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

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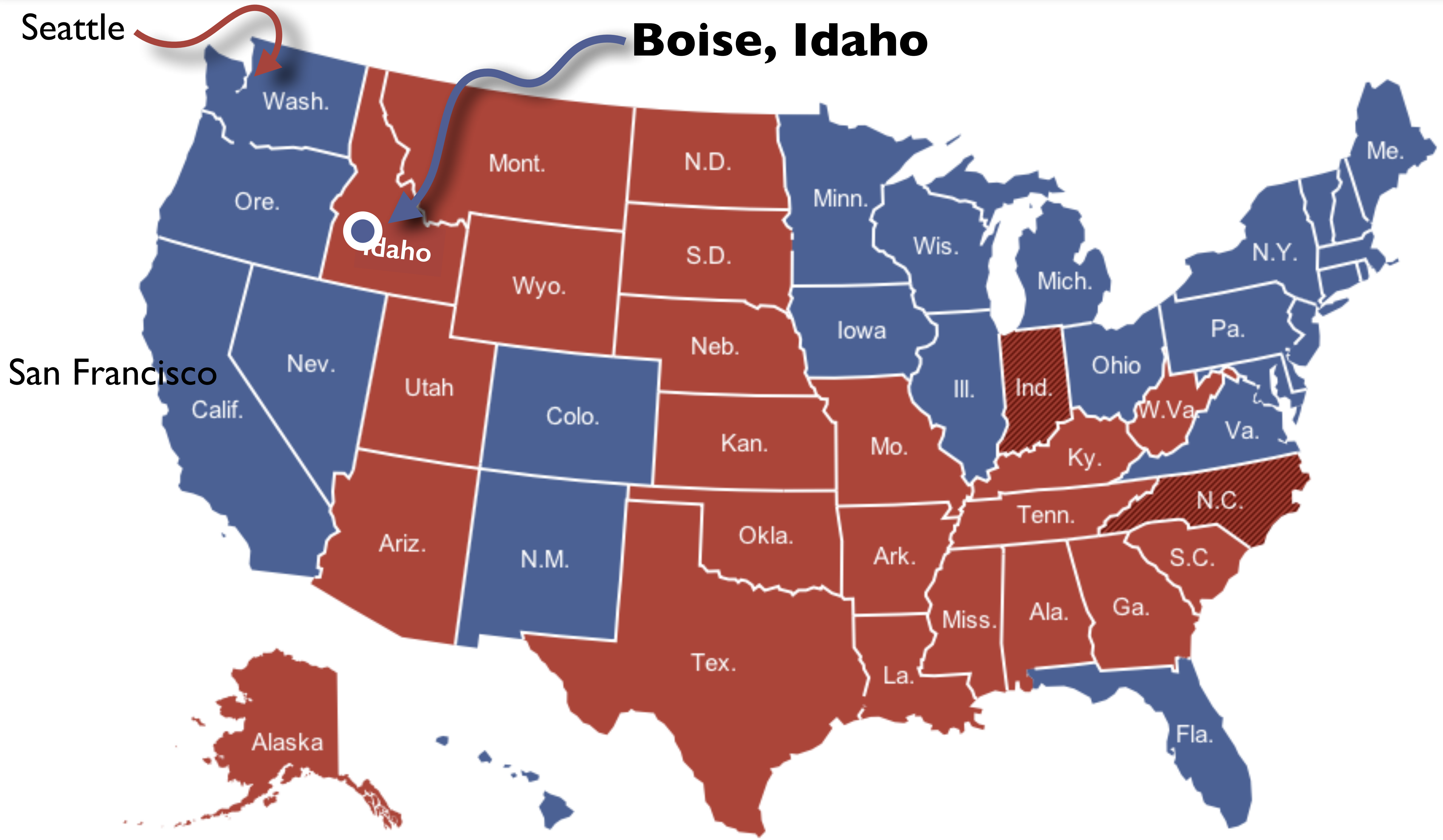
David George (USGS), Marsha Berger (NYU) Randall LeVeque (Univ. of Washington); David Ketcheson (KAUST, Saudi Arabia)

Numerical Analysis Seminar
June 7, 2017
University of Dusseldorf

Where is Boise?



*2012 Electoral map (:-((

What is in Idaho?

More about Idaho

BOISE STATE

Albertsons

Micron

Boise Cascade
Engineered Wood Products

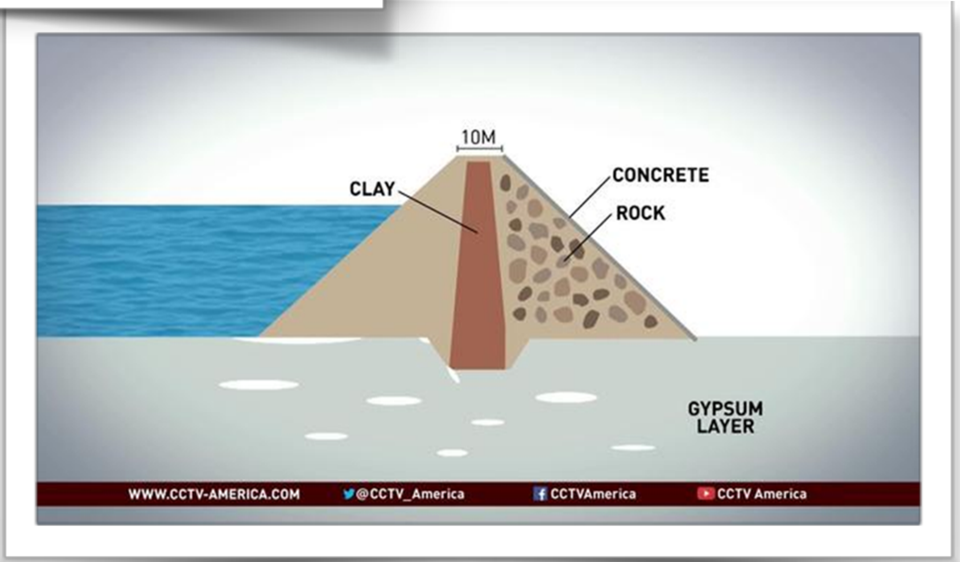
SALMON AIR

NATIONAL INTERAGENCY FIRE CENTER
Boise, 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 results in million and half people losing their lives or becoming homeless.

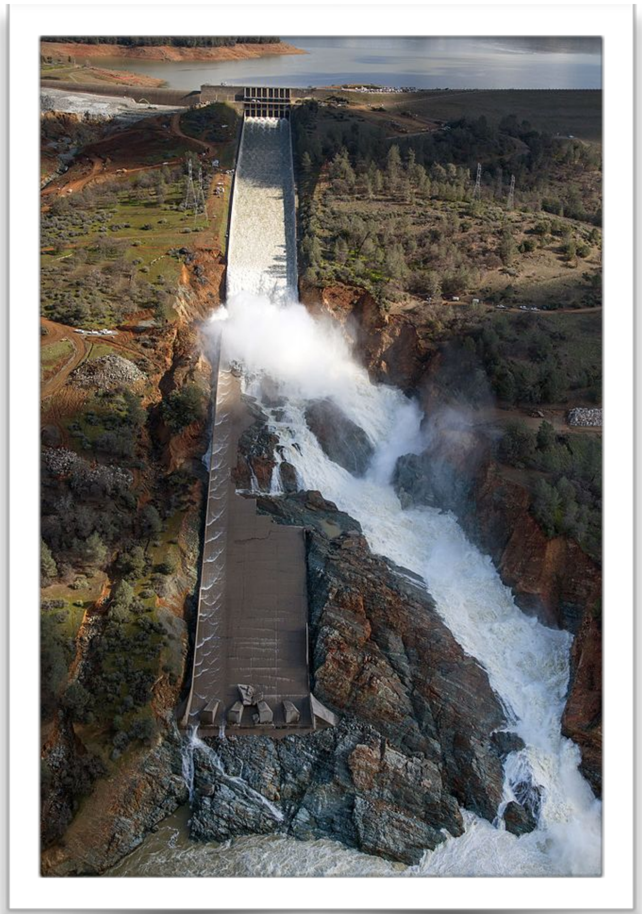
If the dam ruptured, it would likely cause a catastrophe of Biblical proportions, loosing a wave as high as a hundred feet that would roll down the Tigris, swallowing everything in its path for more than a hundred miles. Large parts of Mosul would be submerged in less than three hours. Along the river 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?

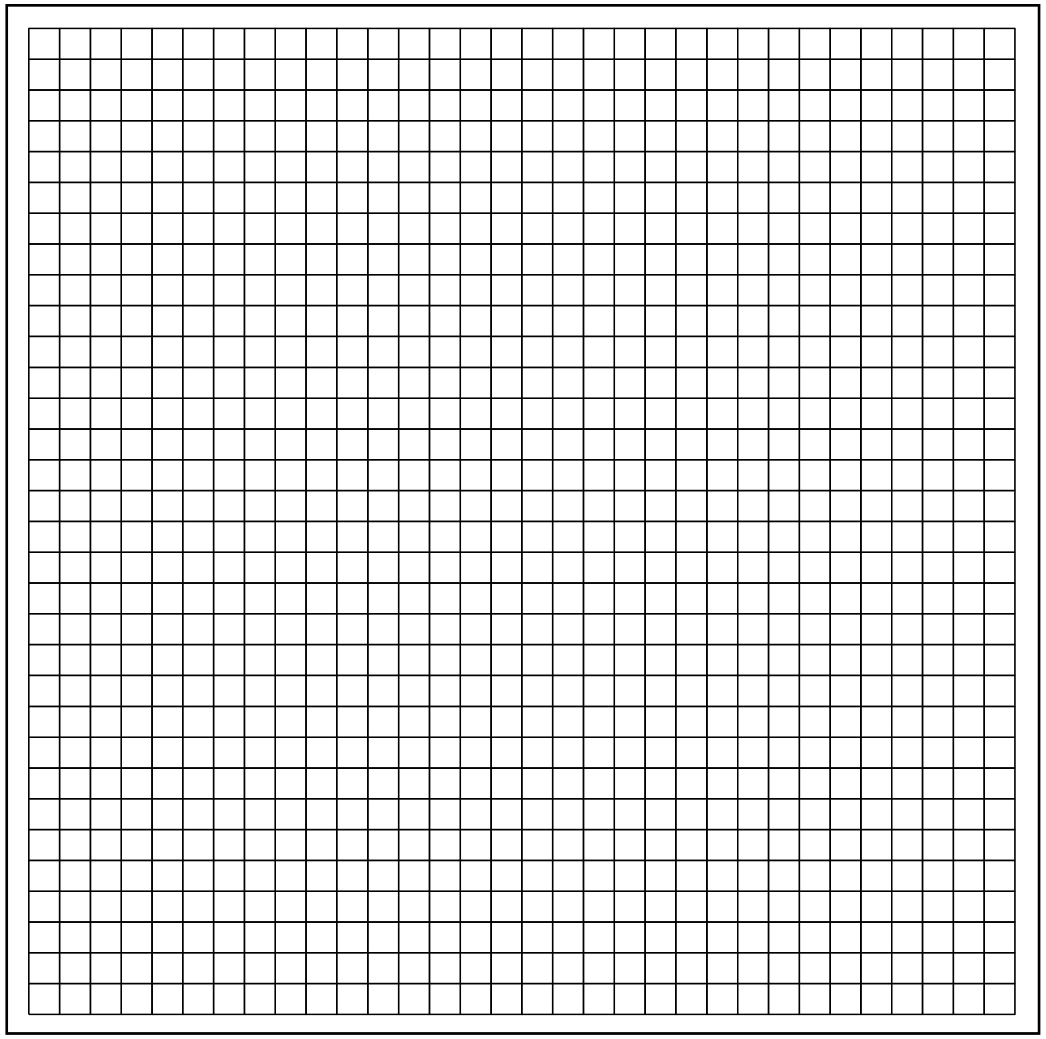
- Create flood maps for local communities
- Communicate threats to lawmakers in visually impactful way
- Potentially aid in design and location of future dams

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

Basic idea

Embed the evolving flood into a background Cartesian mesh.

- "capture" rather than "track" the evolving flooding front

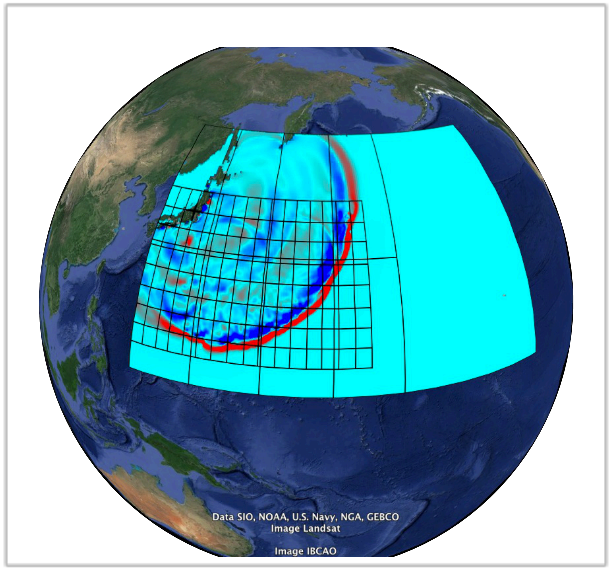


- Use finite volume scheme with suitable Riemann solver that can handle the wet/dry states.
- Handle topography to model realistic flow situations.
- Two dimensional flow makes calculations reasonably inexpensive

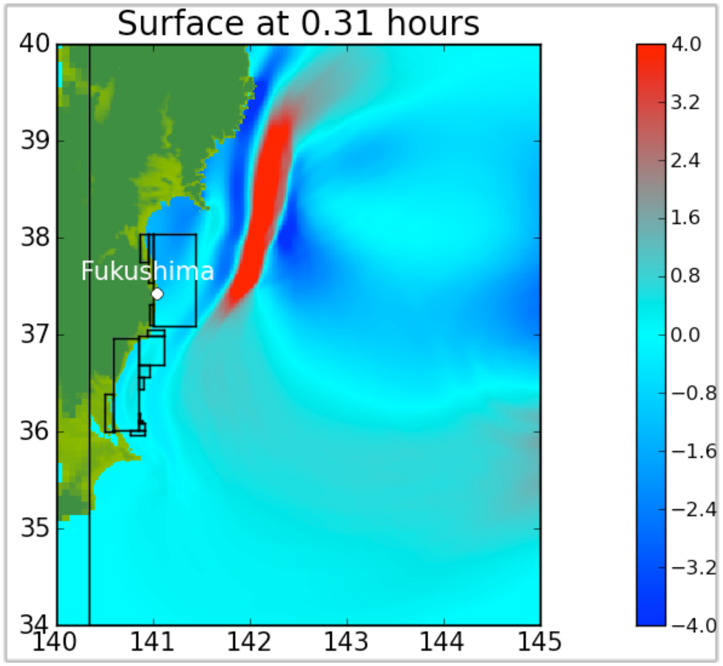
GeoClaw

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).

