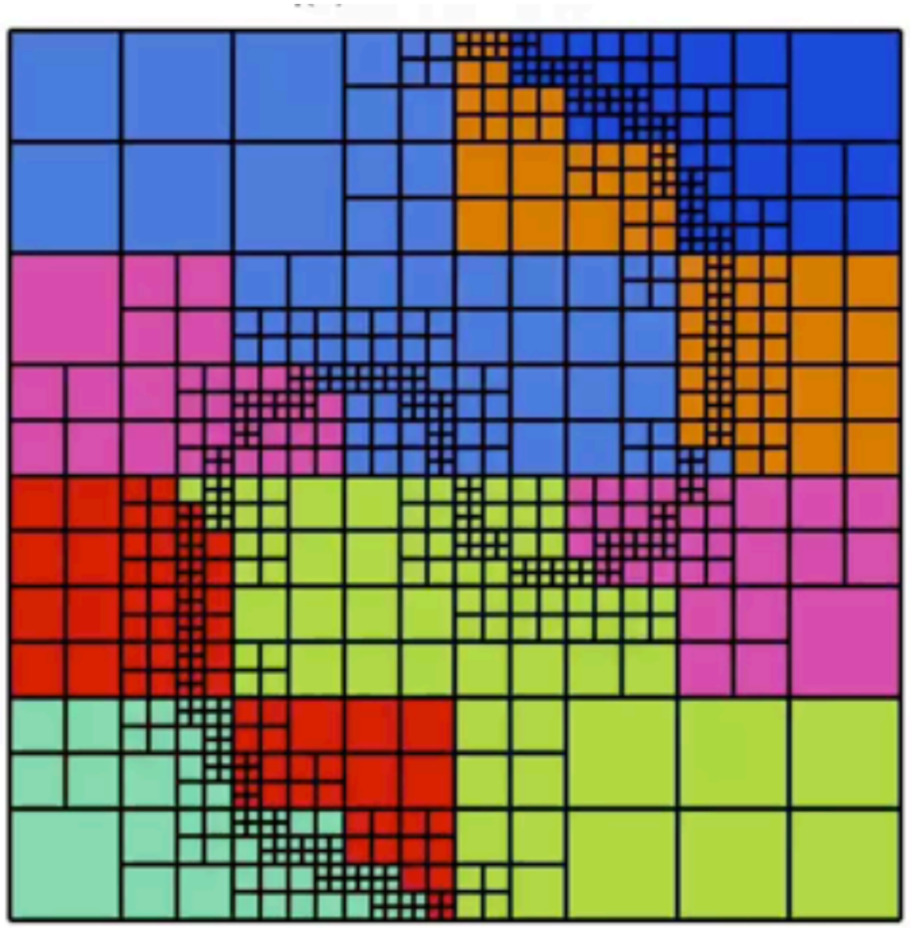
~5.5 min
Adaptive time stepping

Almost 30 times improvement

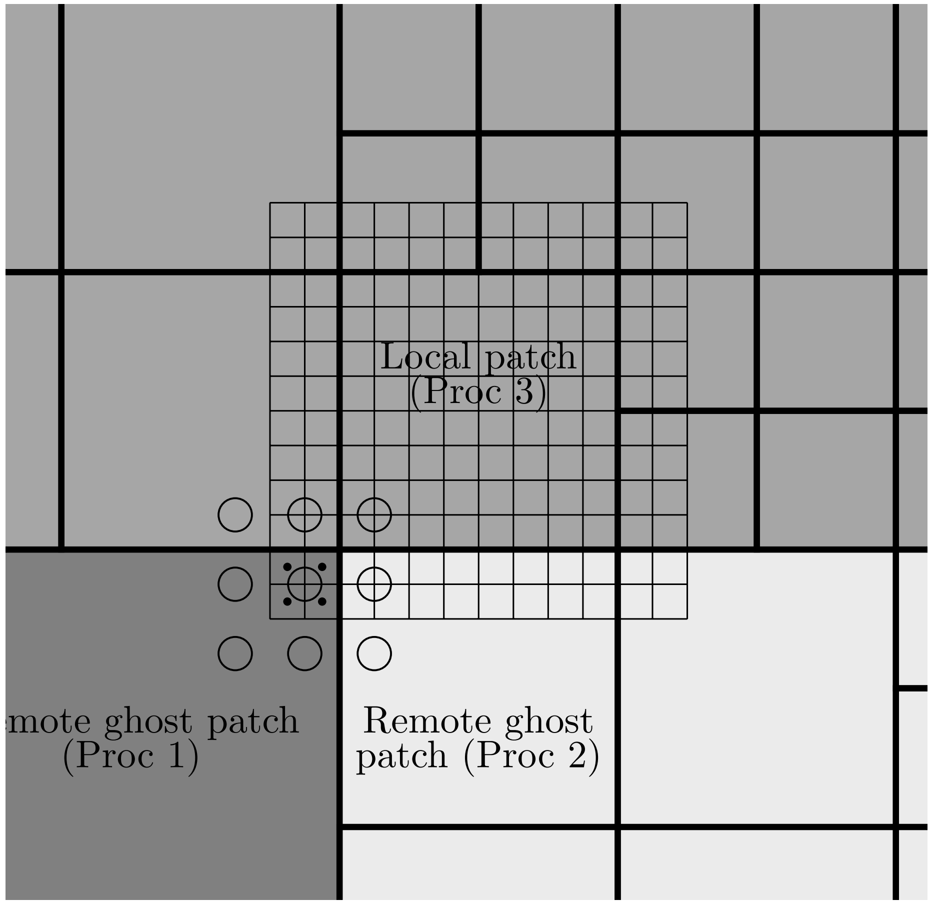




ForestClaw - Parallelism



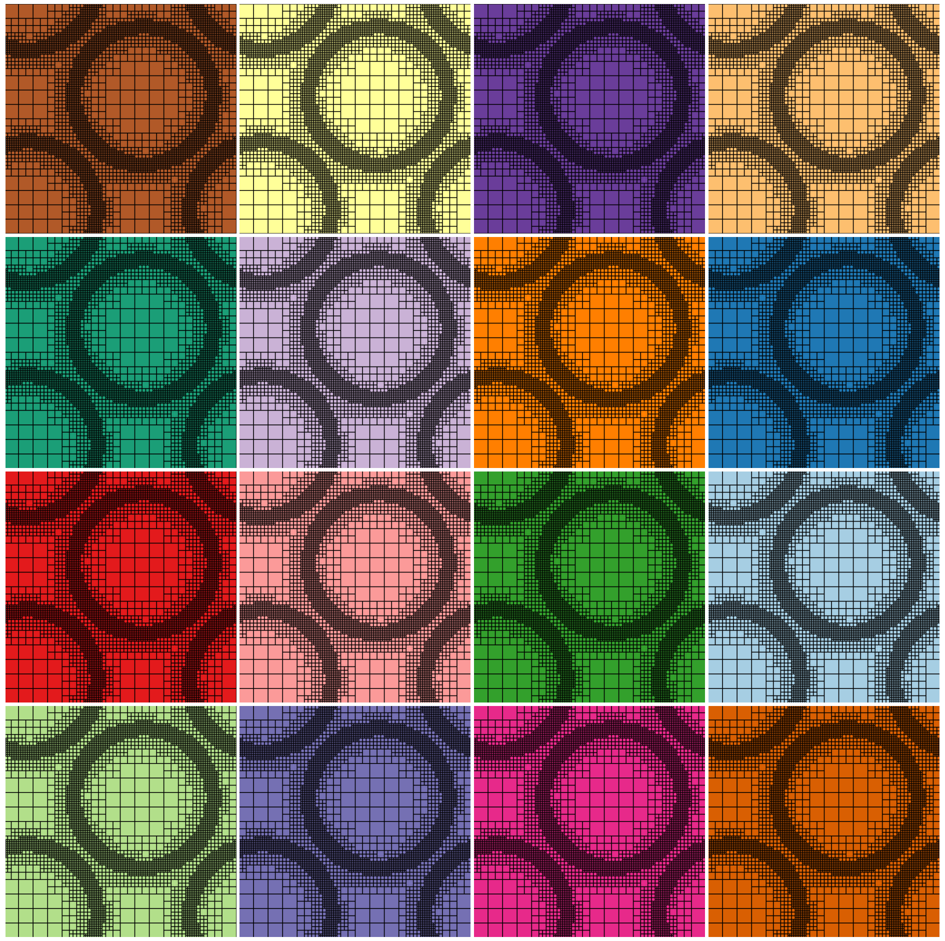
p4est : Load balancing using a space filling curve



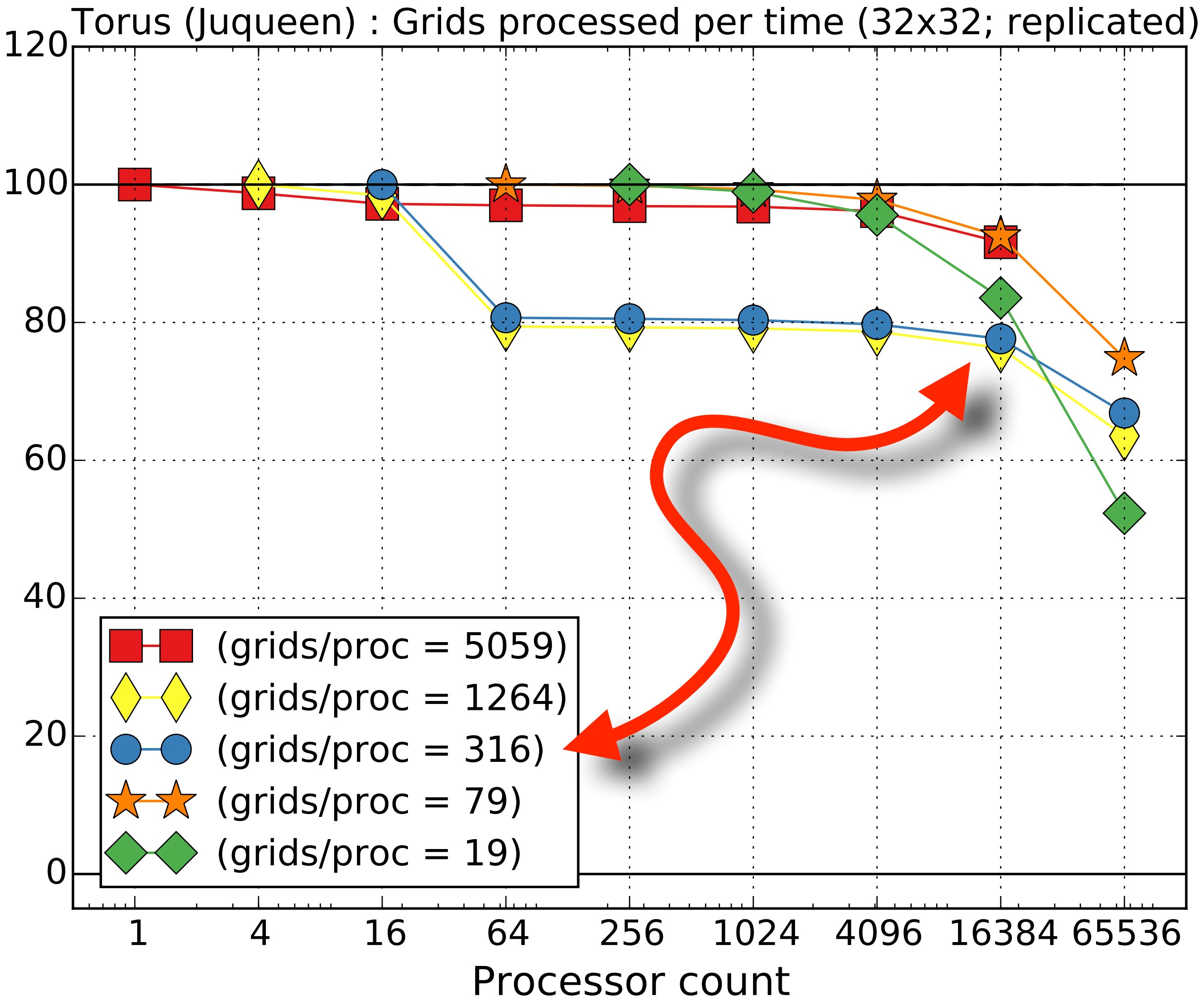
Fine grid corner ghost cells at corners where 3 or more processors meet