- Assume that 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

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

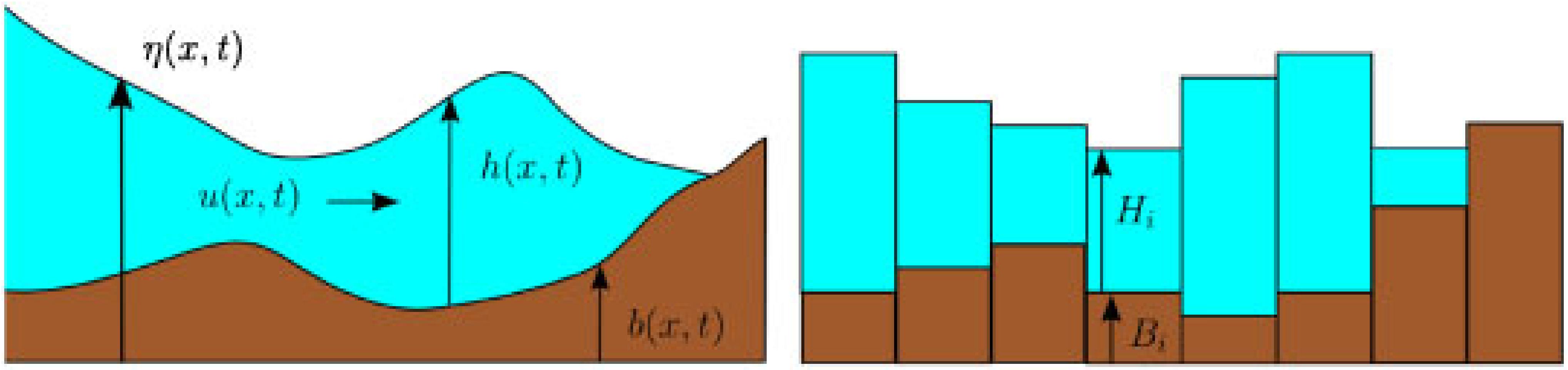
$h(x,t)$	depth-averaged *height*
$u(x,t)$	velocity

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

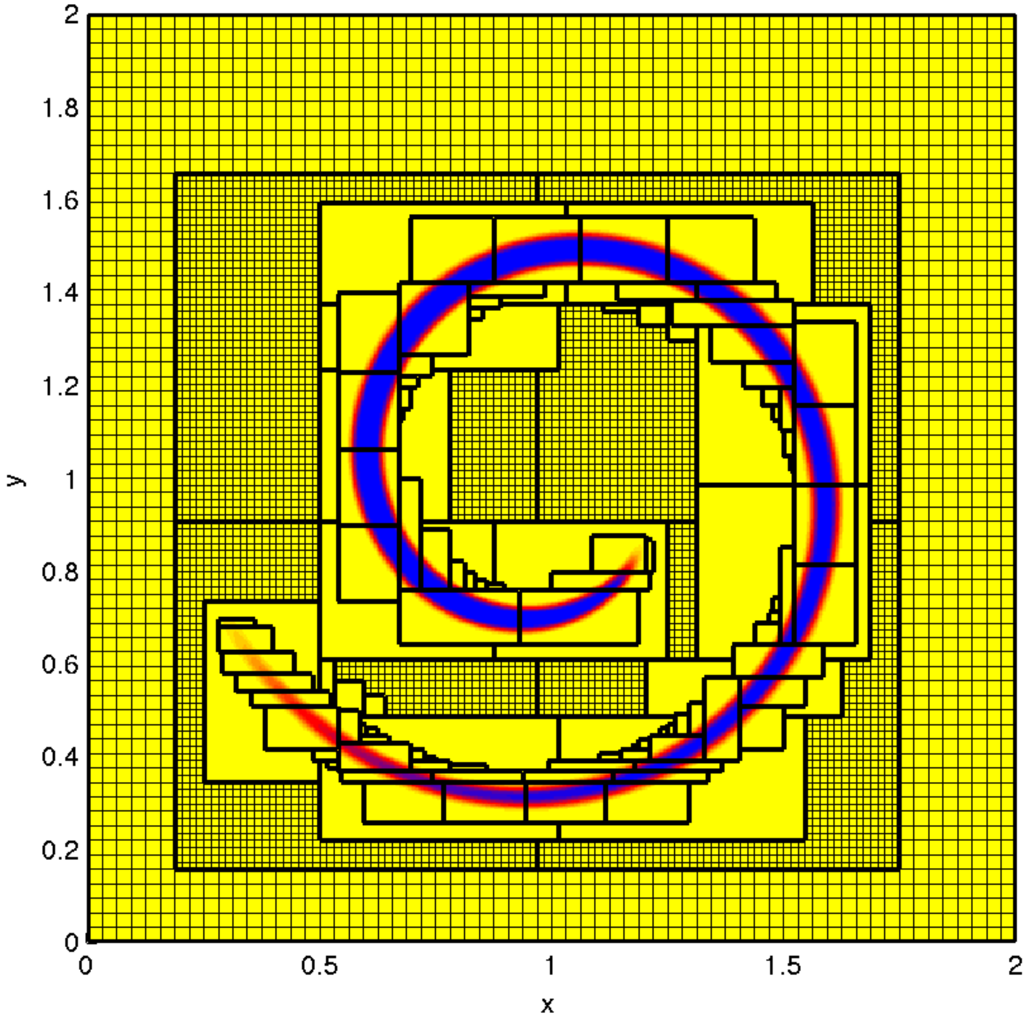
- Riemann solver robustly handles wet and dry states and discontinuities in topography - *no need to track the evolving flood boundary.*
- Seamlessly handles reading and interpolation of multiple, possibly overlapping, topography files for given computational domain
- Well-balanced scheme maintains steady states in presence of topography
- Numerical gauges allow for easy comparison with observational data
- Uses OpenMP (shared memory) parallelism

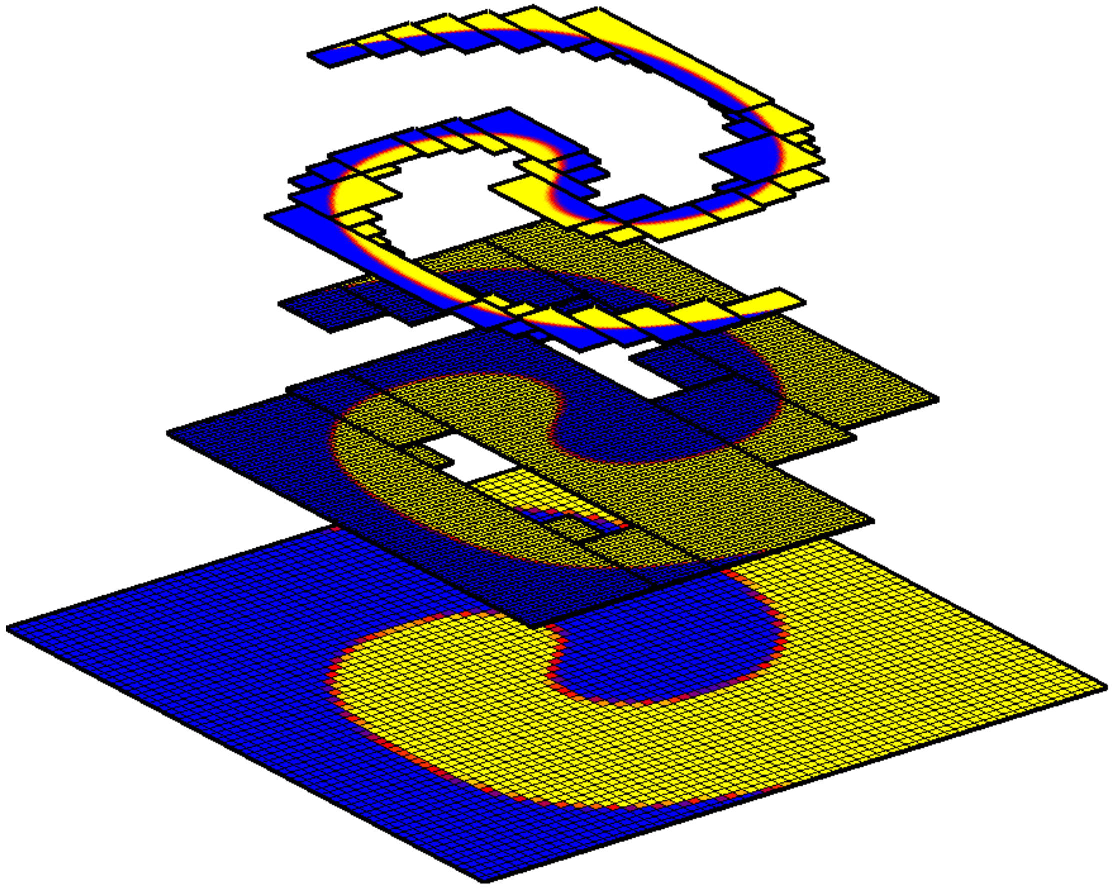
Use of adaptive mesh refinement (AMR) means that resolution is allocated only where needed (dry land is resolved only at the coarsest levels)

Original AMR (GeoClaw)

Overlapping patch-based AMR (Structured AMR or SAMR)

Original approach (Berger, 1984)



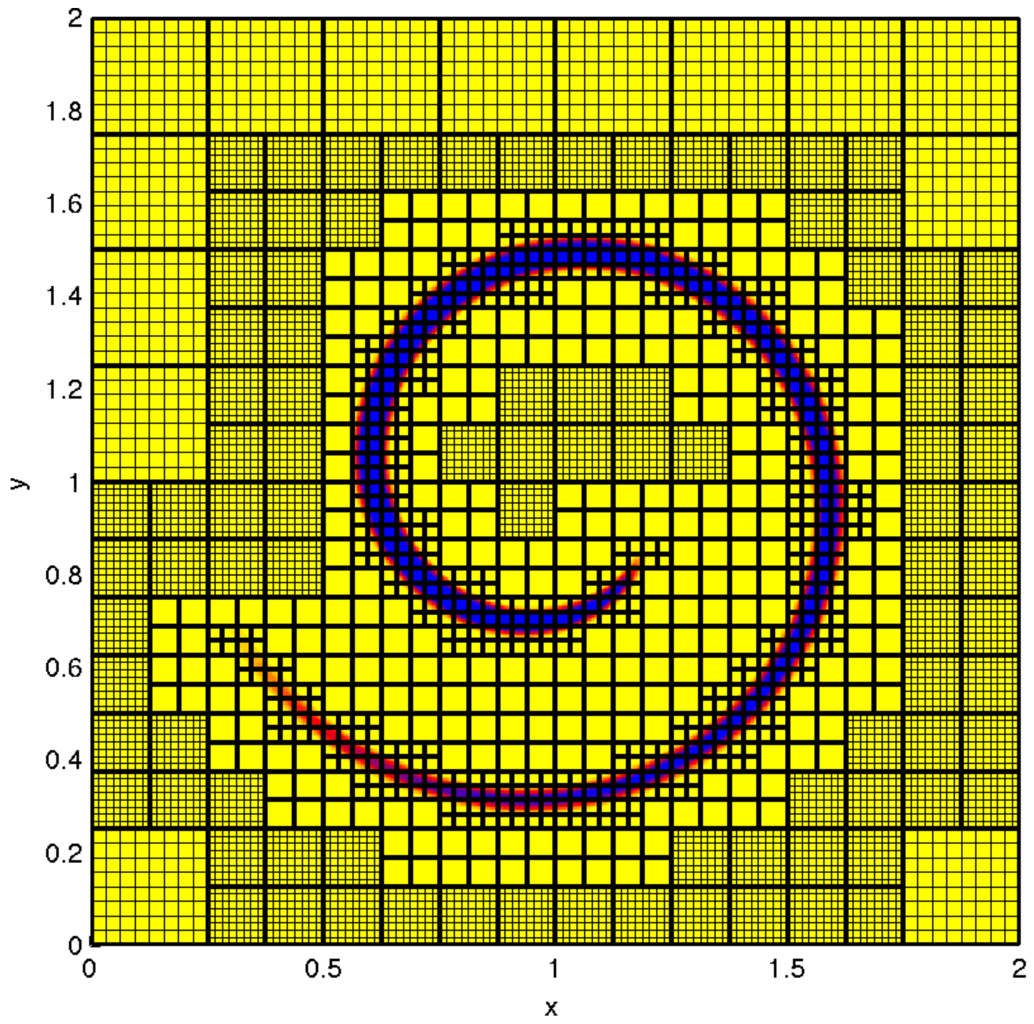


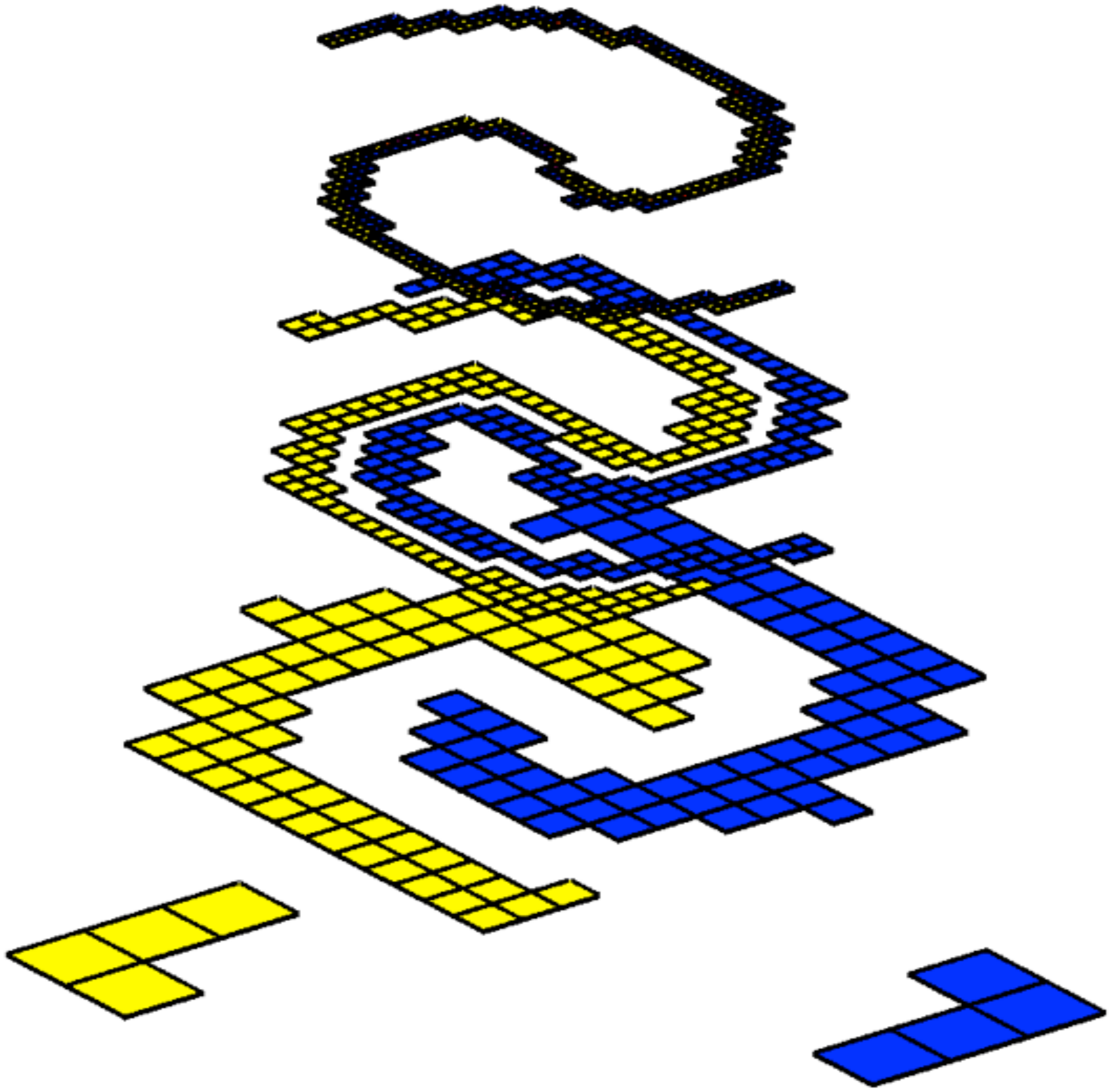
Codes : Chombo (LBL), AMRClaw and GeoClaw (UW, NYU) , **Boxlib* (LBL)**, SAMRAI (LLNL), AMROC (Univ. of South Hampton) and many others

Adaptive Mesh Refinement (AMR)