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)*

Parallel scaling (BlueGene/Q)



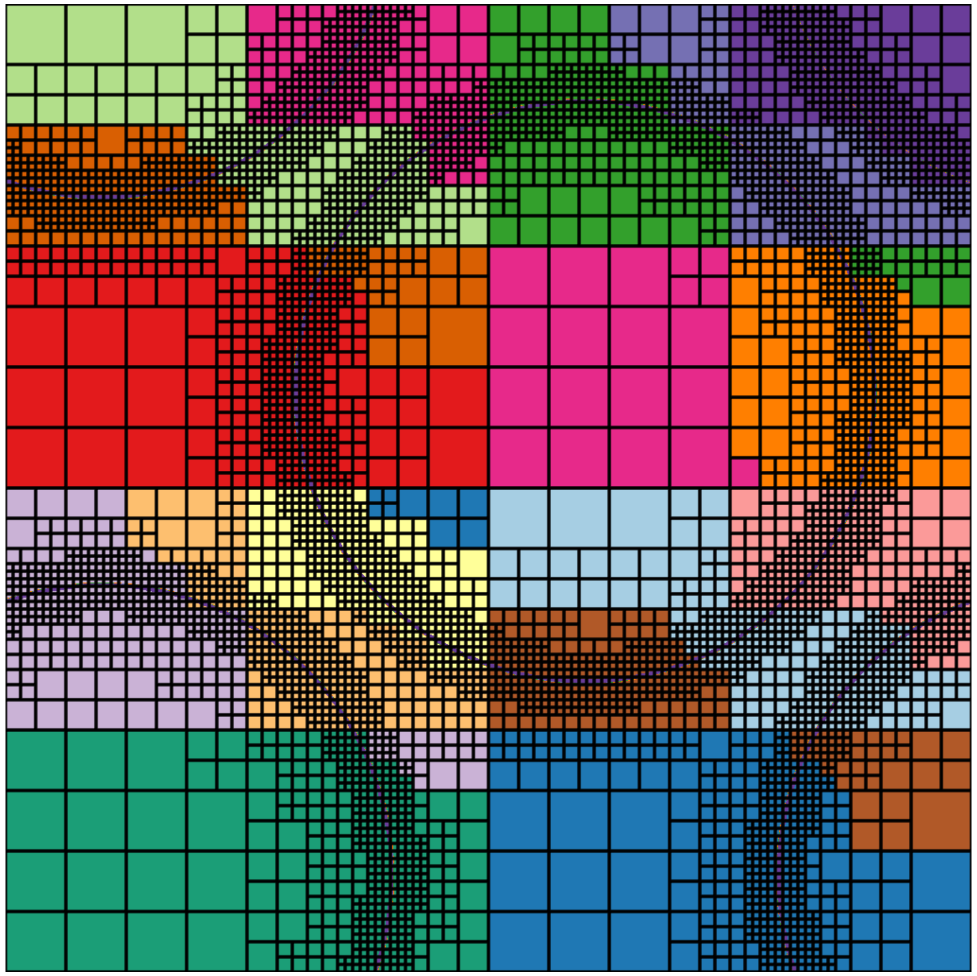
Scalar advection on replicated domain using 32x32 patches

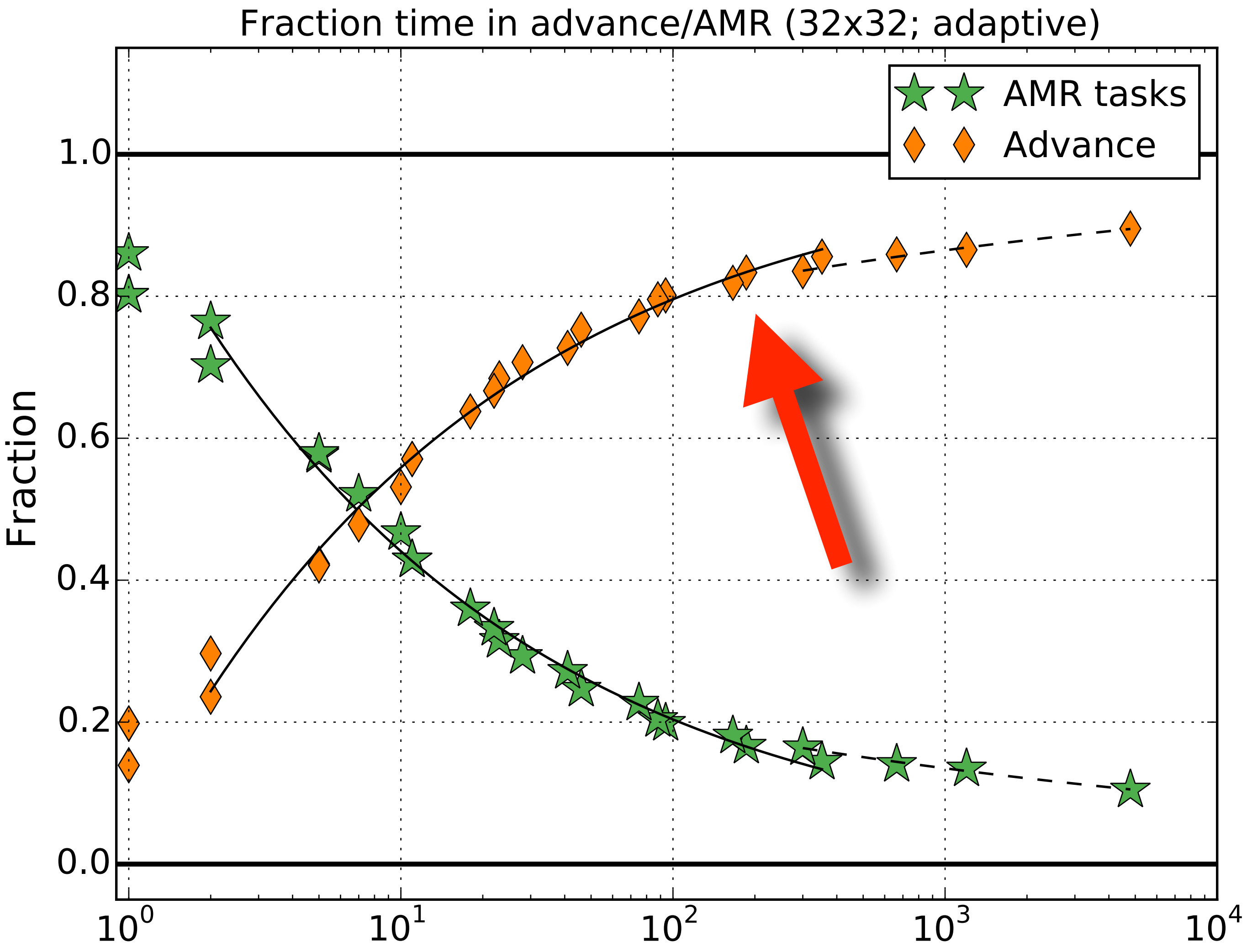


90% (or better) efficiency at 16K cores

Weak scaling

Parallel scaling (BlueGene/Q)



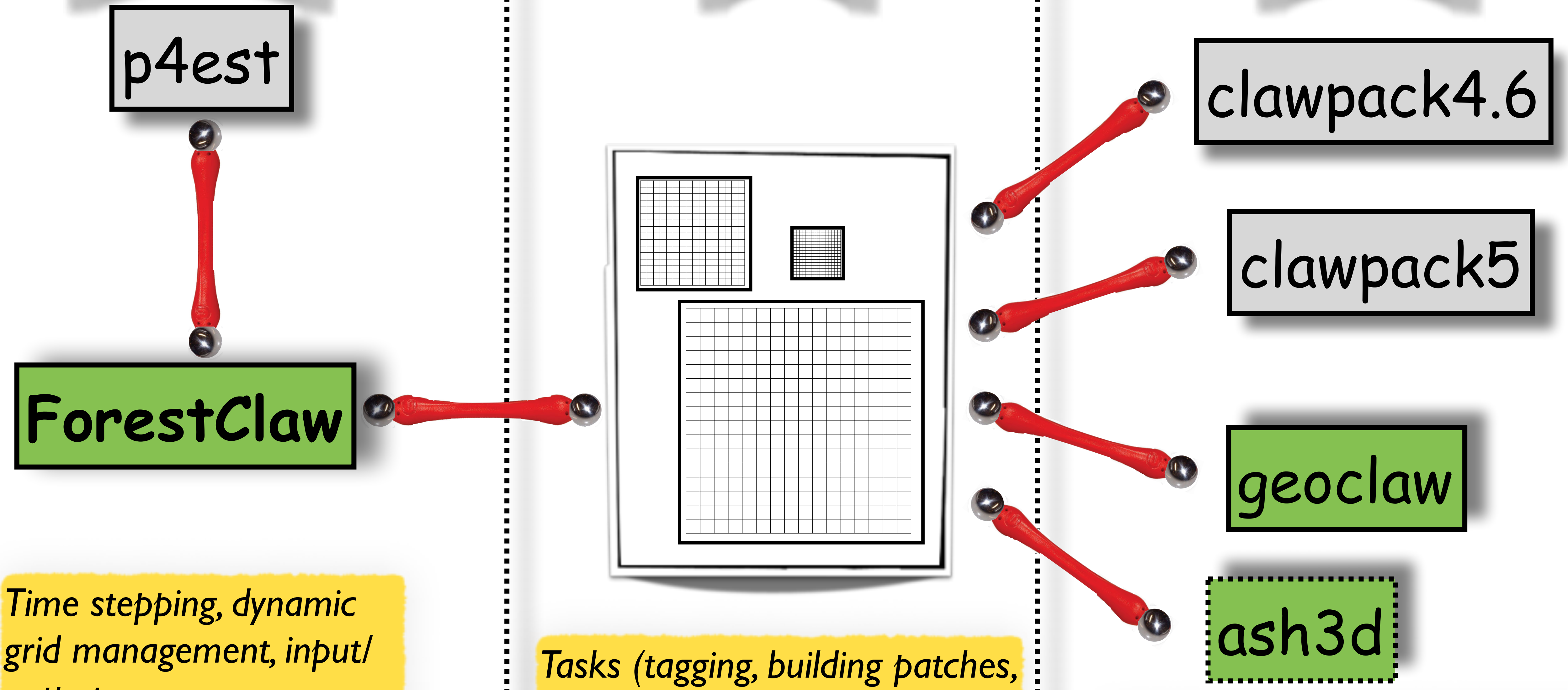


Strong scaling for single grid

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)

Extending ForestClaw



Time stepping, dynamic grid management, input/output.

Tasks (tagging, building patches, etc) customized through use of function pointers stored in "virtual tables"

ForestClaw is mostly C; solvers extension libraries left largely untouched (in original Fortran)

GeoClaw Extension of ForestClaw

ForestClaw/Geo :

- Uses existing GeoClaw Riemann solvers, bathymetry handling routines, and refinement criteria.
- Replaces Berger-Oliger AMR with adaptive quad tree AMR (coarsening criteria had to be supplied)
- Replaces OpenMP parallelism in GeoClaw with MPI parallelism.
- Multi-rate time stepping needs special treatment, due to dependence of speed on depth in SWE.
- Developer(s) : Melody Shih (Columbia Univ./NYU); Kyle Mandi (Columbia); D. Calhoun, C. Burstedde (Univ. of Bonn, Germany)

Teton Dam Failure, June 5, 1976

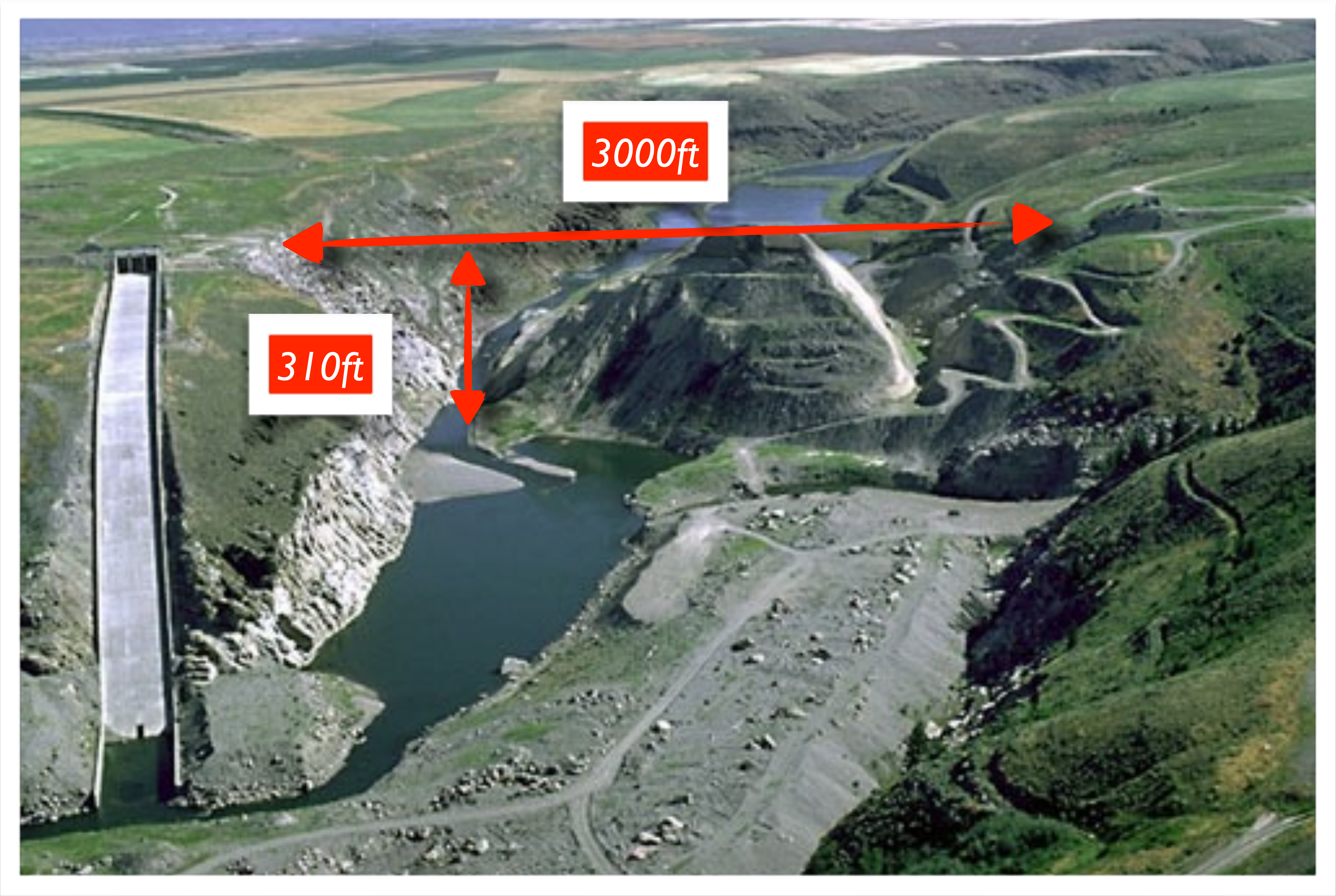
In collaboration with Idaho National Laboratories, we have been using ForestClaw to simulate the Teton Dam failure

- Earthen dam built on inadequate soil base
- On June 5, 1976, the Teton Dam in eastern Idaho suffered catastrophic failure, after being filled for the first time.
- 11 people died and $2b in damages; several cites were inundated, including Rexburg, ID.

Existence of good historical data makes this dam failure a. good validation for using ForestClaw in burst flooding scenarios.

Project in collaboration with Idaho National Laboratory (Steve Prescott) and Centroid Lab (Ram Sampath)

Teton Dam Failure, June 5, 1976



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

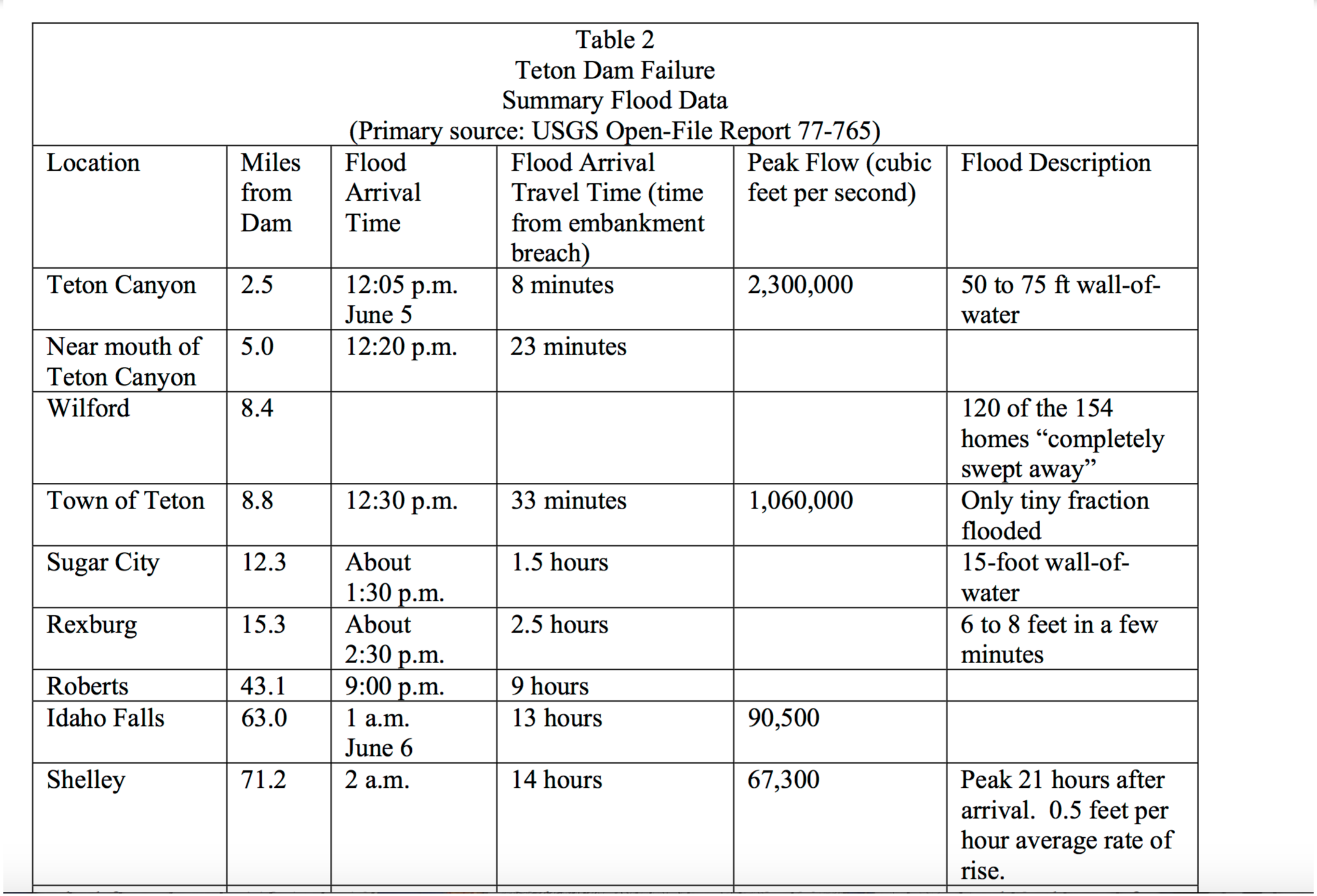


Table 2
Teton Dam Failure
Summary Flood Data
(Primary source: USGS Open-File Report 77-765)