Quadtree/Octree based AMR

Quad-tree approach





p4est (U. Bonn), PARAMESH (U. Chicago), ForestClaw, Gerris (Paris VI), Racoon II (U. Bochum), RAMSES (U Zurich), Nirvana (Potsdam), “Building Cubes” (Tohoku)

Brief history of AMR

Refinement based on quadtree and octree grid layouts

- 2000 : P. MacNiece, K. Olson et al, "**PARAMESH**: A parallel adaptive mesh refinement community toolkit" (FLASH code based on PARAMESH)
- 2002 : R. Tessyier, "Cosmology Hydrodynamics with adaptive mesh refinement. A new high resolution code called **RAMSES**" (Lausanne, Switzerland)
- 2003 : S. Popinet, "**Gerris**: A tree-based adaptive solver for the incompressible Euler equations in complex geometries" (Paris IV, France)
- 2004 : U. Ziegler, "An ADI-based adaptive mesh Poisson solver for the MHD code **NIRVANA**" (Potsdam, Germany)
- 2005 : J. Dreher and R. Grauer, "**Racoon**: A parallel mesh-adaptive framework for hyperbolic conservation laws" (Bochum, Germany)
- 2011 : C. Burstedde, L. Wilcox, O. Ghattas, "**p4est**: Scalable Algorithms for Parallel Adaptive Mesh Refinement on Forests of Octrees" (Univ. Texas)
- 2011 : K. Komatsu, T. Soga et al "Parallel processing of the **Building-Cube Method** on a GPU platform" (Tohoku, Japan)

2000 ↔ present

ForestClaw Project

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

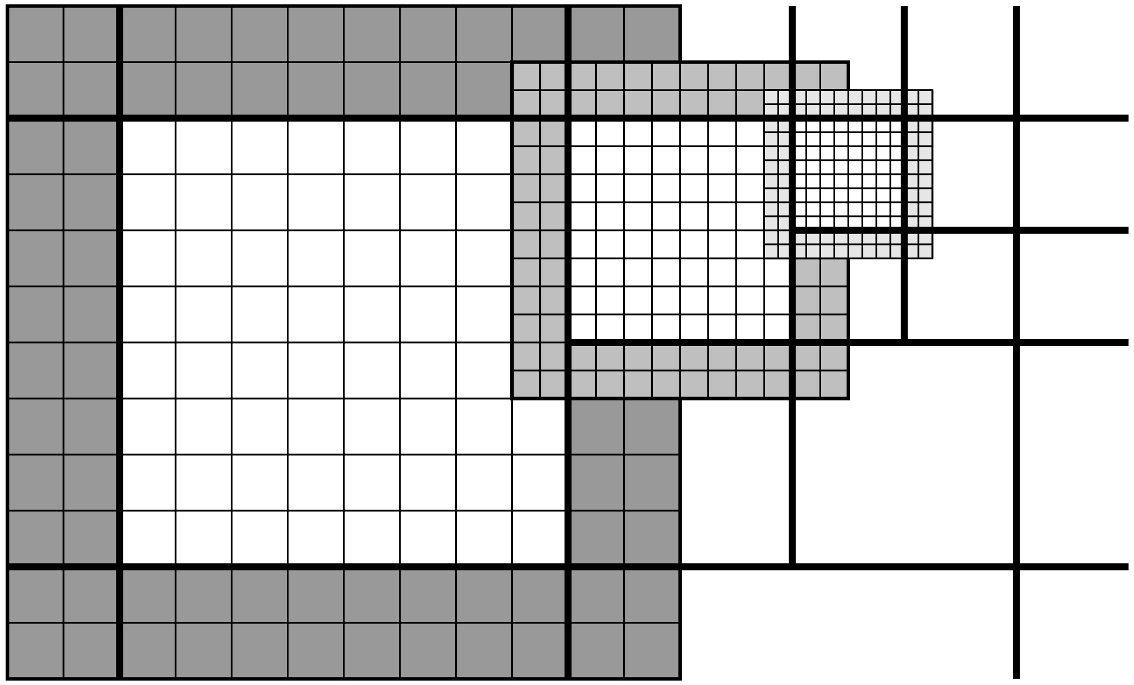
Features of ForestClaw include :

- 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

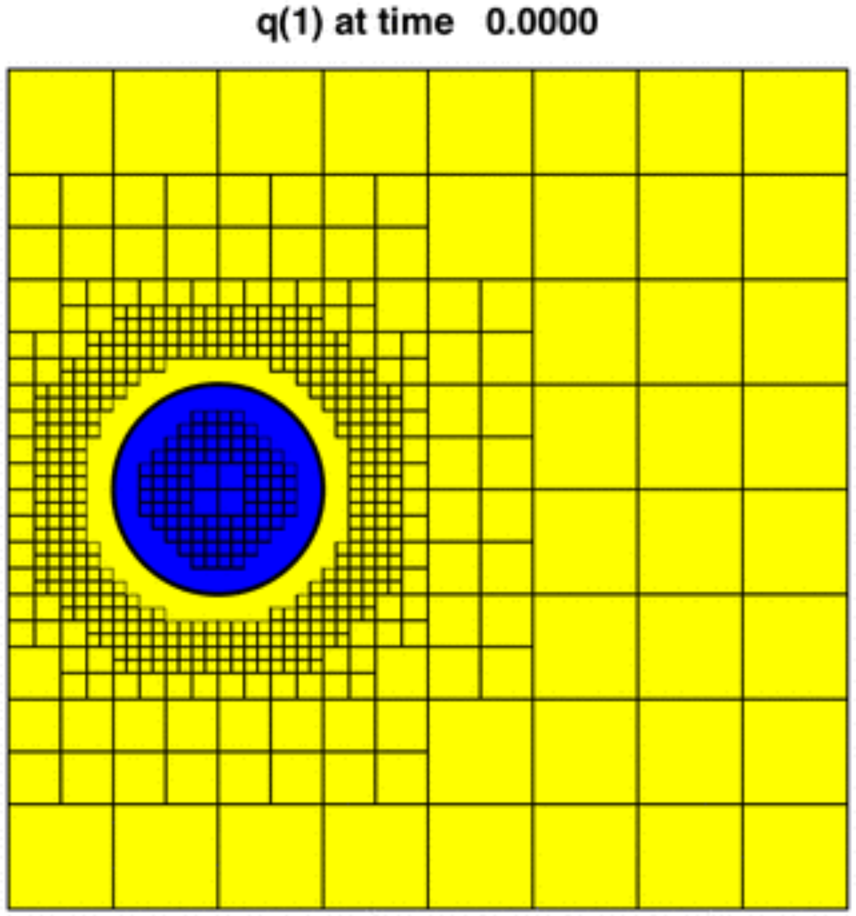
Thanks to NSF for supporting this work

www.forestclaw.org

ForestClaw adaptivity

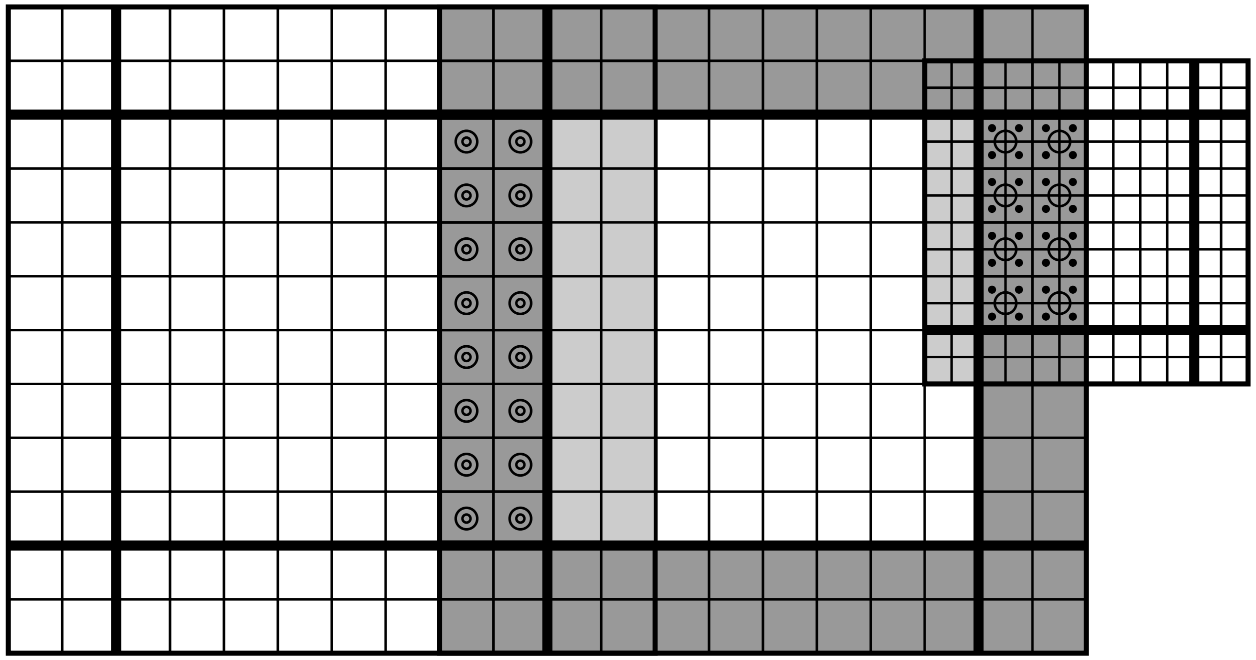


Each quadrant is a single logically grid, designed for finite volume or finite difference solvers.

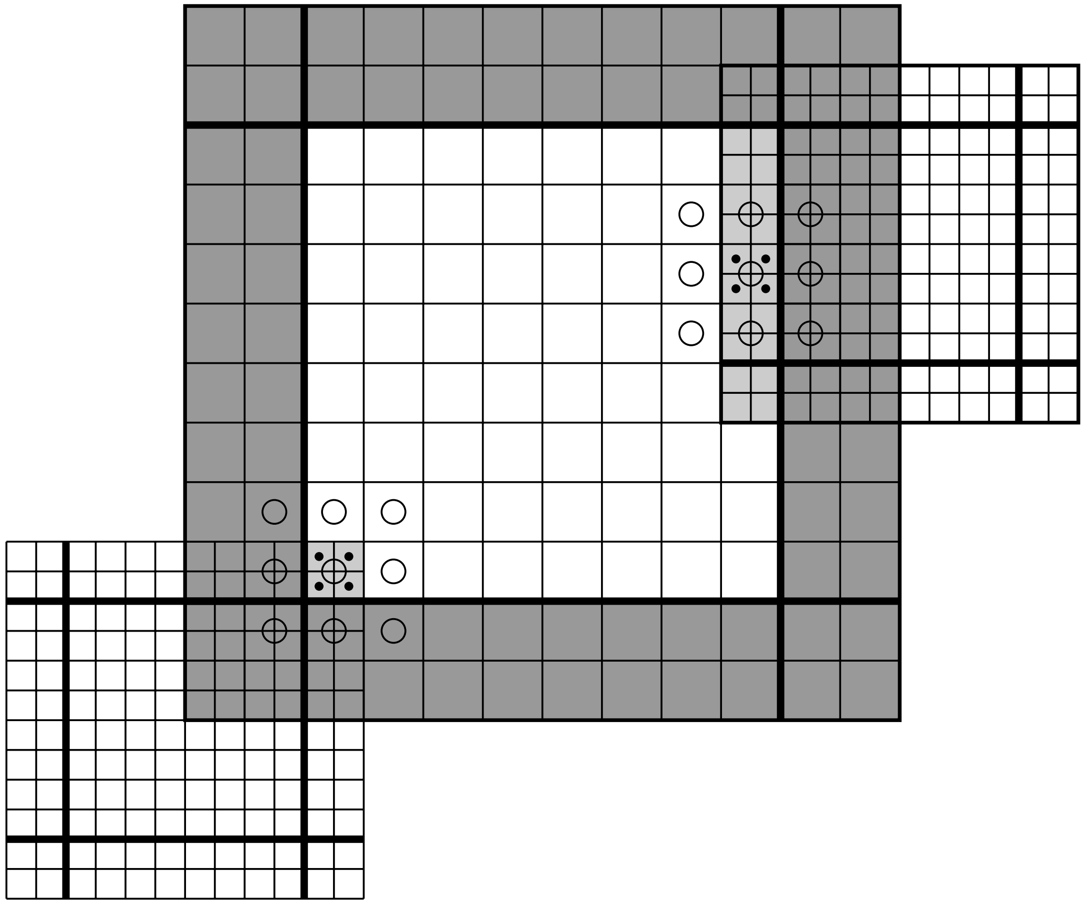


Regridding, connectivity done using p4est

Filling ghost cells



Step 1 :Averaging or copying to coarse ghost regions



Step 2 : Interpolation to fine ghost regions, using coarse grid ghost regions

Each grid (or "leaf", in p4est terminology) has one of more layers of ghost cells used for communication between grids

Computational performance

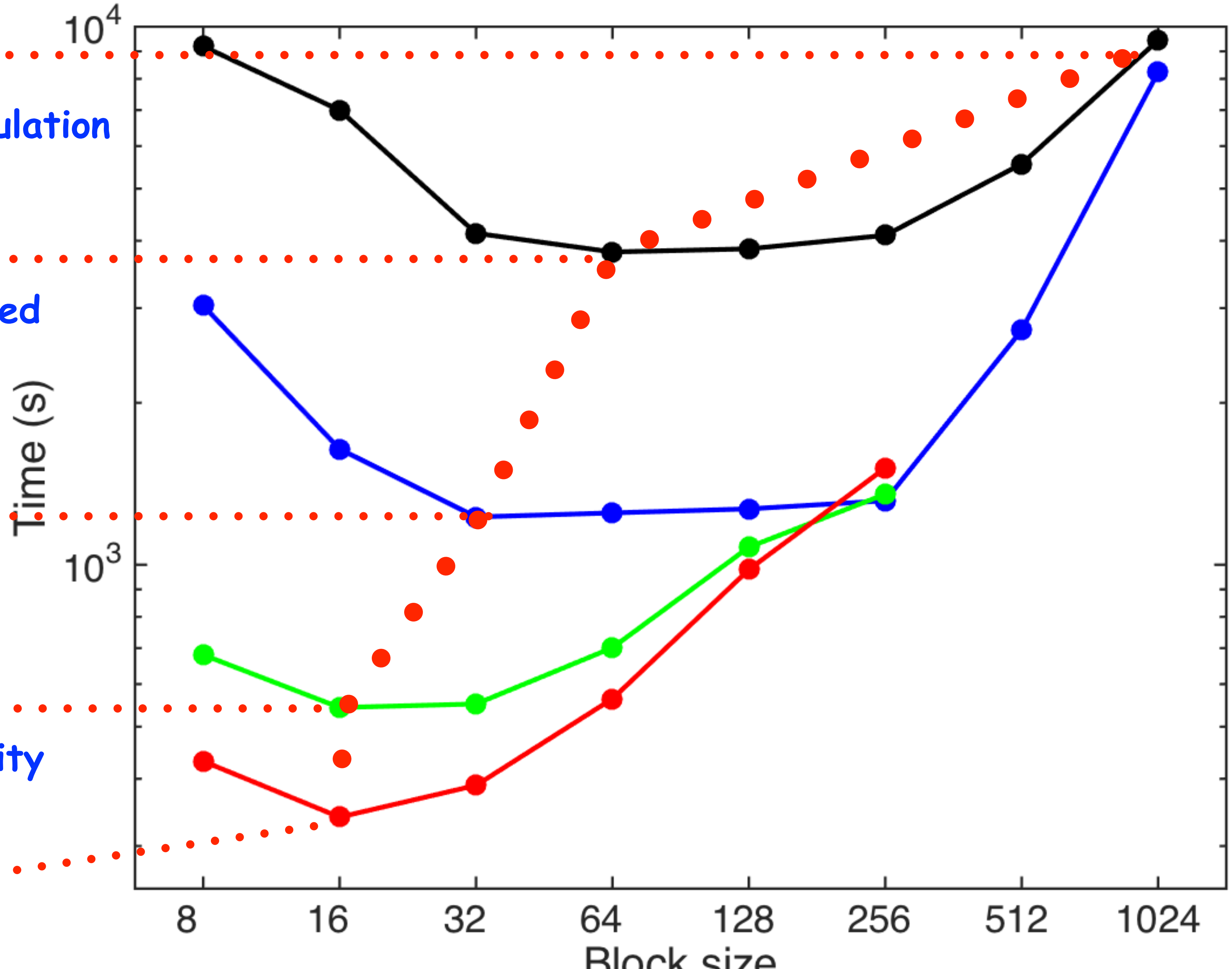
~2.5 h
Single grid calculation

~1 h
Uniformly refined

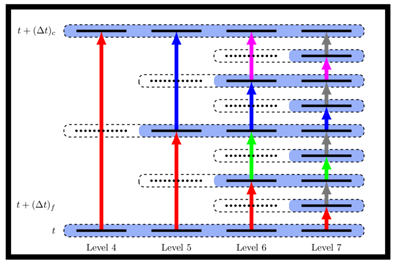
~12.5 min
Parallelism

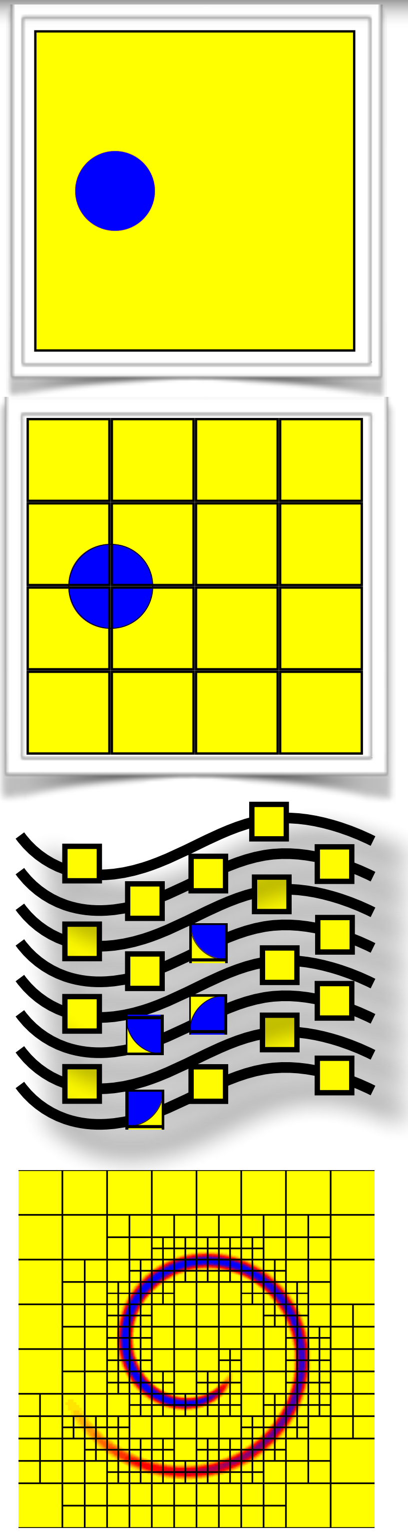
~9 min
Spatial adaptivity

~5.5 min
Adaptive time stepping

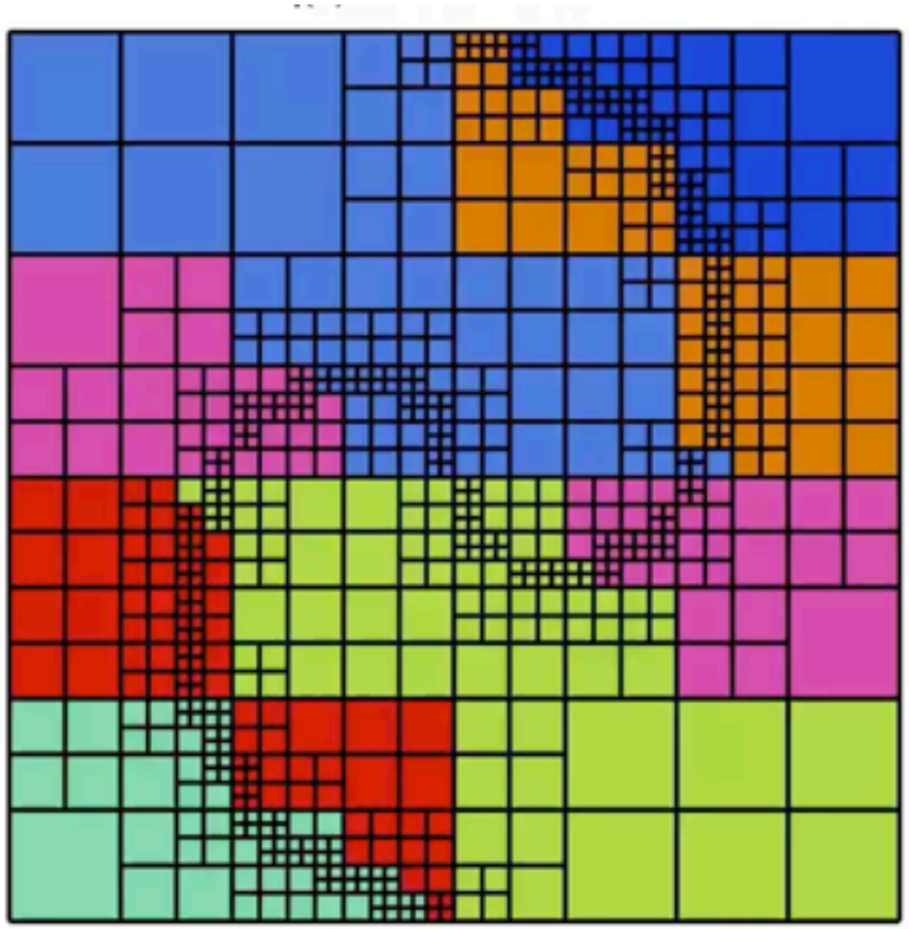


Almost 30 times improvement

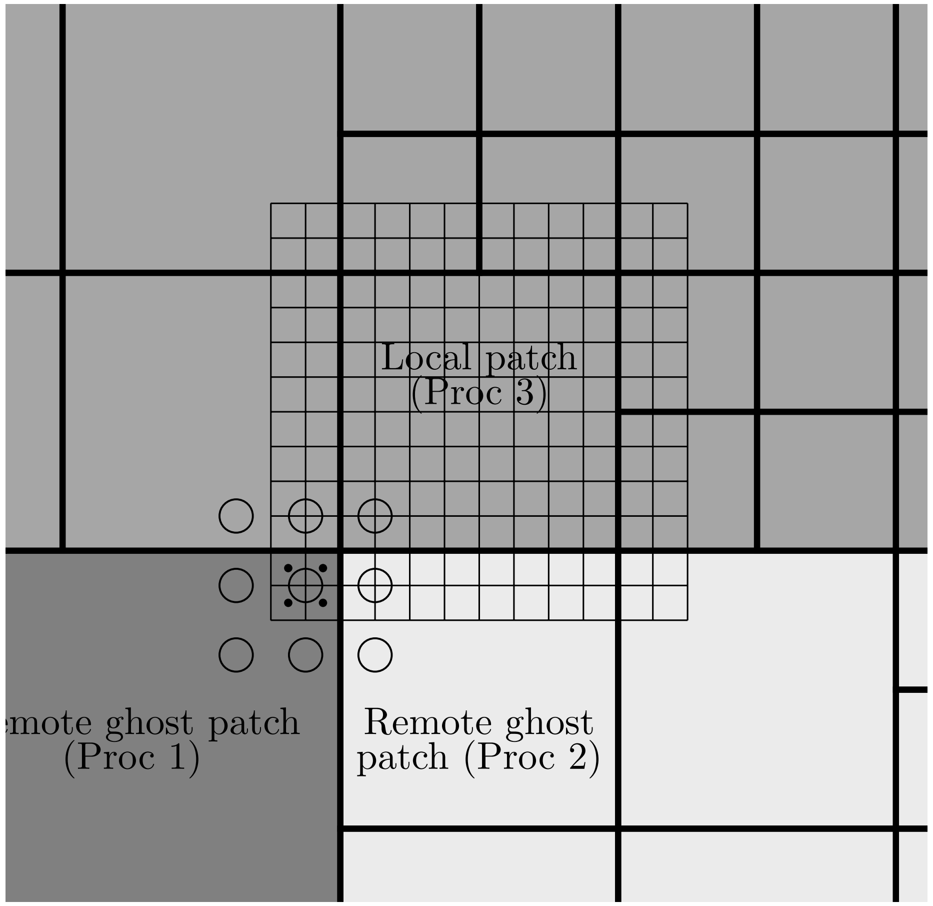




ForestClaw - Parallelism



p4est : Load balancing using a space filling curve



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

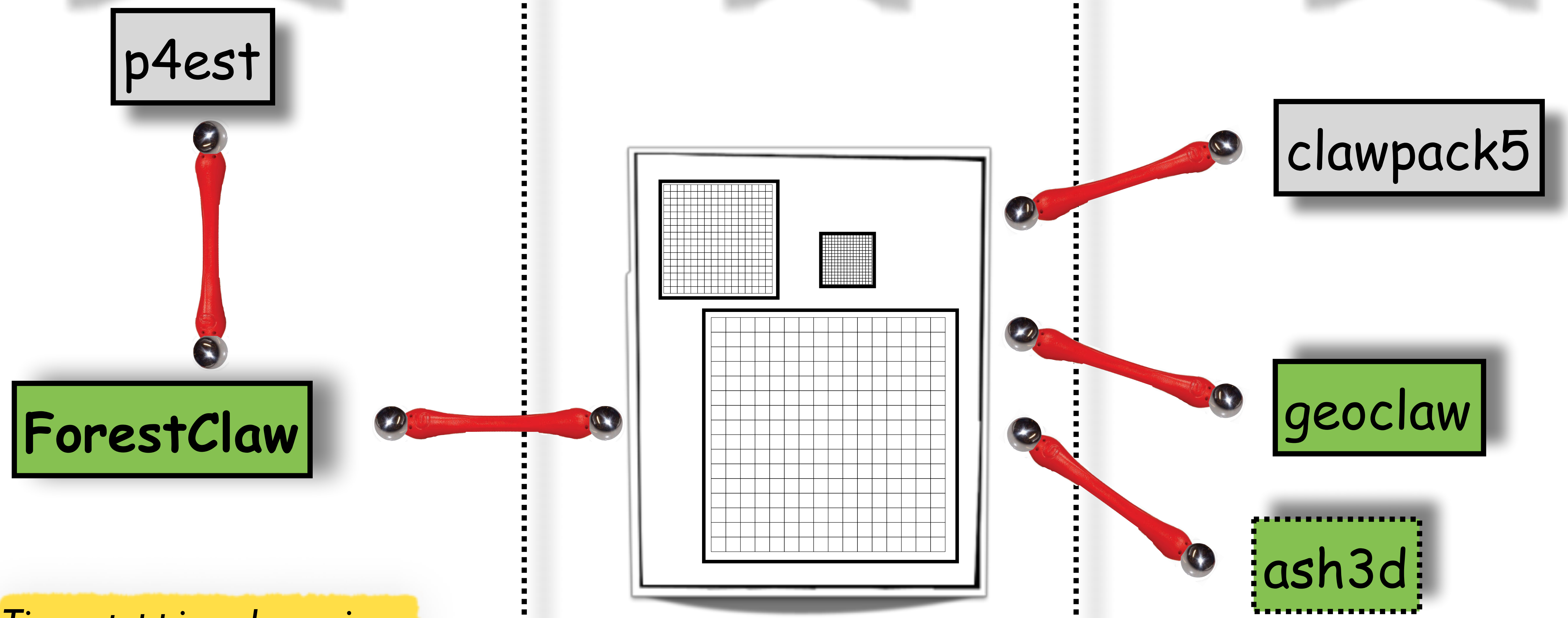
D. Calhoun and C. Burstedde, *"ForestClaw : A parallel algorithm for patch-based adaptive mesh refinement on a forest of quadtrees", (submitted), 2017. (arXiv:1703.03116)*

Extending ForestClaw

Core routines

Patches

Extensions

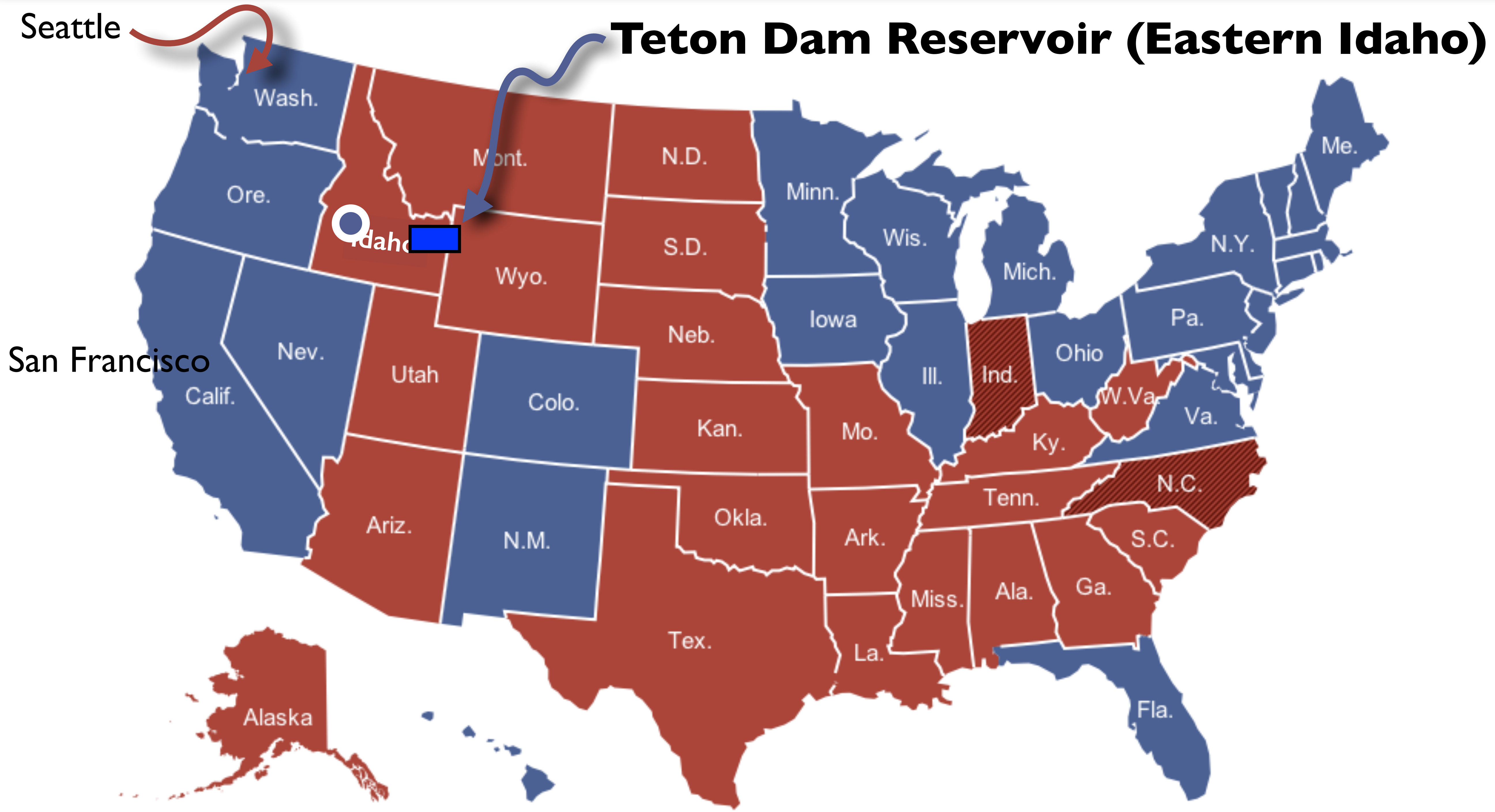


Time stepping, dynamic grid management, input/output.