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

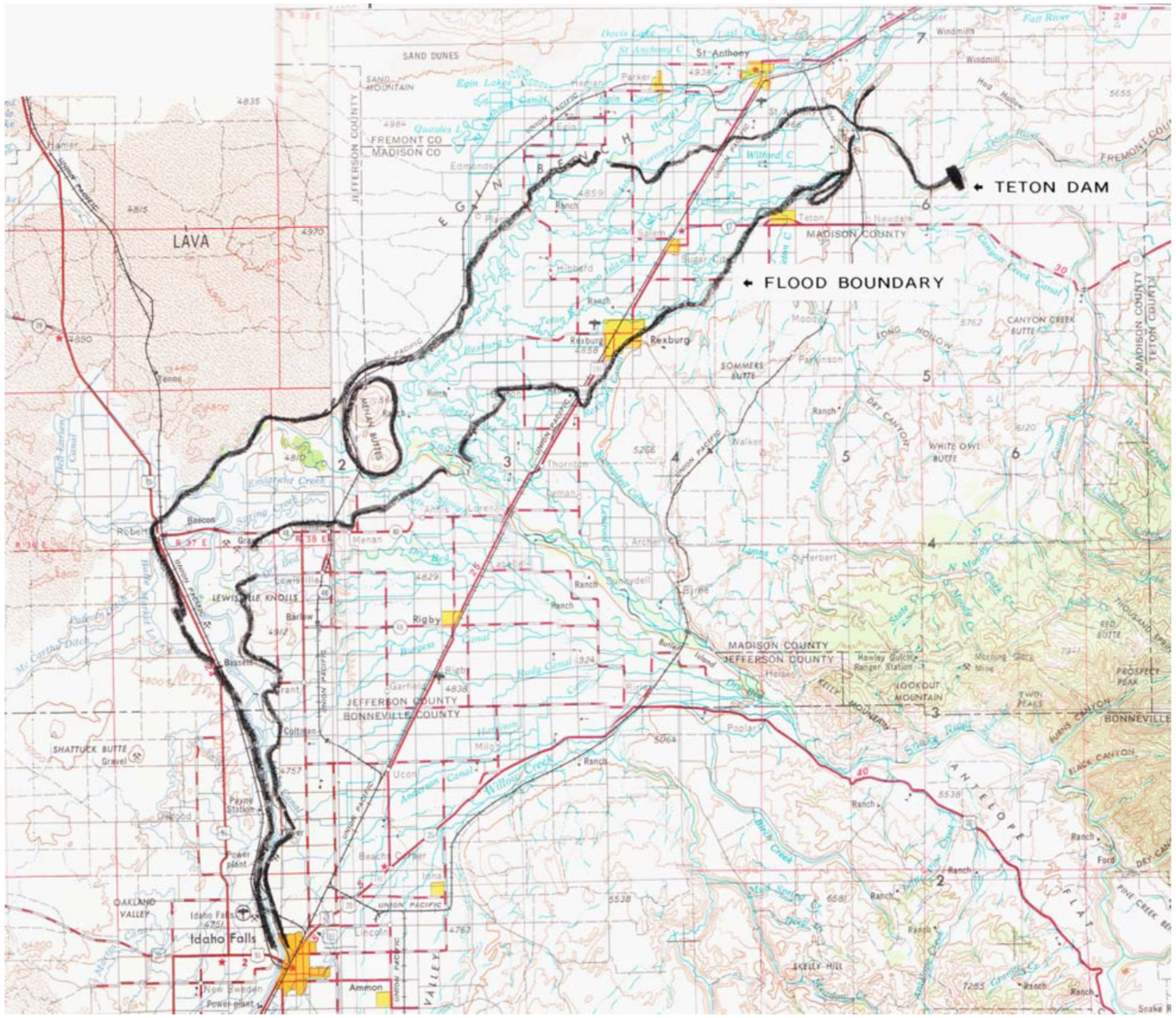


Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

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

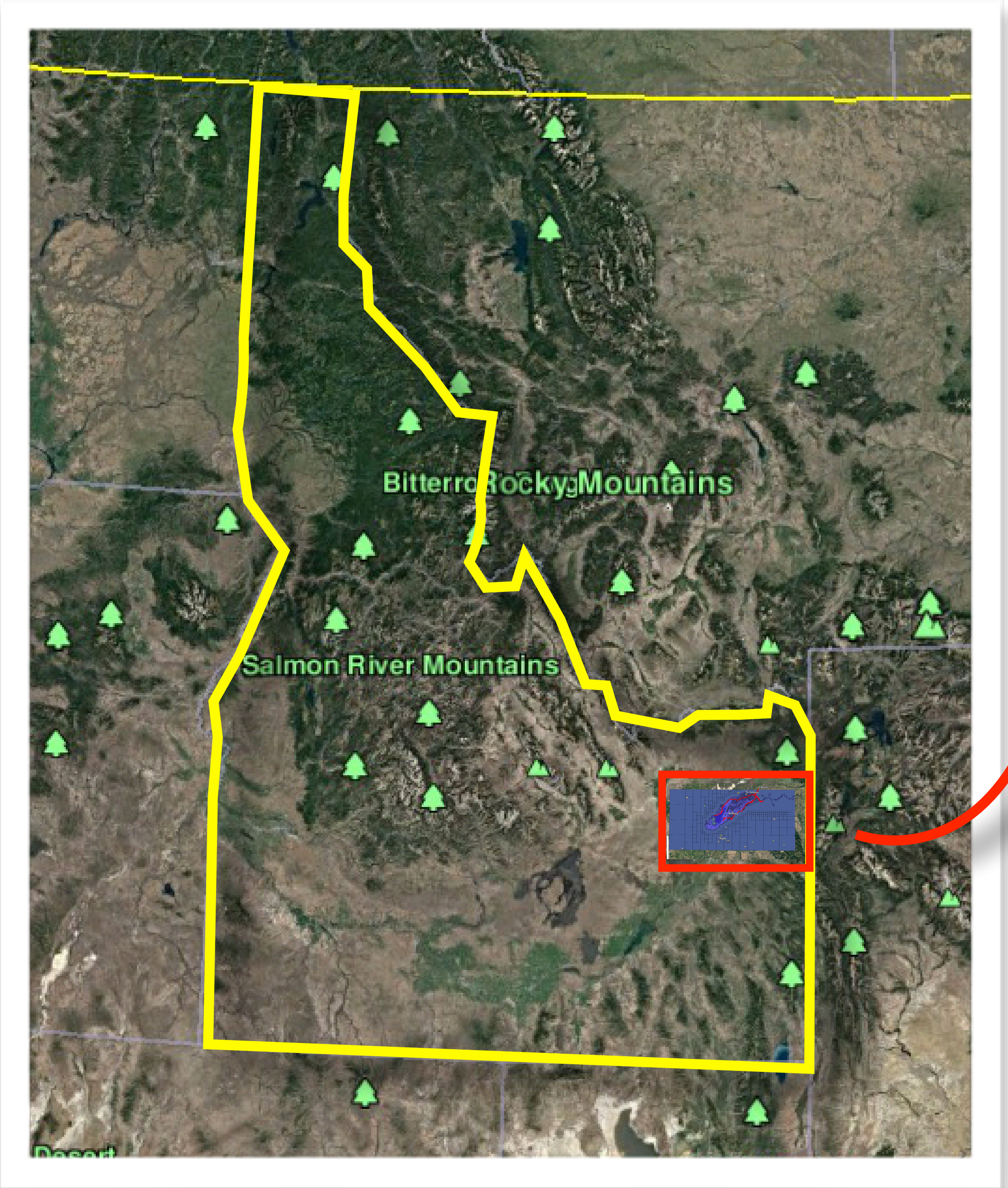
Numerical parameters

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

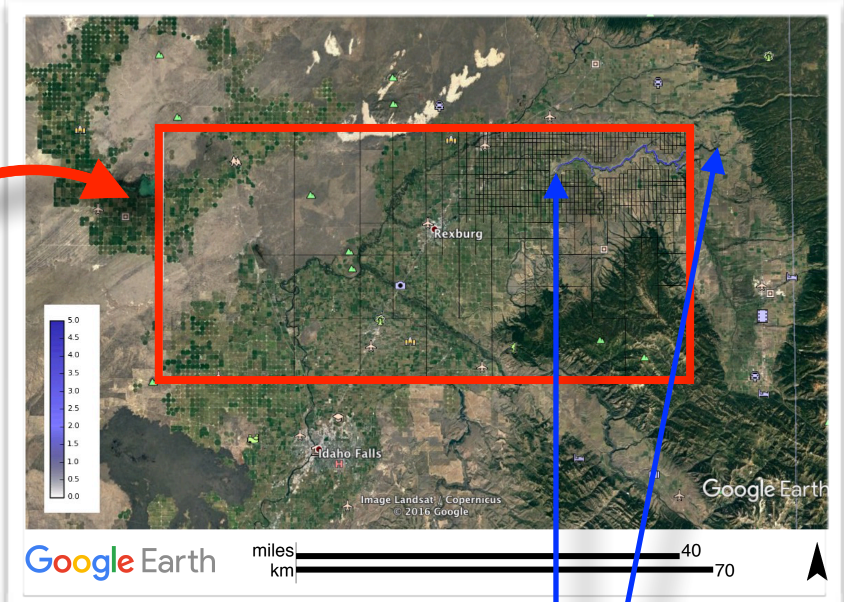
Platform

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

Teton Dam Failure, June 5, 1976