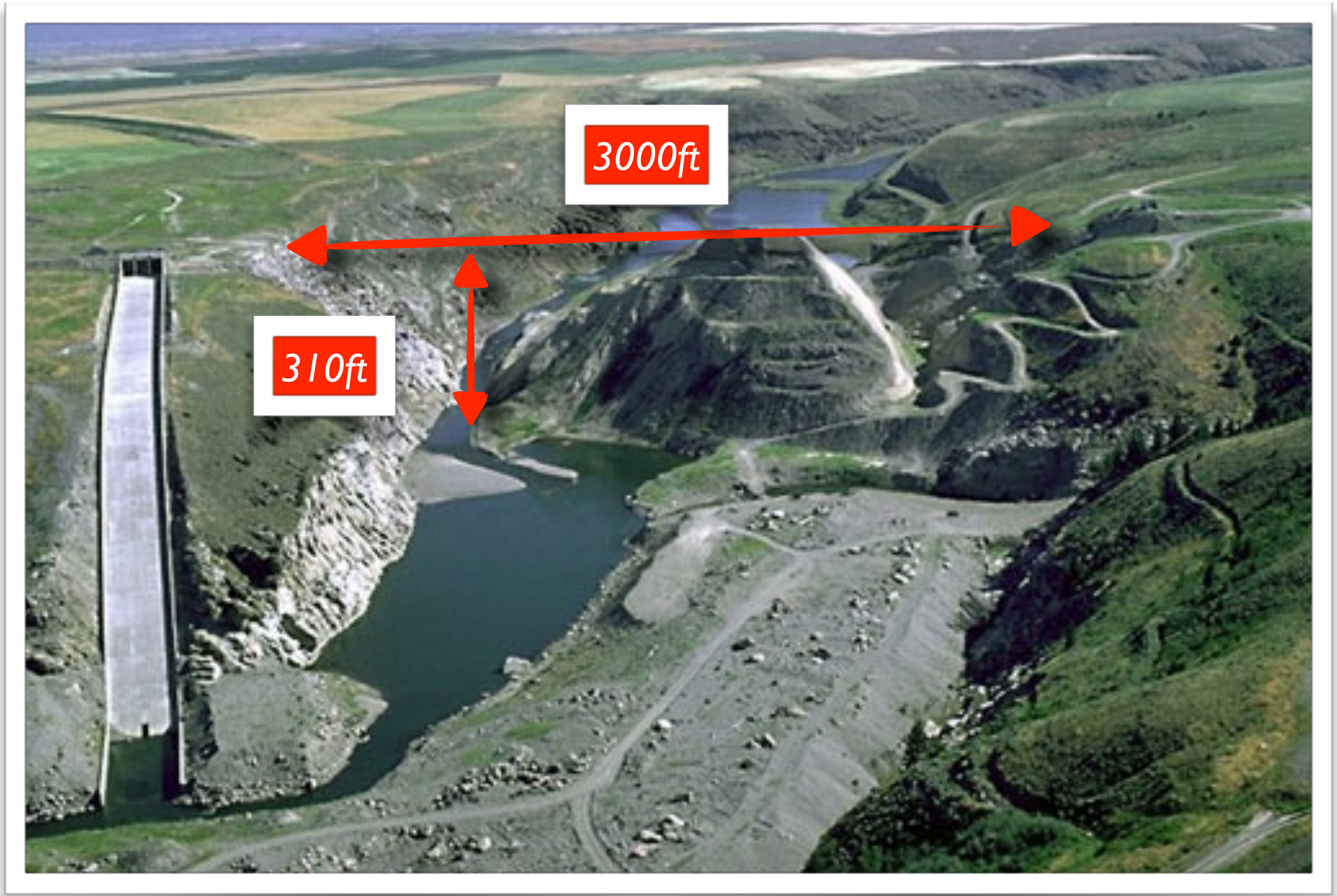
Tasks (tagging, building patches, etc) customized through use of function pointers stored in "virtual tables"

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

Teton Dam


Seattle
Teton Dam Reservoir (Eastern Idaho)
San Francisco
Wash.
Ore.
Idaho
Mont.
N.D.
S.D.
Wyo.
Neb.
Minn.
Wis.
Mich.
Iowa
Nev.
Calif.
Utah
Colo.
Kan.
Mo.
Ill.
Ind.
Ohio
Pa.
N.Y.
Me.
W.Va.
Va.
Ky.
N.C.
Tenn.
S.C.
Okla.
Ark.
Ariz.
N.M.
Tex.
Miss.
Ala.
Ga.
La.
Fla.
Alaska

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

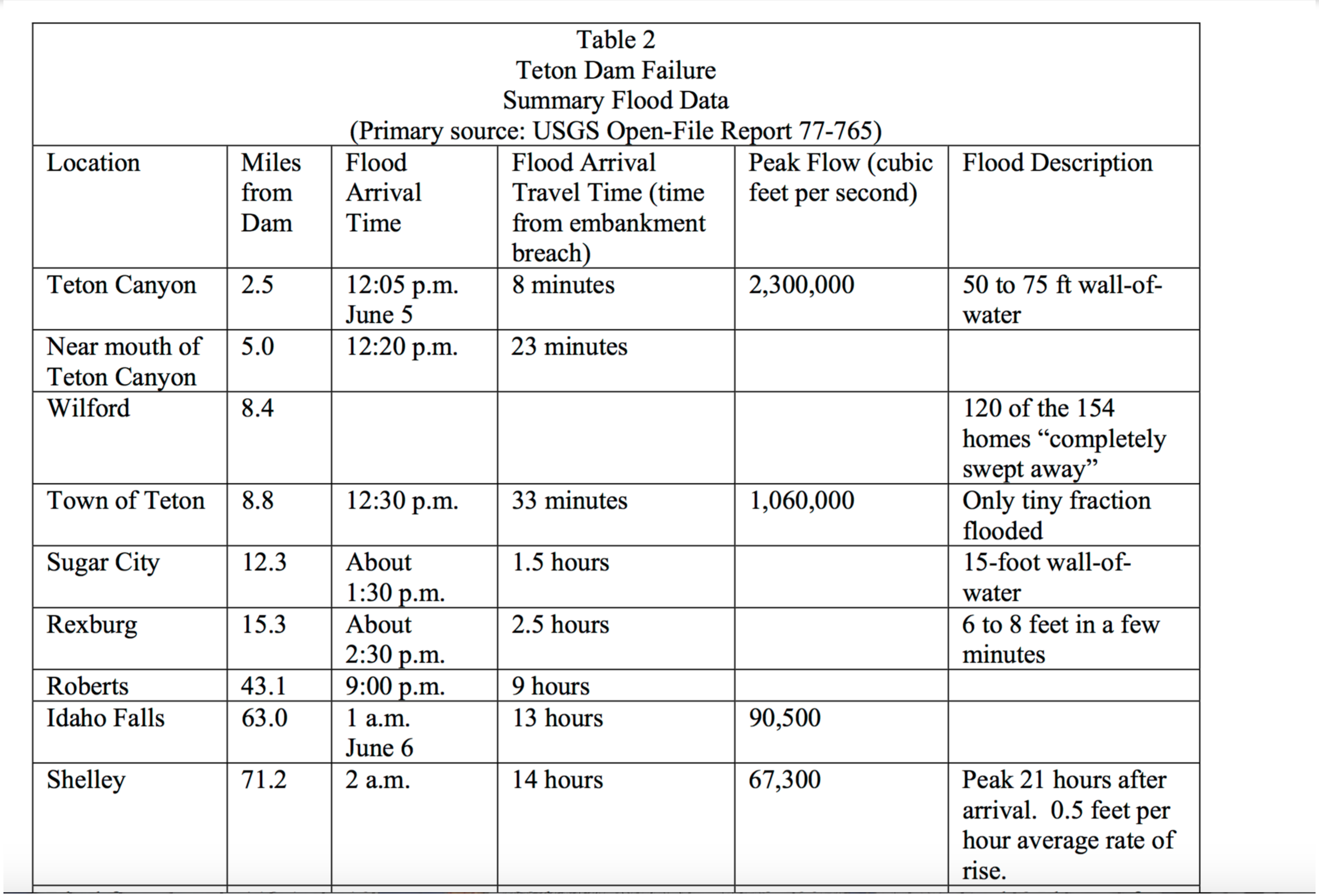


Table 2
Teton Dam Failure
Summary Flood Data
(Primary source: USGS Open-File Report 77-765)