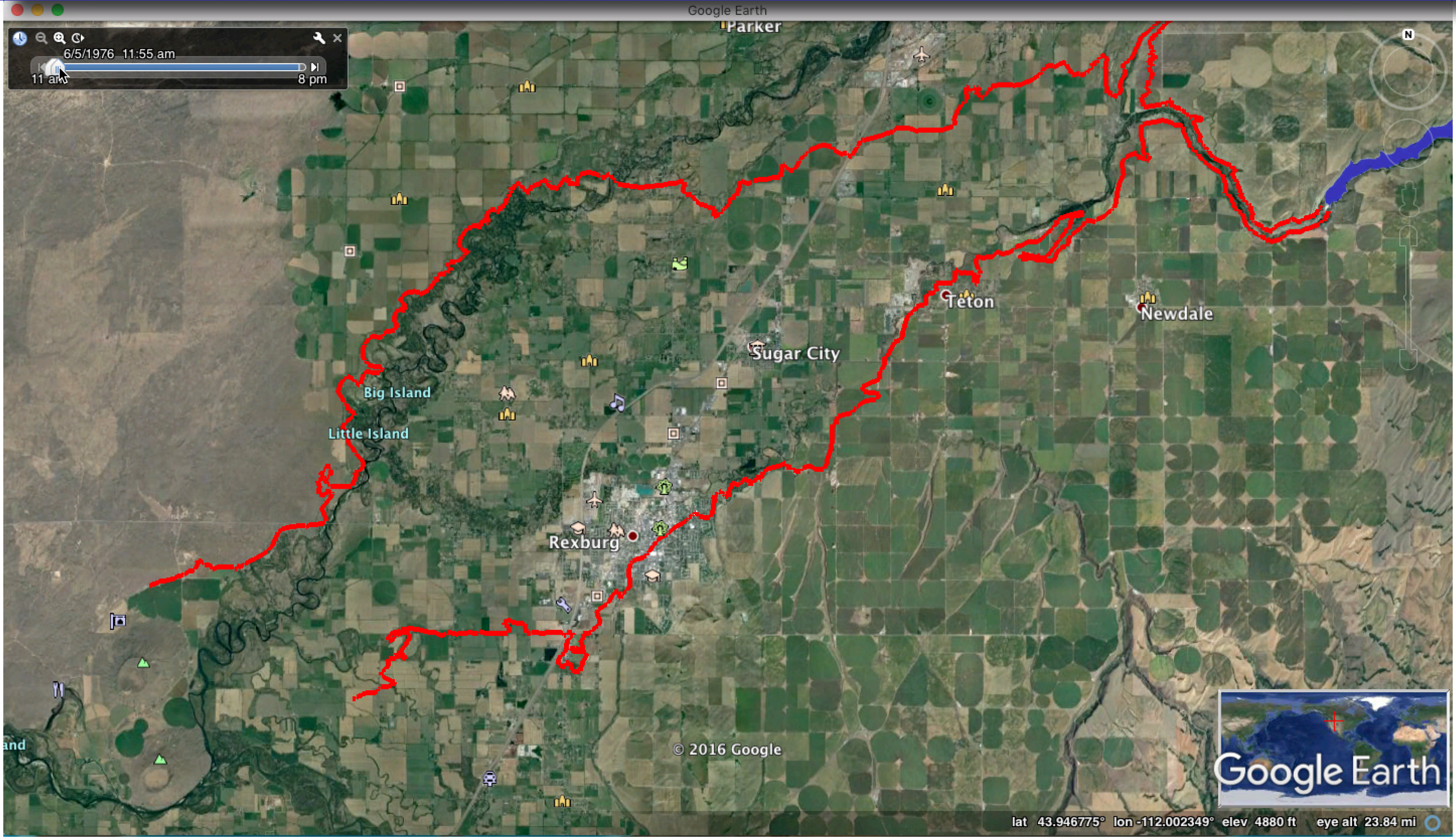
Computational Area : 88km x 42km



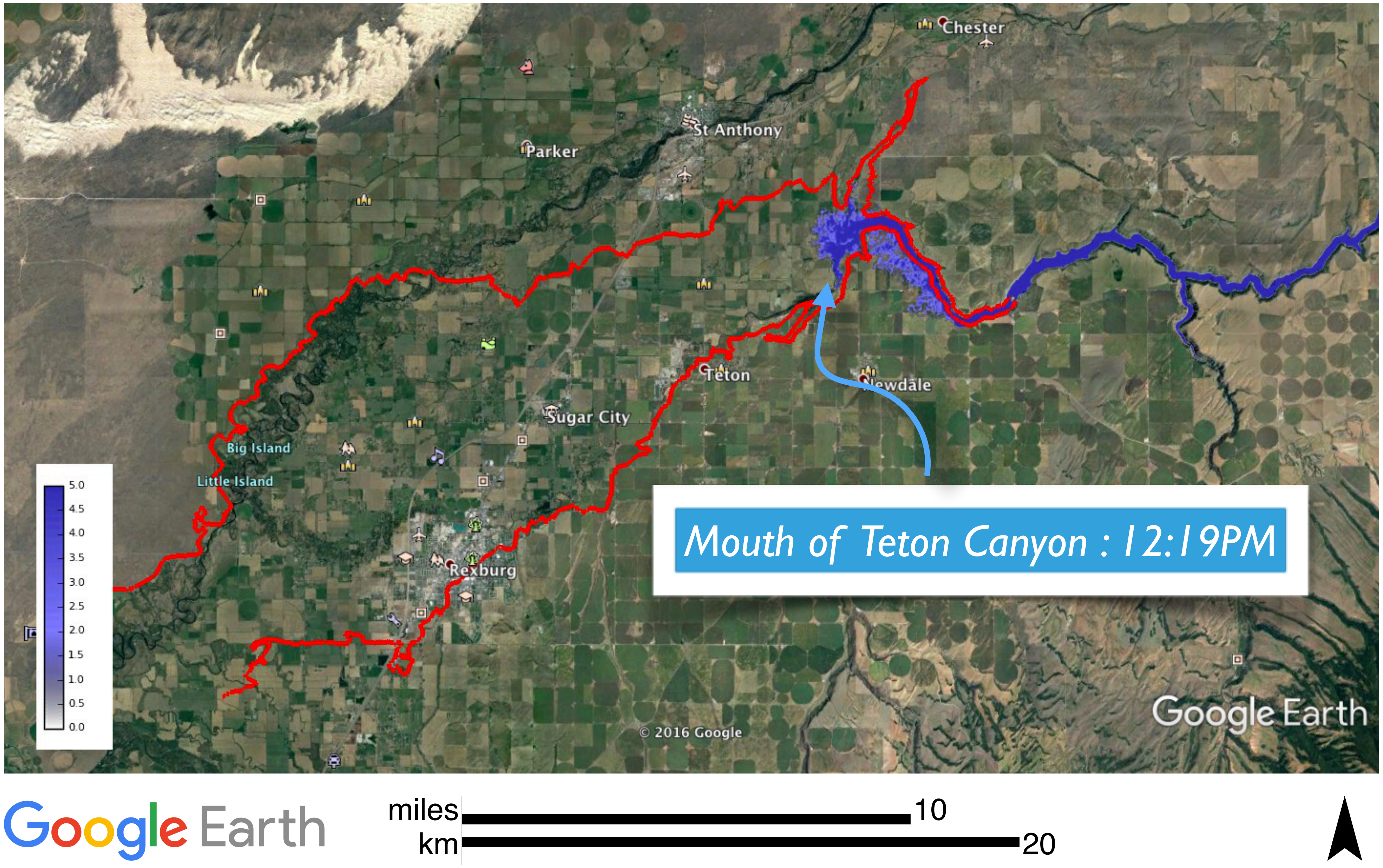
Reservoir

~10m resolution : ~8192 x 4096 effective resolution

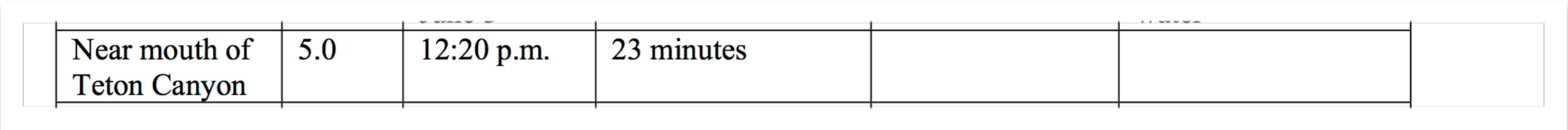
Simulation results



Simulation results

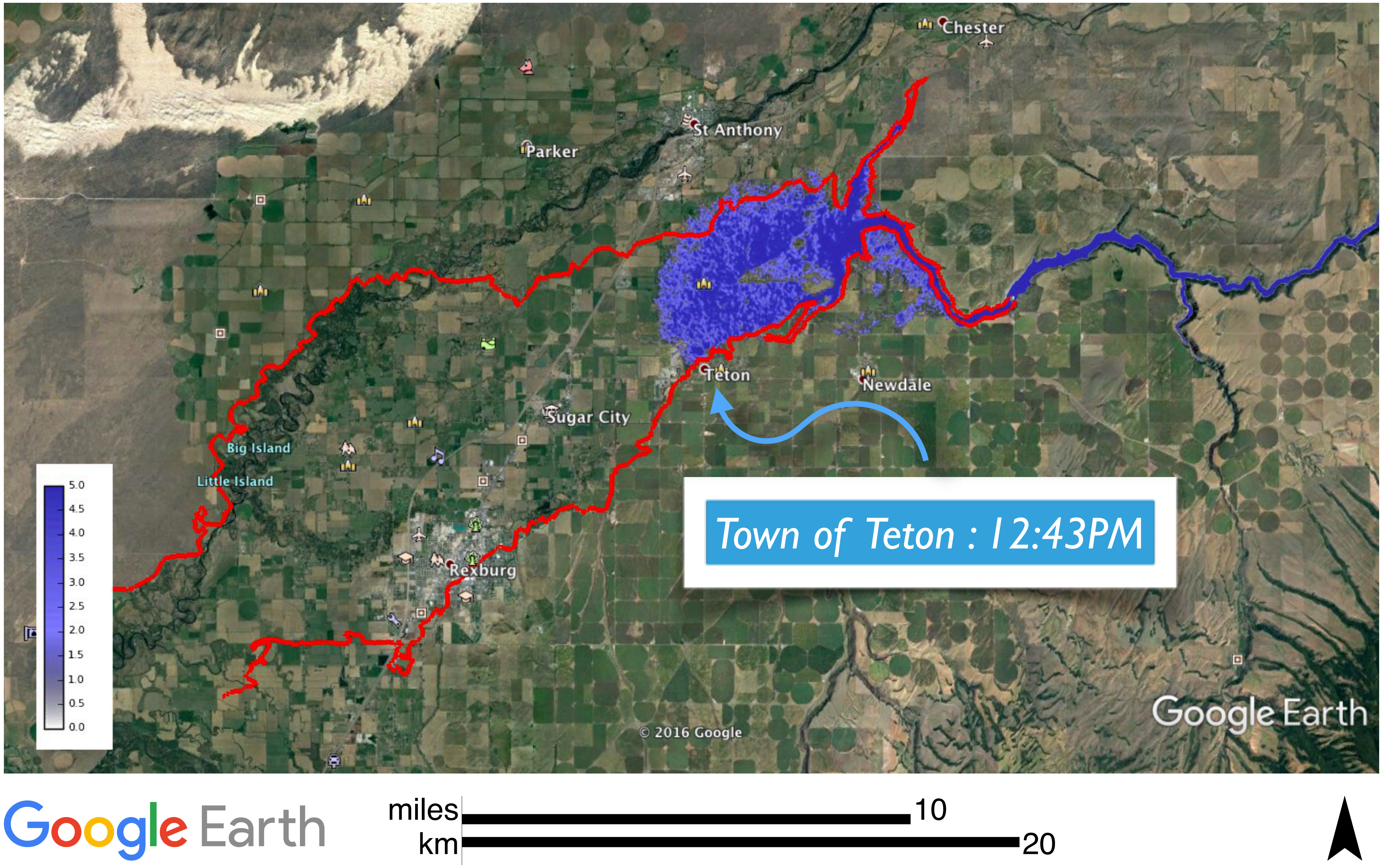


Mouth of Teton Canyon : 12:19PM



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

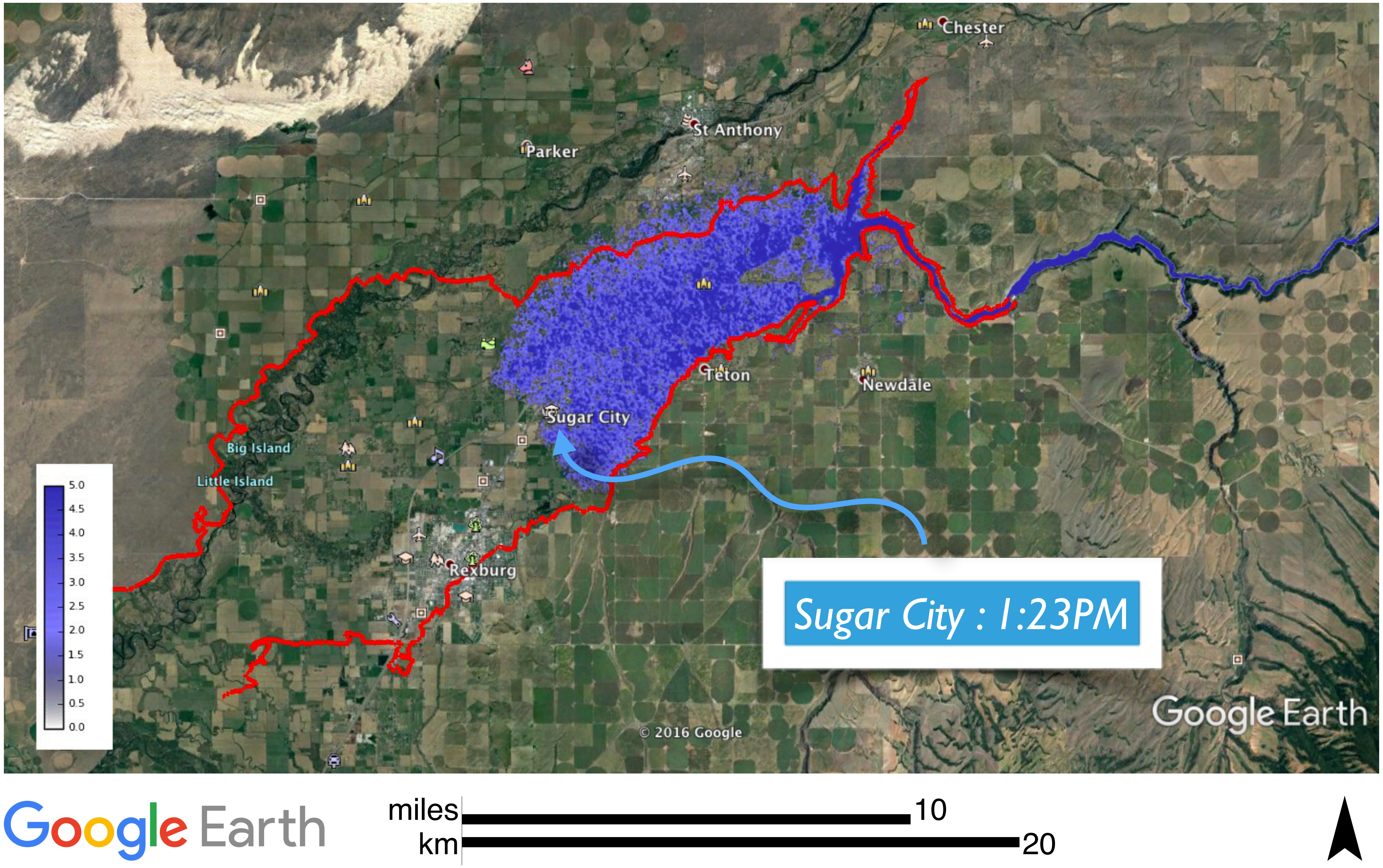