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

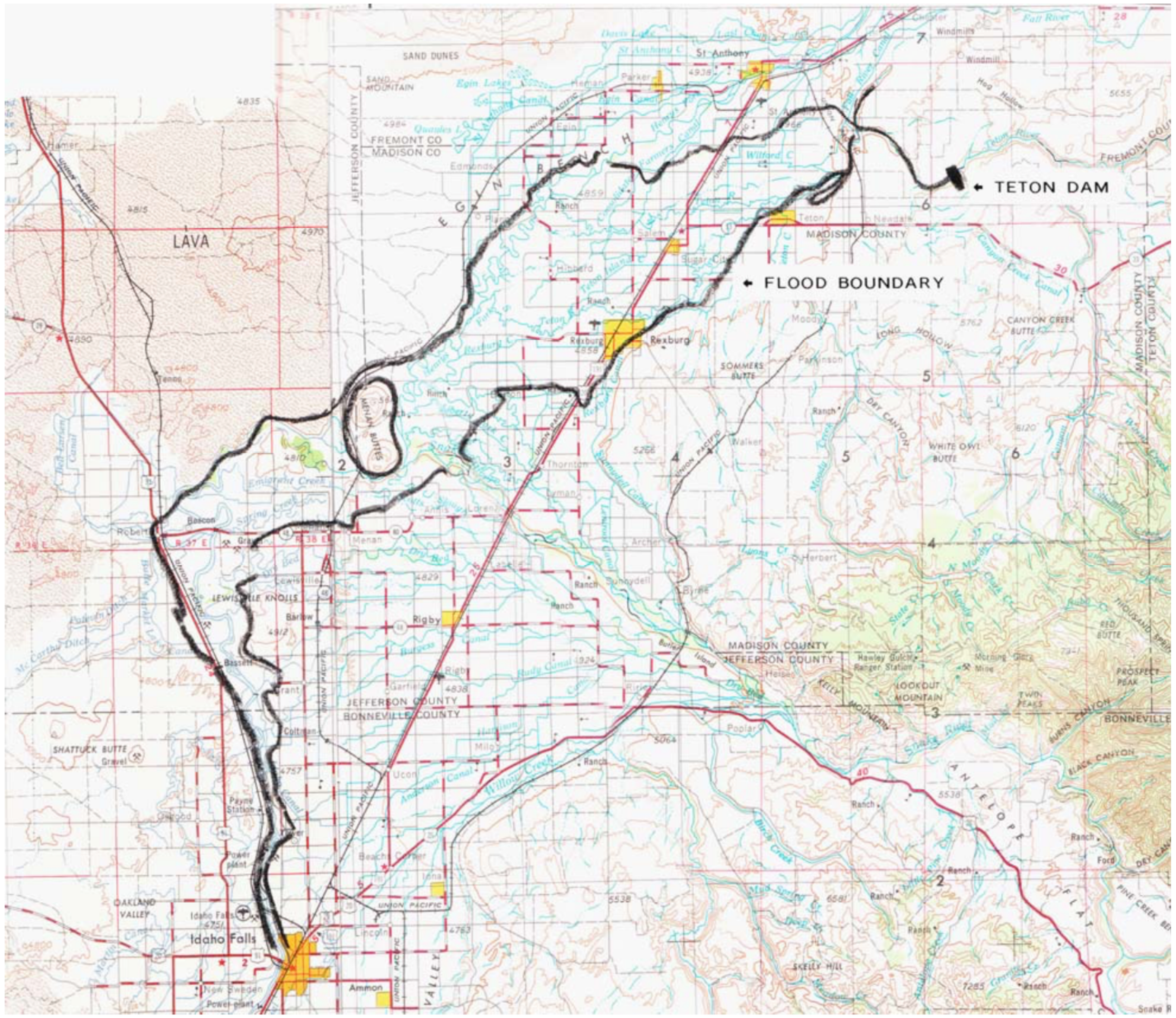


Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

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

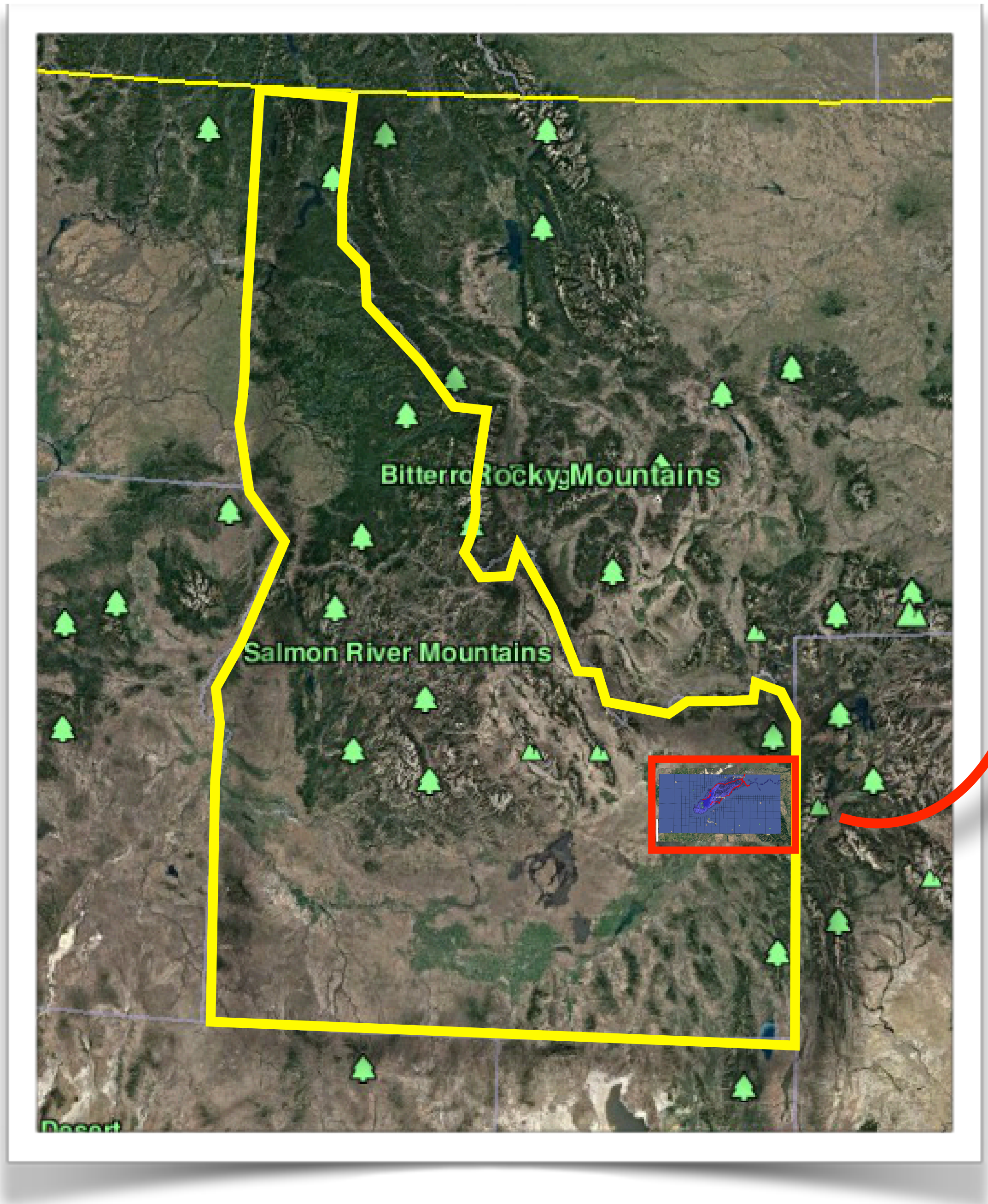
Numerical parameters

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

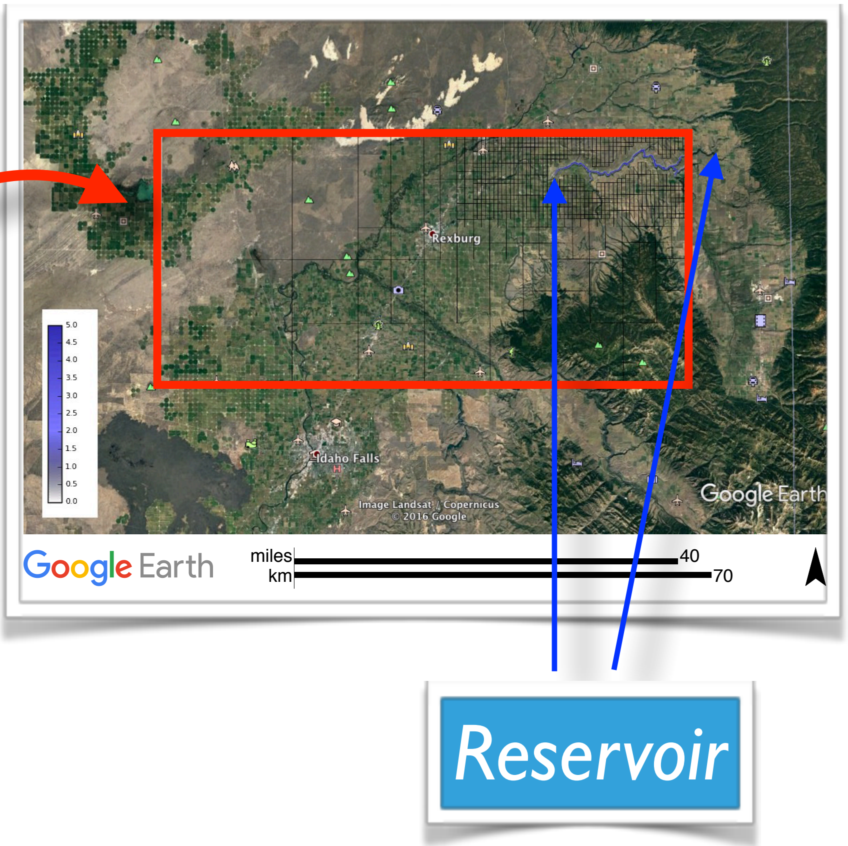
Platform

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

Teton Dam Failure, June 5, 1976



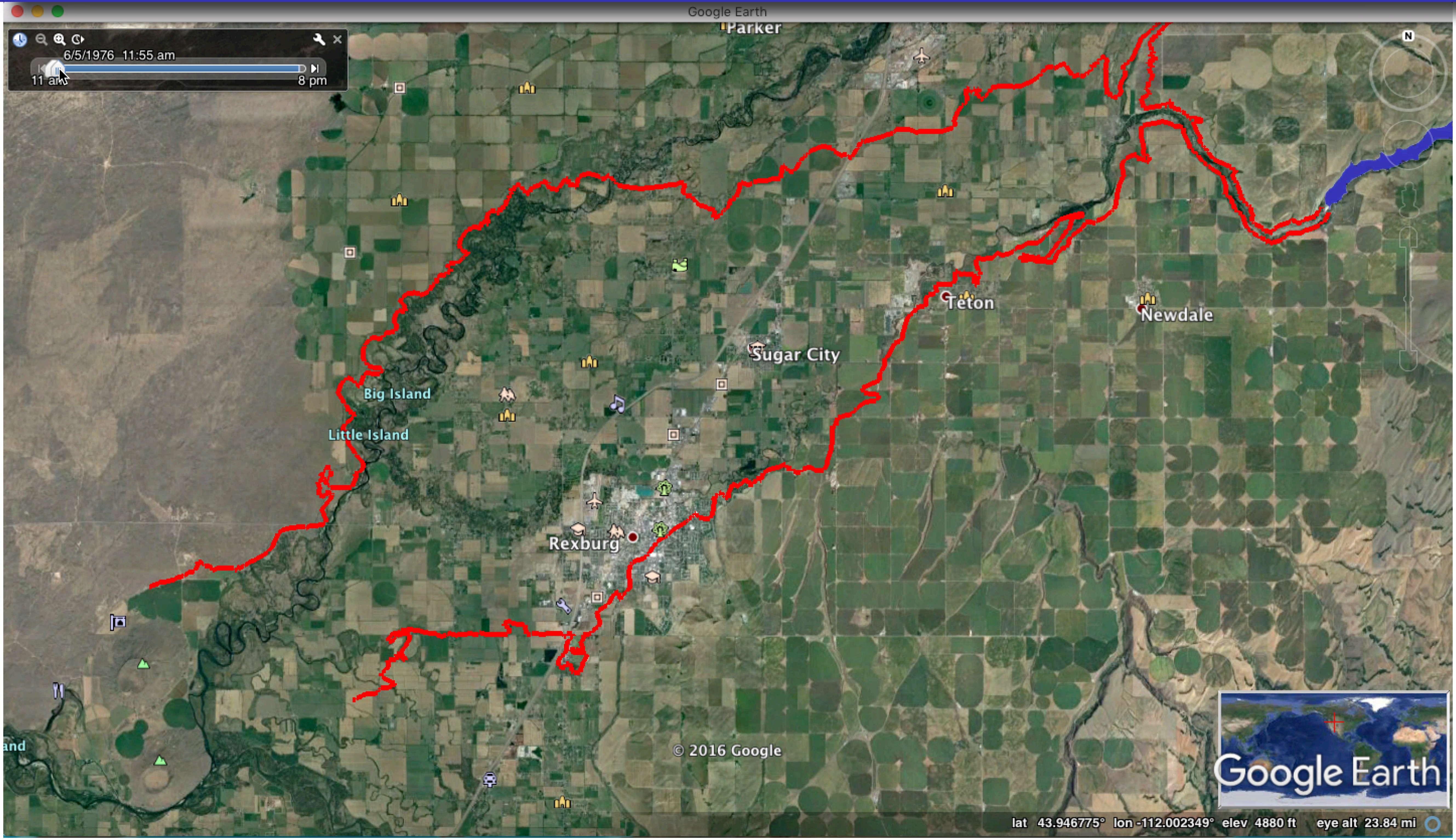
Computational Area : 88km x 42km



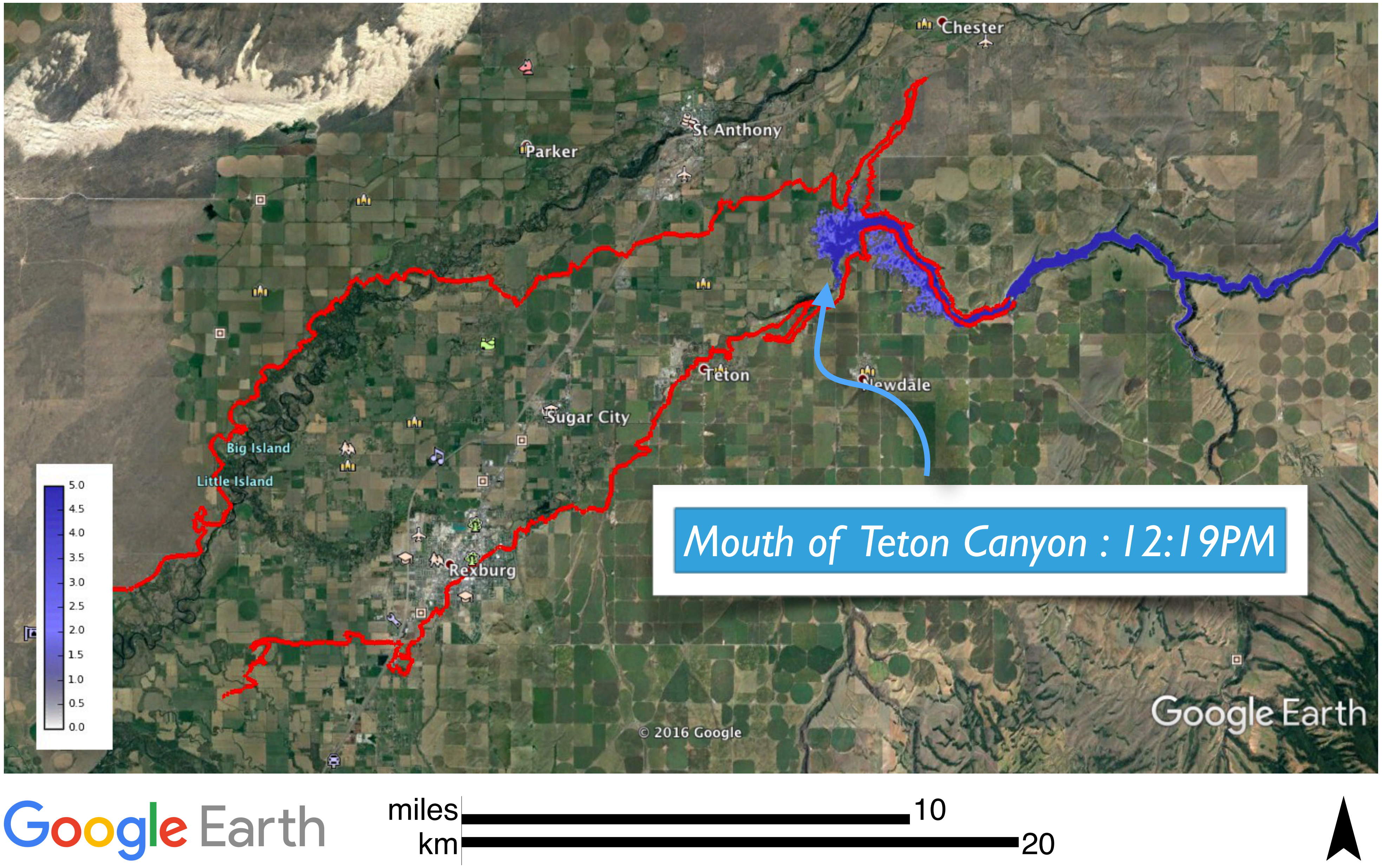
Reservoir

~10m resolution : ~8192 x 4096 effective resolution

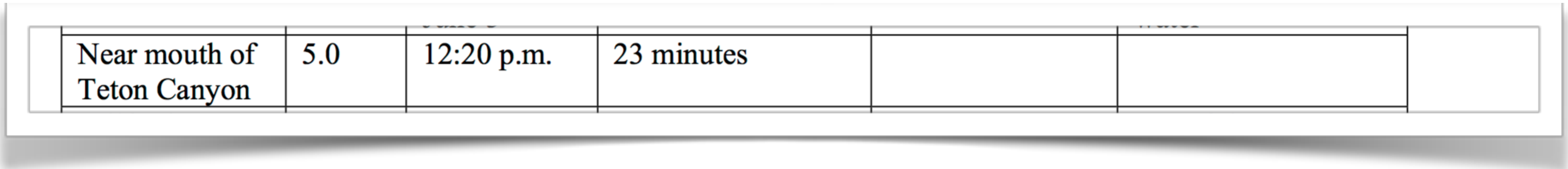
Simulation results



Simulation results

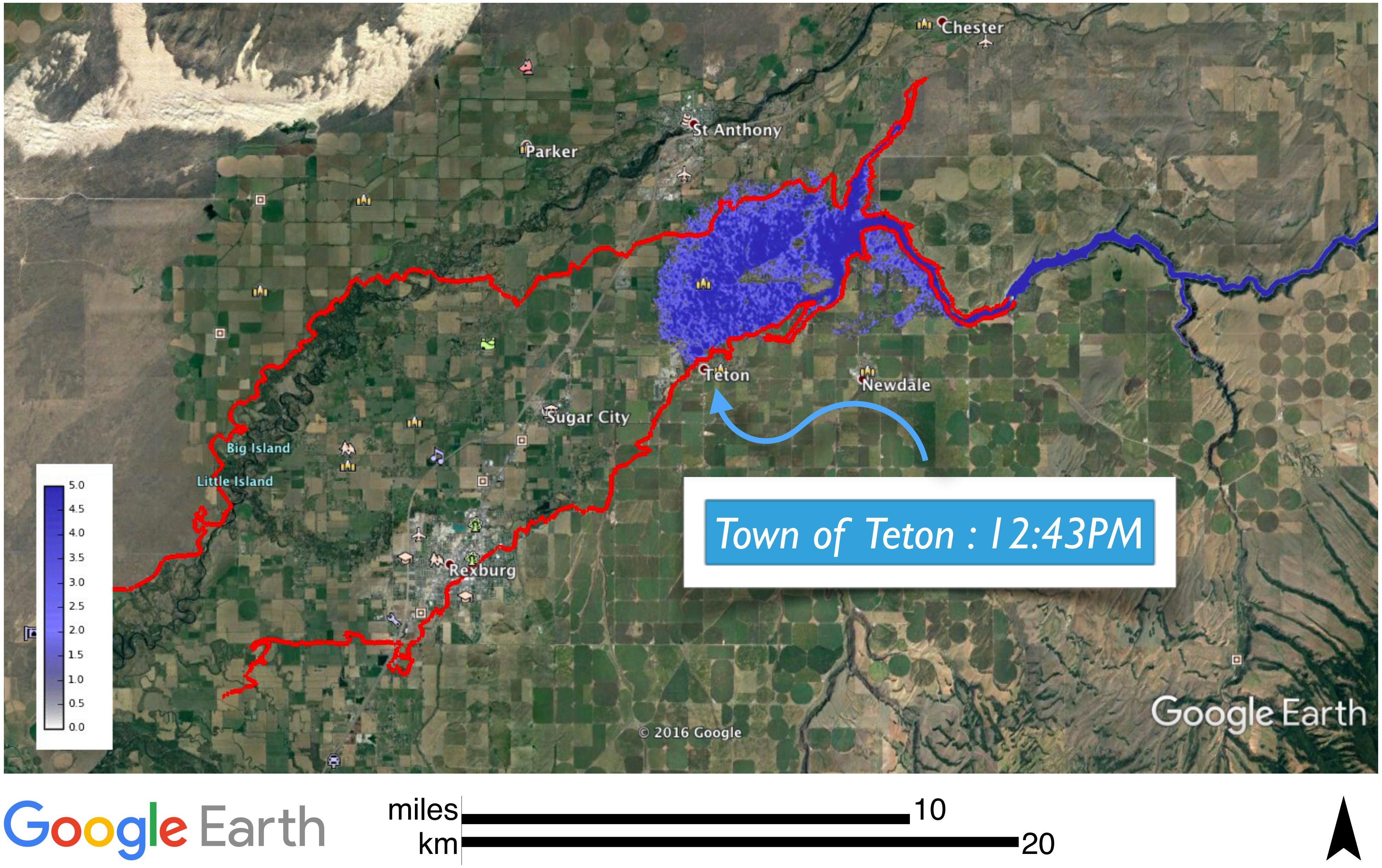


Mouth of Teton Canyon : 12:19PM



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

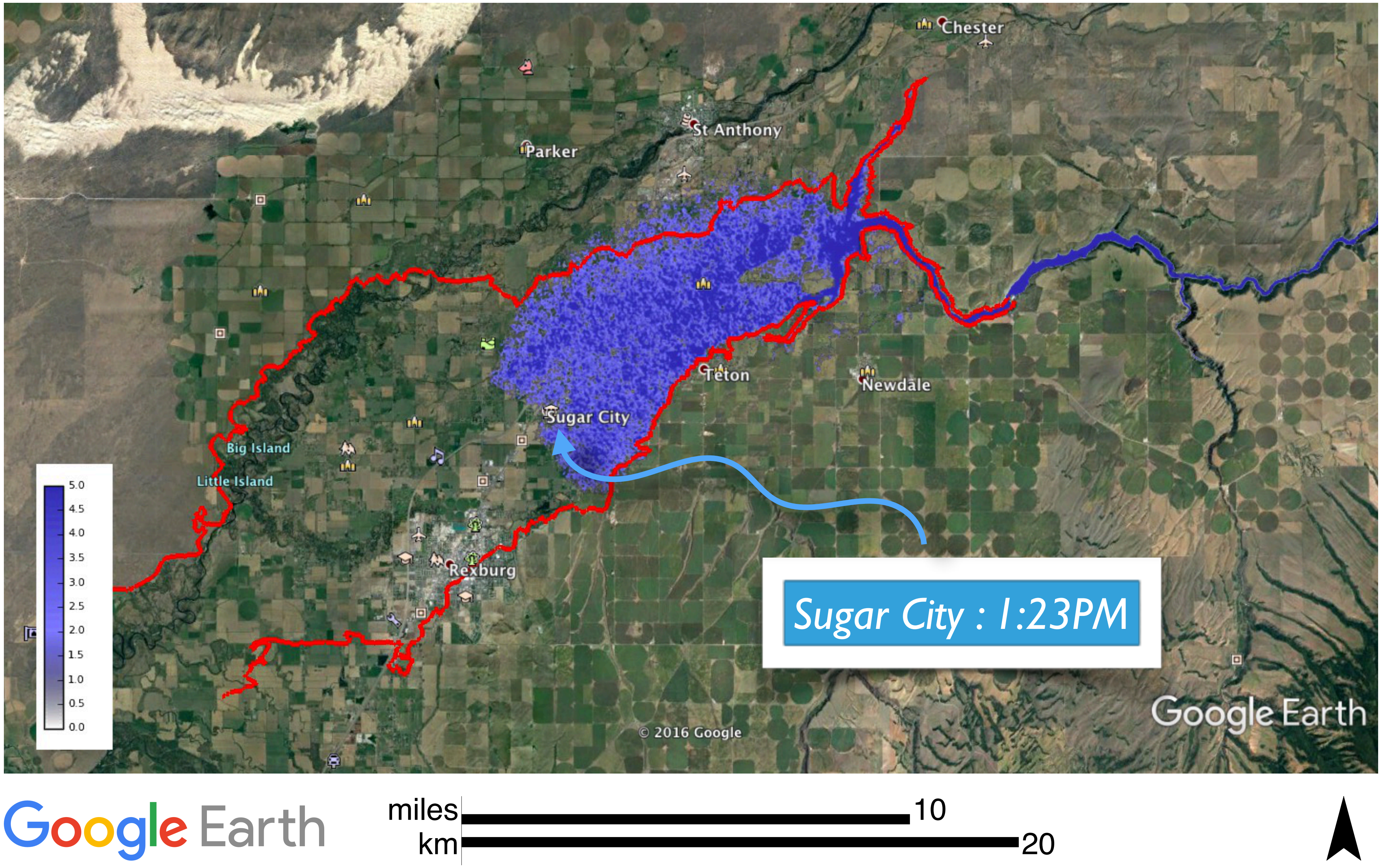
Simulation results



Town of Teton : 12:43PM

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

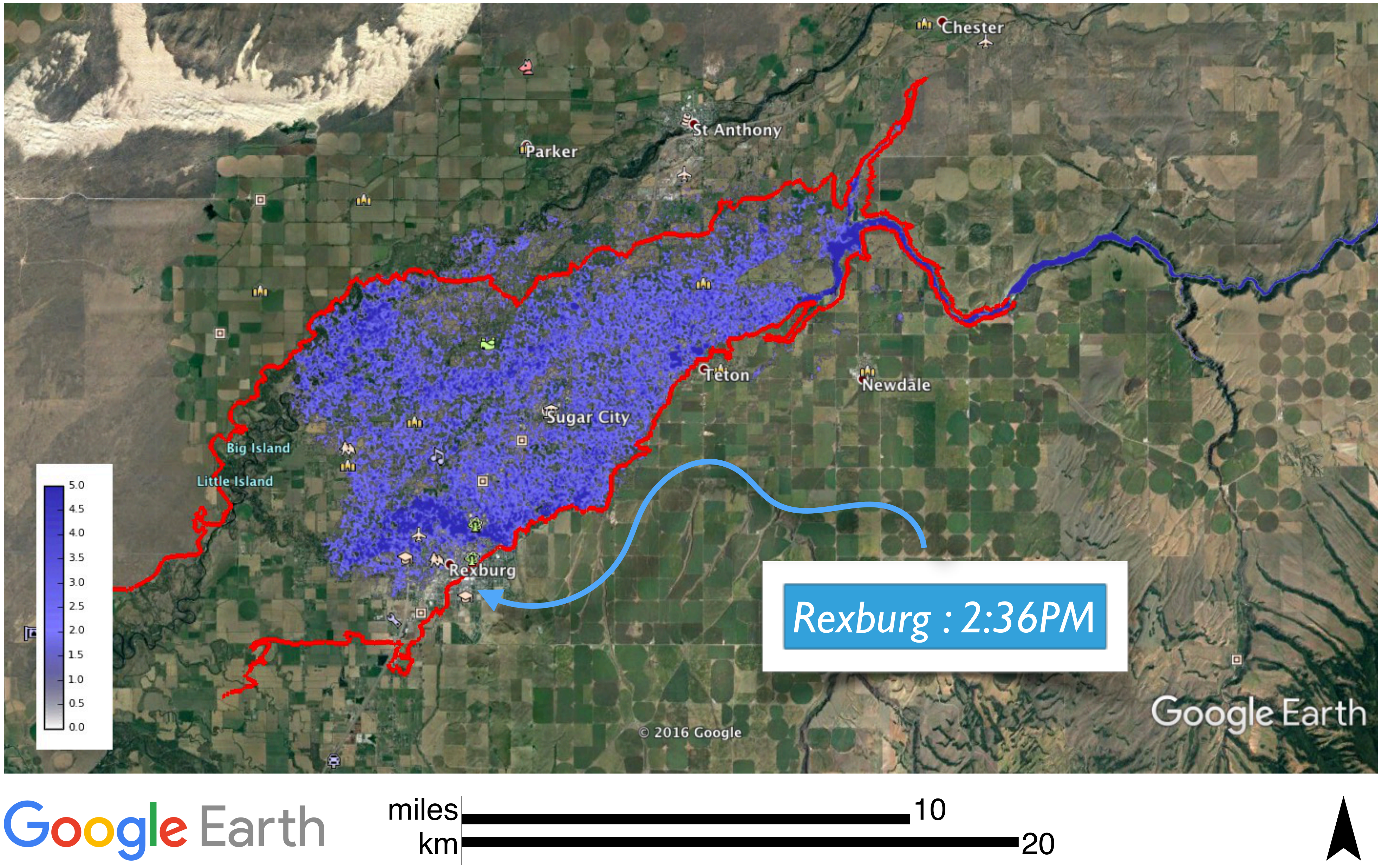
Simulation results



Sugar City : 1:23PM

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

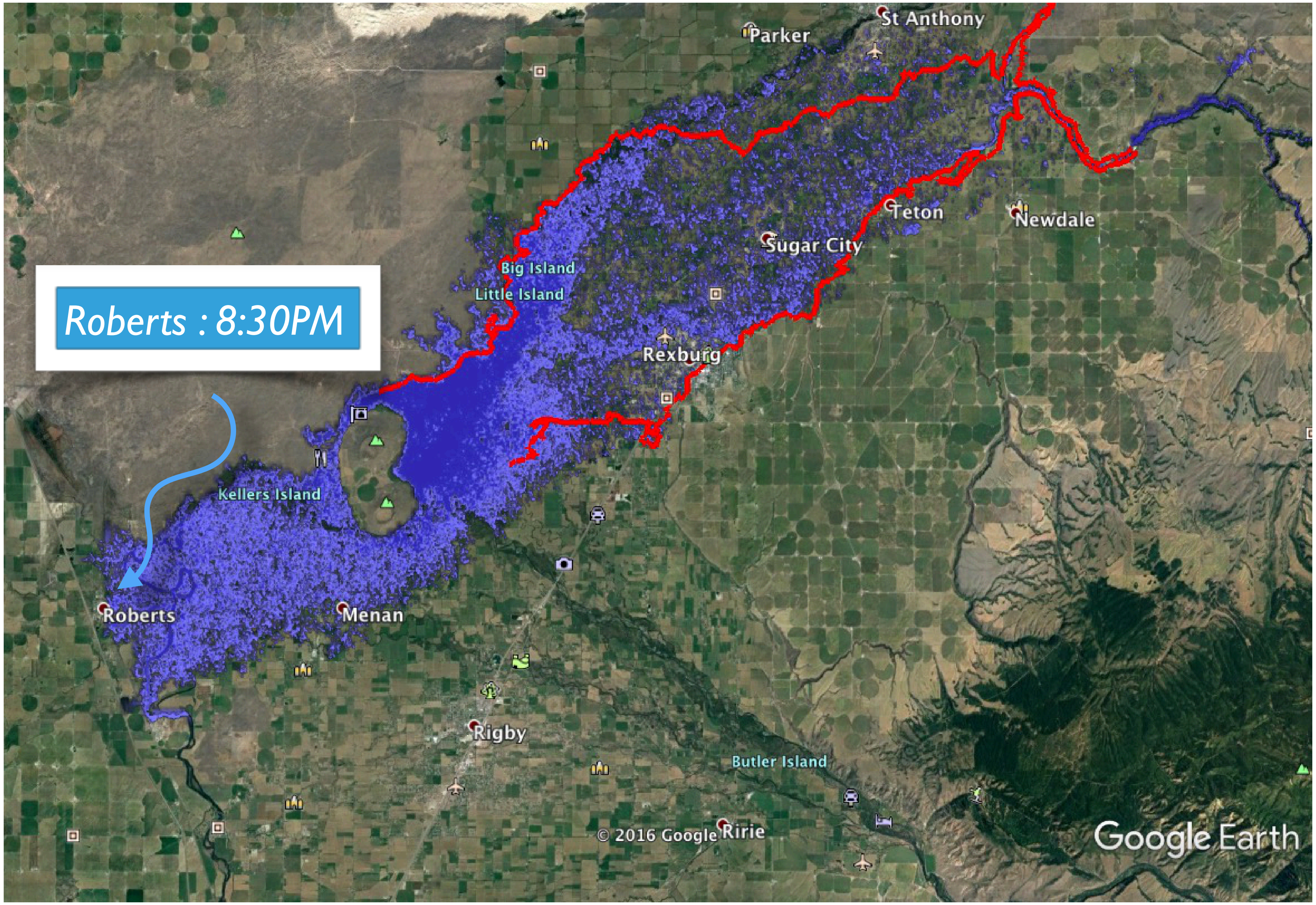
Simulation results



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 : 8:30PM

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

Simulation results

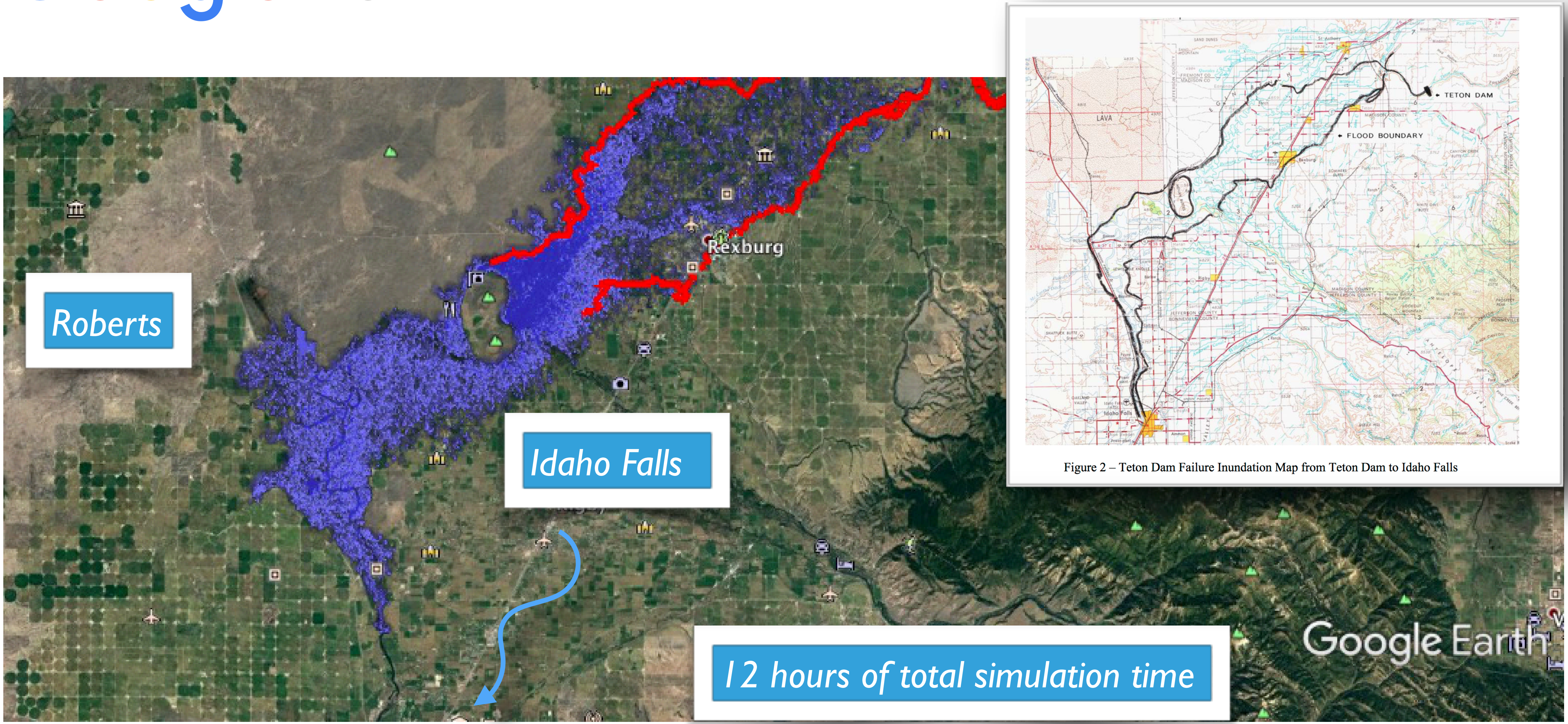
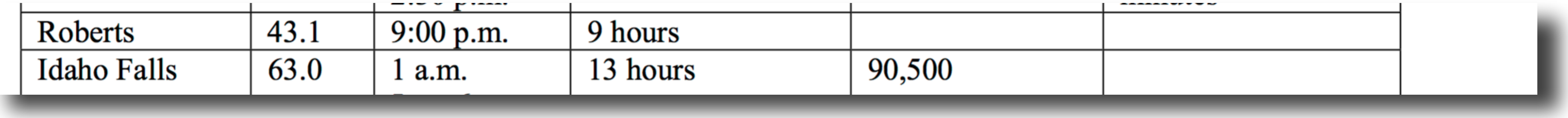