Simulation results



Town of Teton : 12:43PM

Town of Teton	8.8	12:30 p.m.	33 minutes	1,060,000	Only tiny fraction flooded

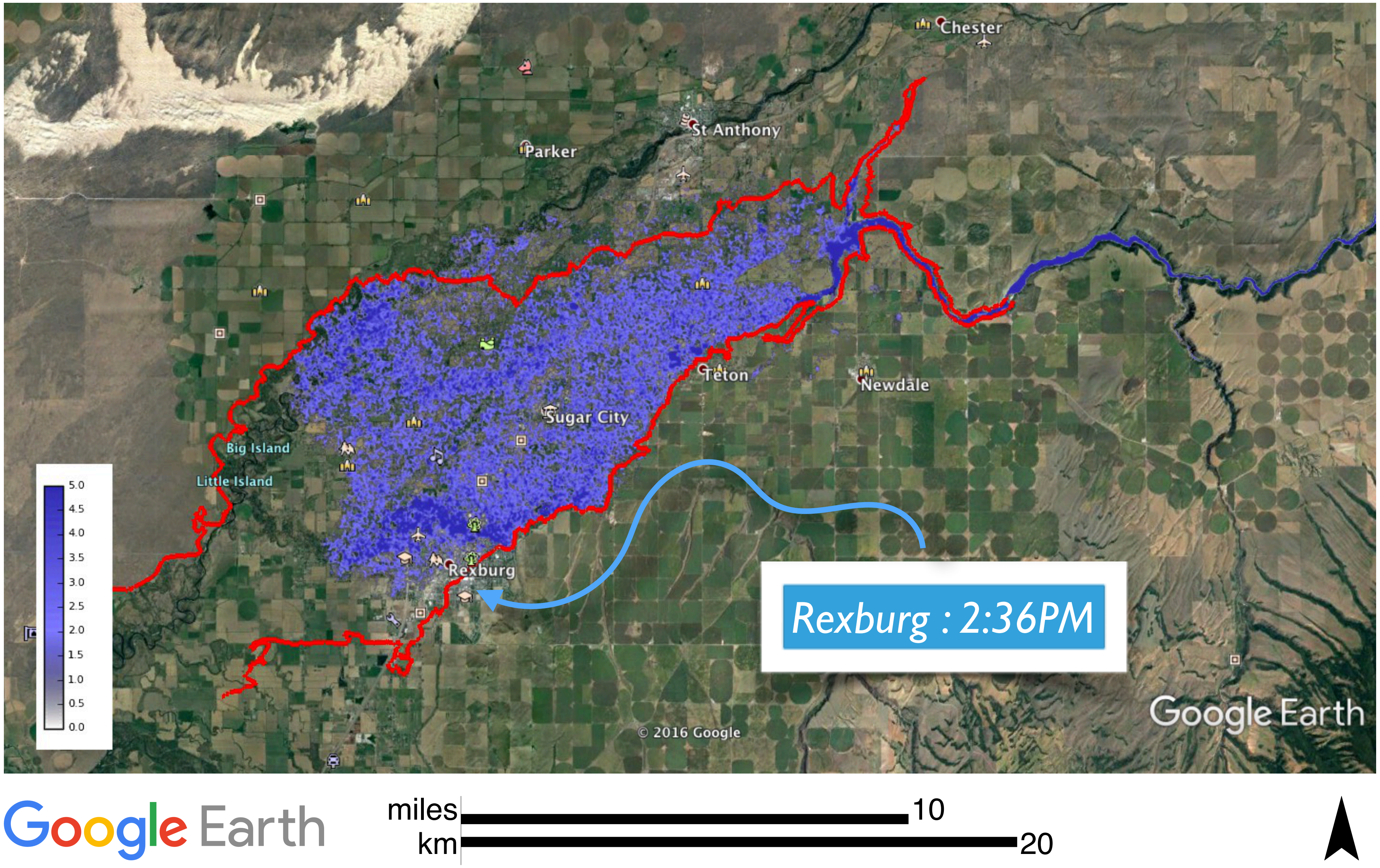
Simulation results



Sugar City : 1:23PM

Sugar City	12.3	About 1:30 p.m.	1.5 hours		15-foot wall-of-water

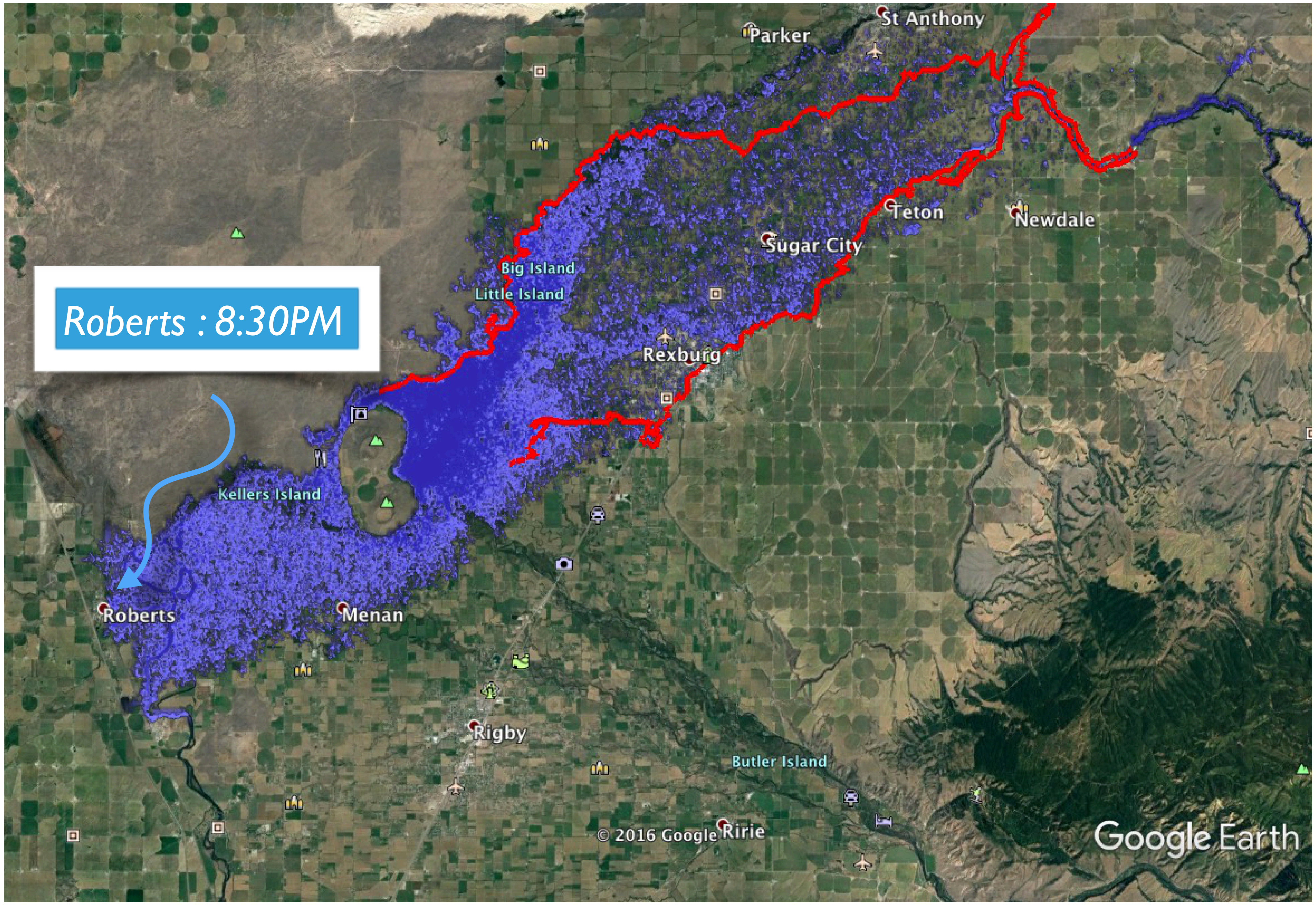
Simulation results



Rexburg : 2:36PM

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

Simulation results



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

Simulation results

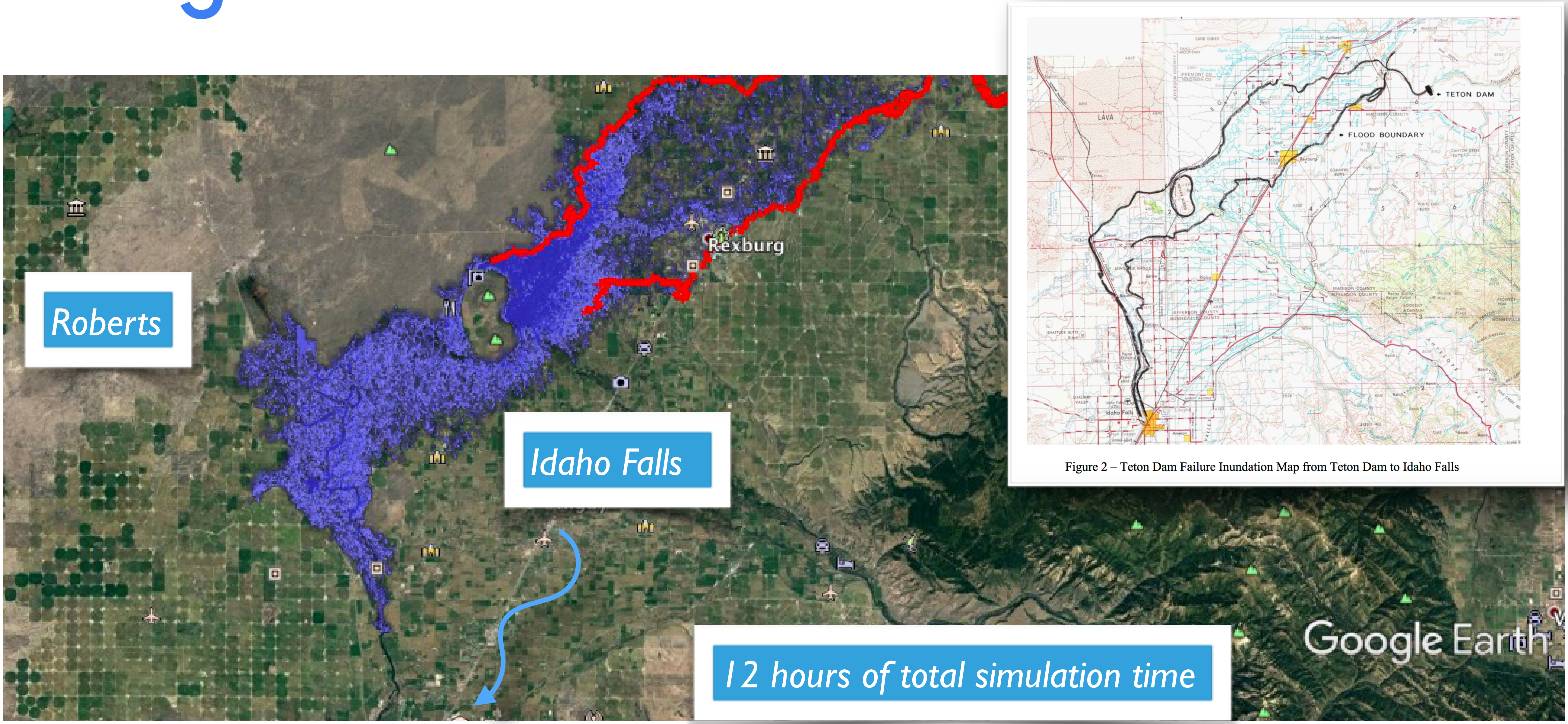


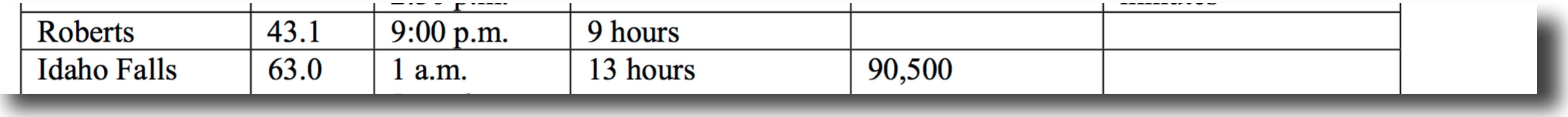
Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

Roberts

Idaho Falls

12 hours of total simulation time

Level 0



Roberts	43.1	9:00 p.m.	9 hours		
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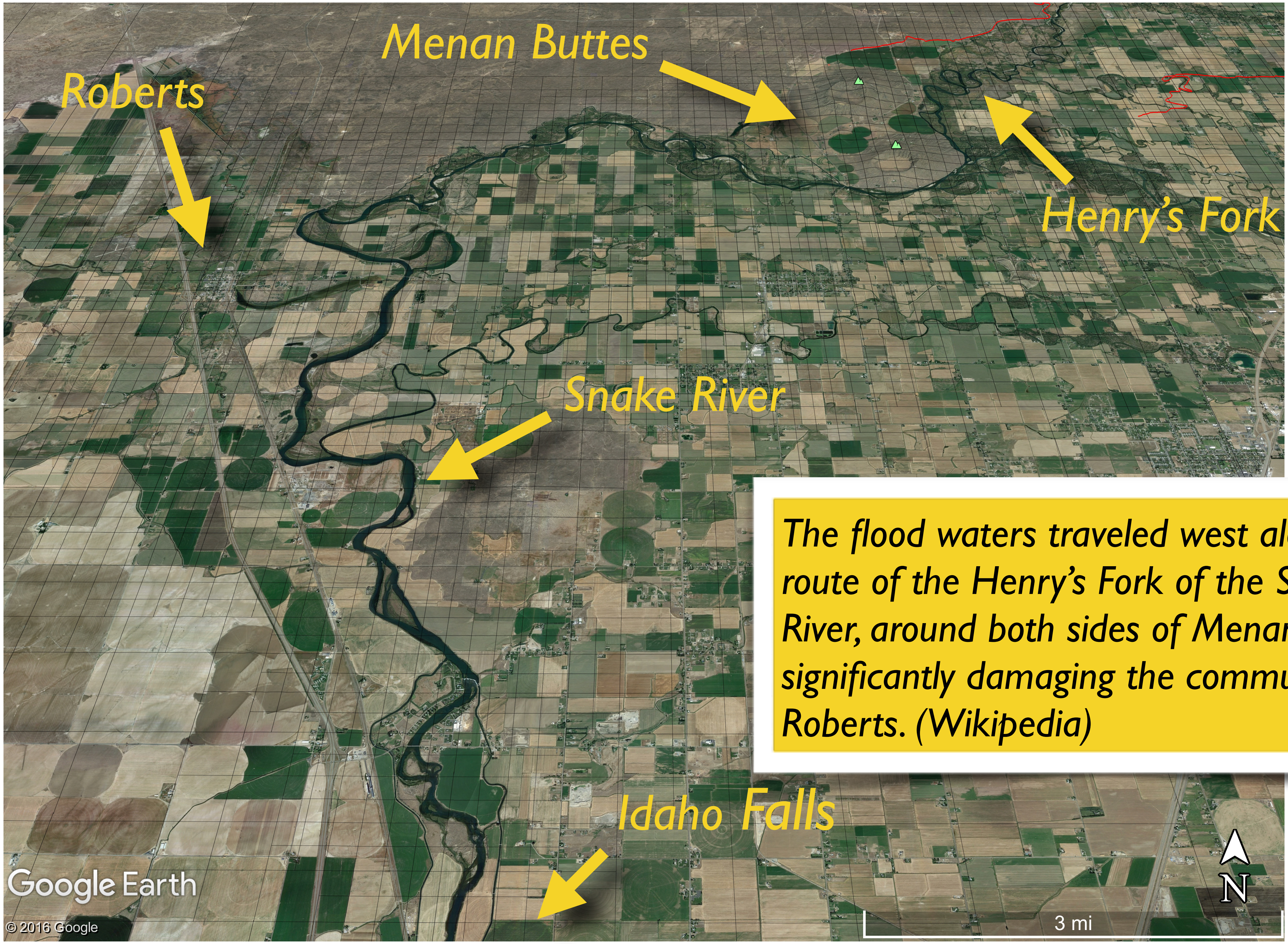
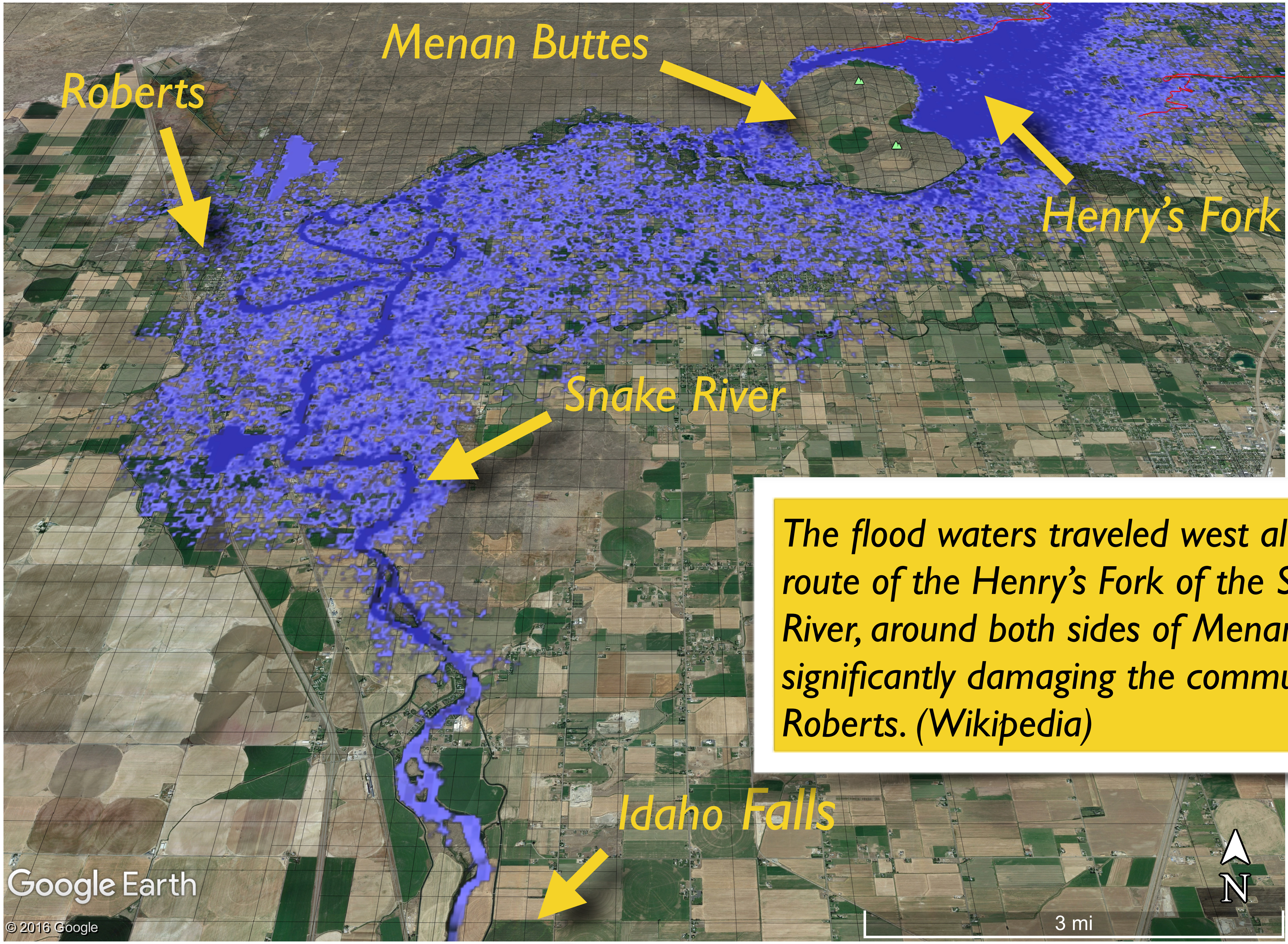
Snake River



The flood waters traveled west along the route of the Henry's Fork of the Snake River, around both sides of Menan Buttes, significantly damaging the community of Roberts. (Wikipedia)

Snake River



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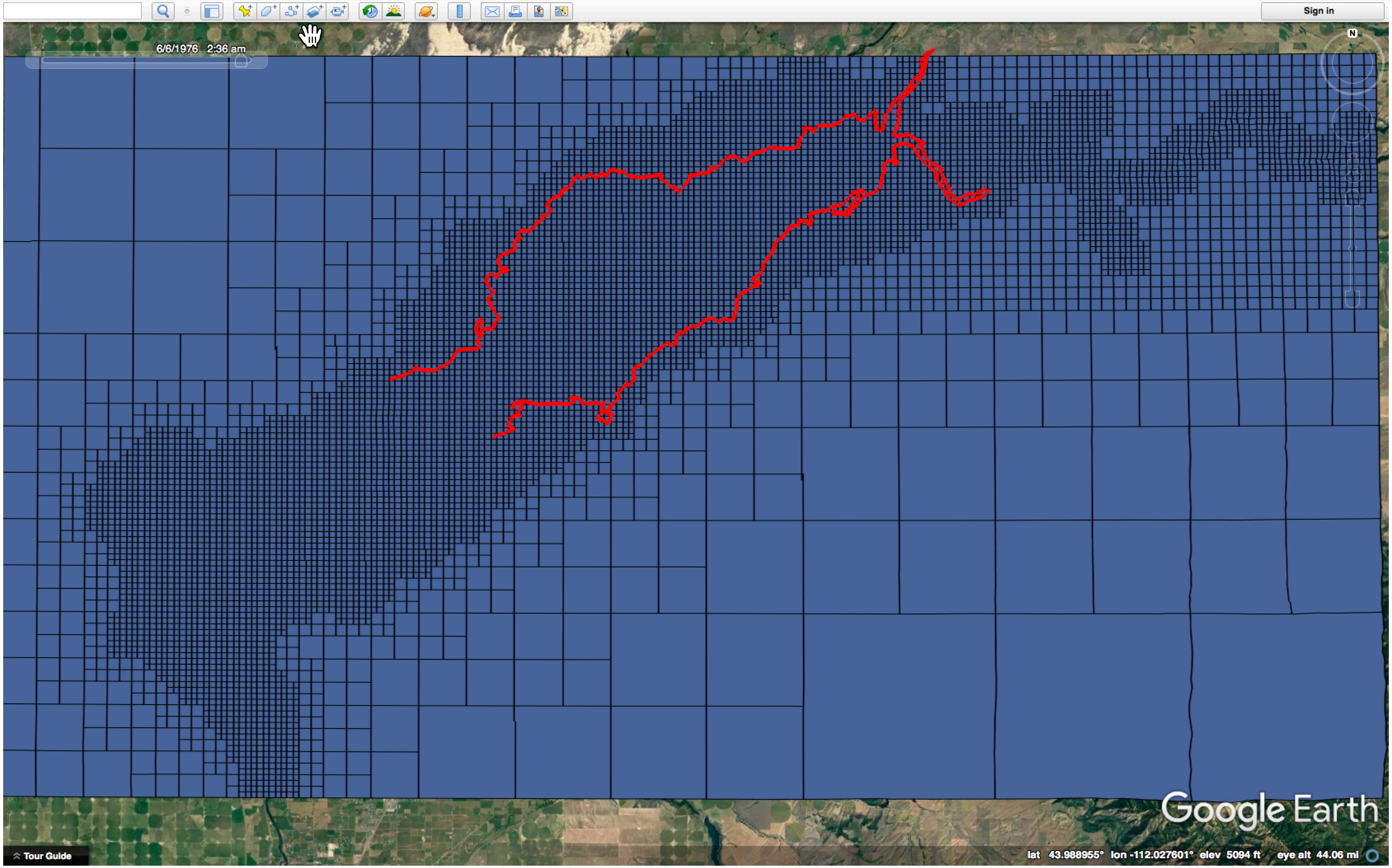
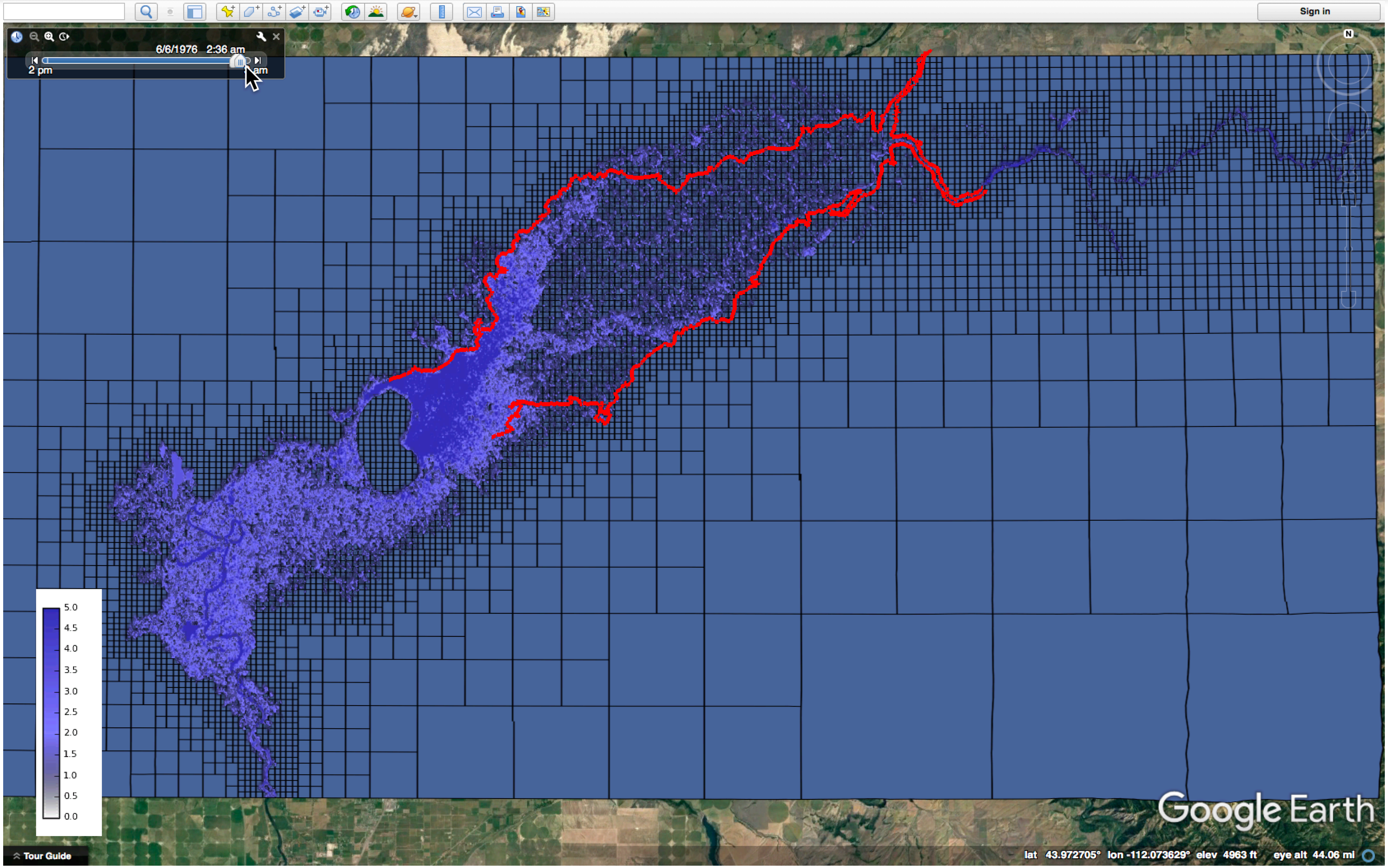
Adaptive Mesh



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.

Future?

- Collaboration with Univ. of Washington to develop tool to allow easier simulation of flooding scenarios (K. Huntingon, FloodMap)

Interested students are always welcome!