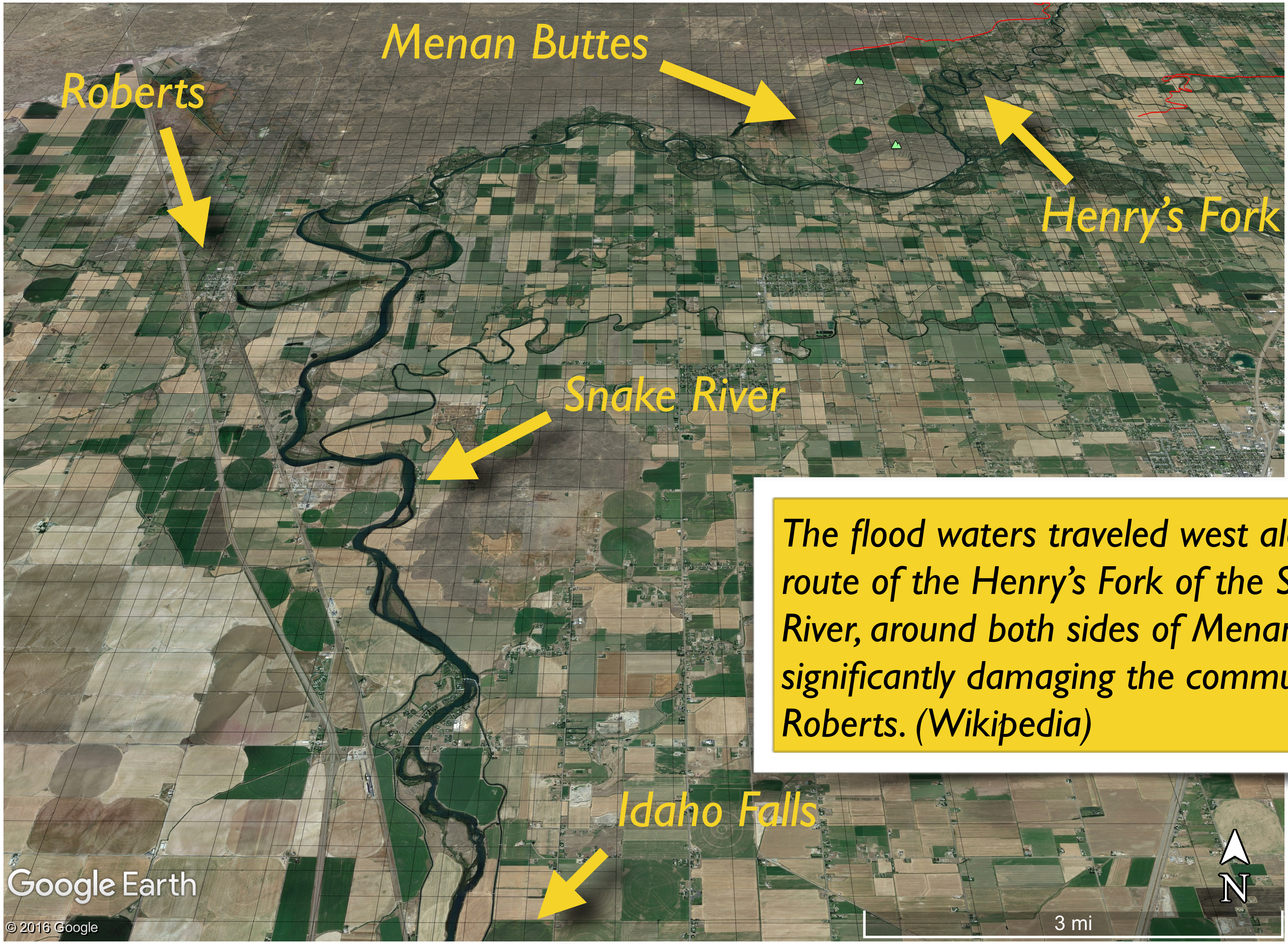
Figure 2 – Teton Dam Failure Inundation Map from Teton Dam to Idaho Falls

Level 0



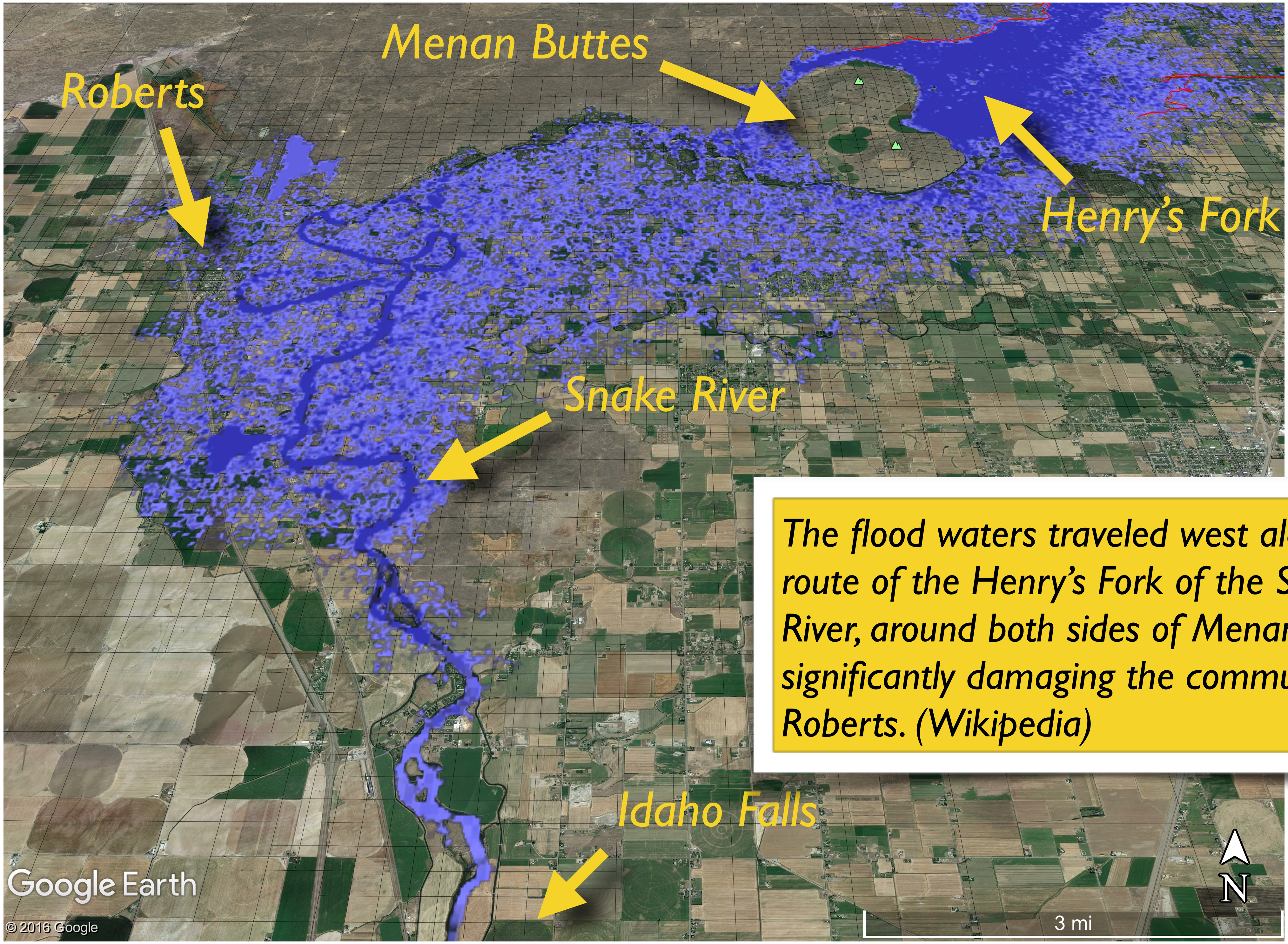
Roberts	43.1	9:00 p.m.	9 hours		
Idaho Falls	63.0	1 a.m.	13 hours	90,500	

Snake River



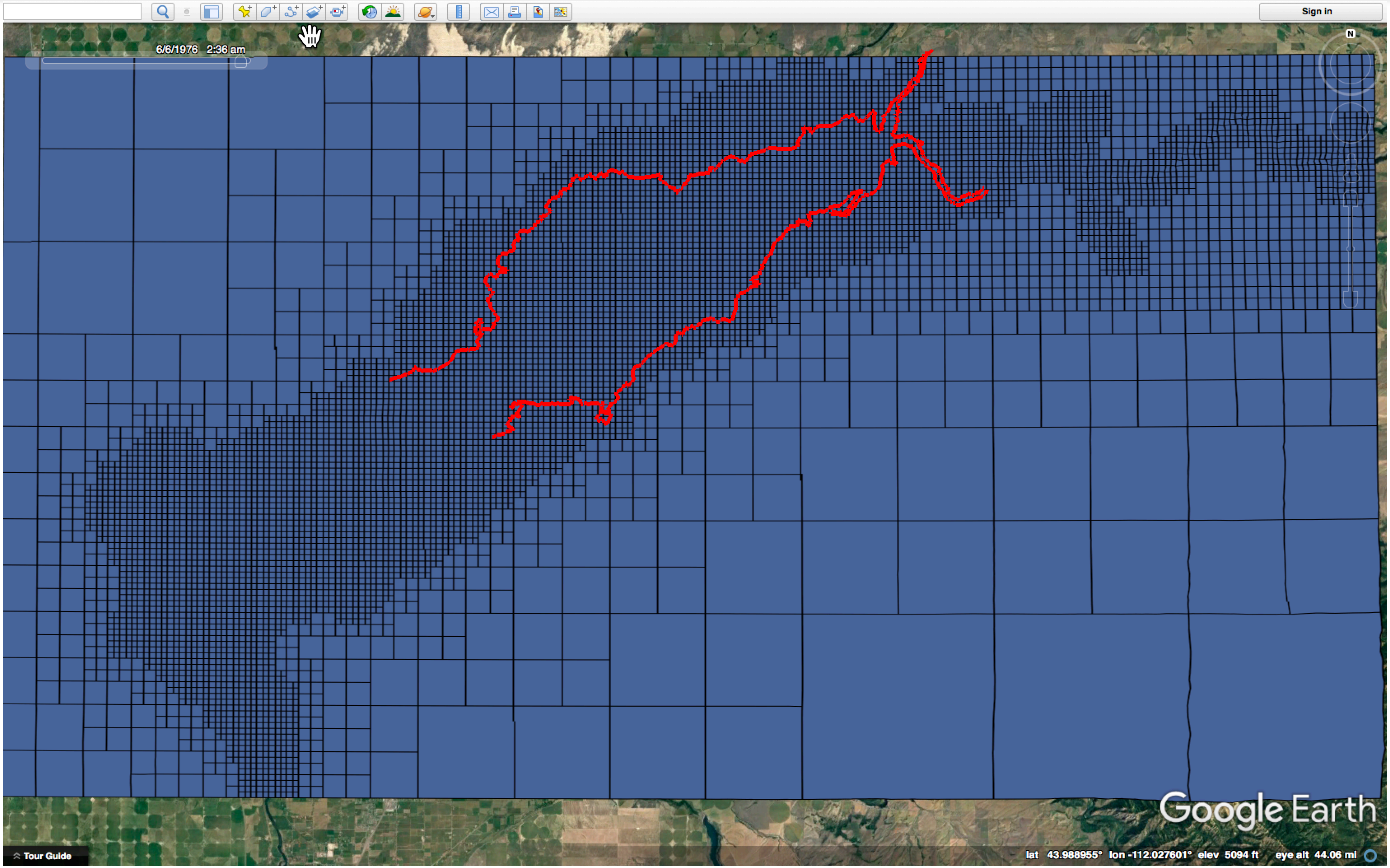
The flood waters traveled west along the route of the Henry's Fork of the Snake River, around both sides of Menan Buttes, significantly damaging the community of Roberts. (Wikipedia)

Snake River

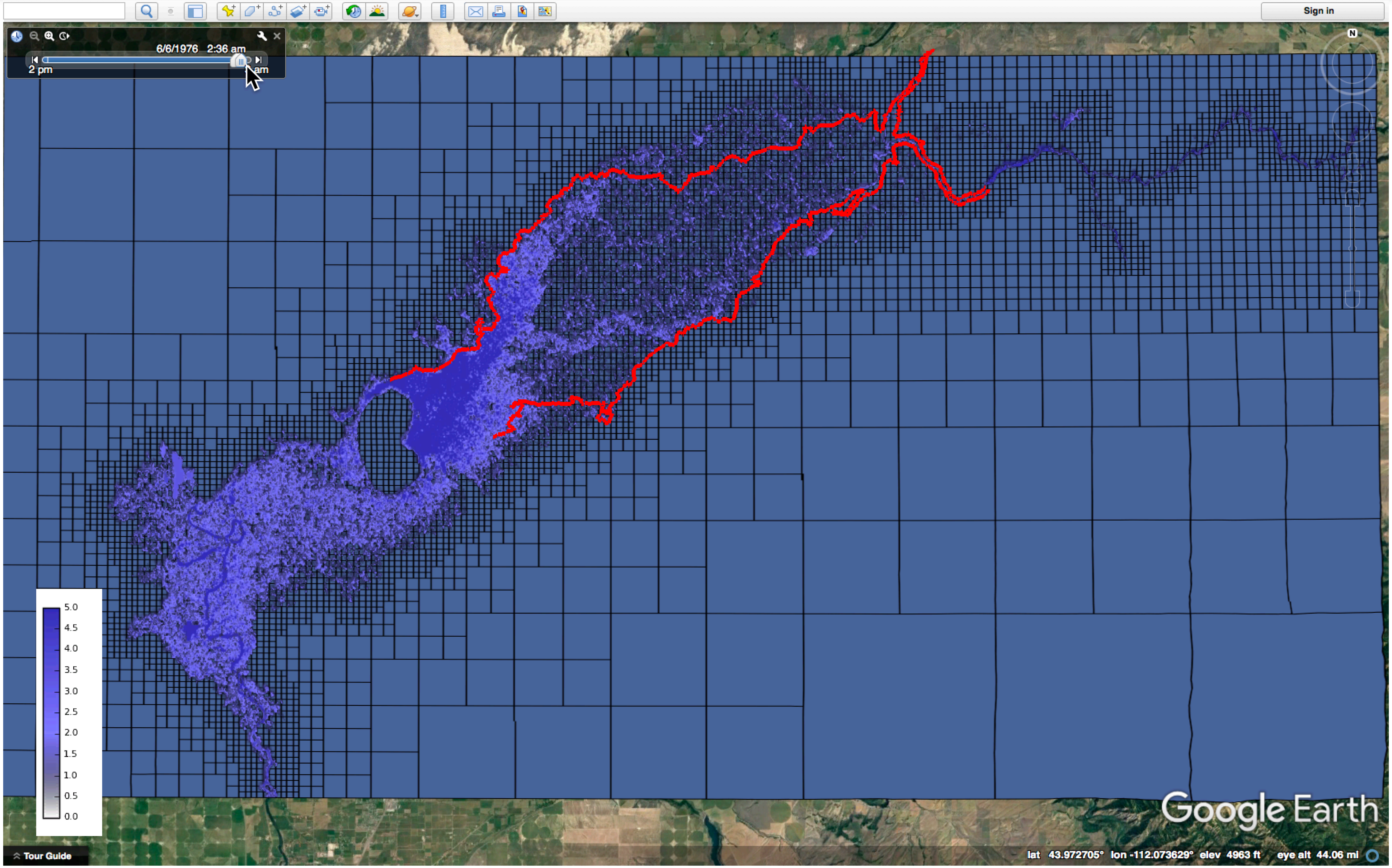


The flood waters traveled west along the route of the Henry's Fork of the Snake River, around both sides of Menan Buttes, significantly damaging the community of Roberts. (Wikipedia)

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?

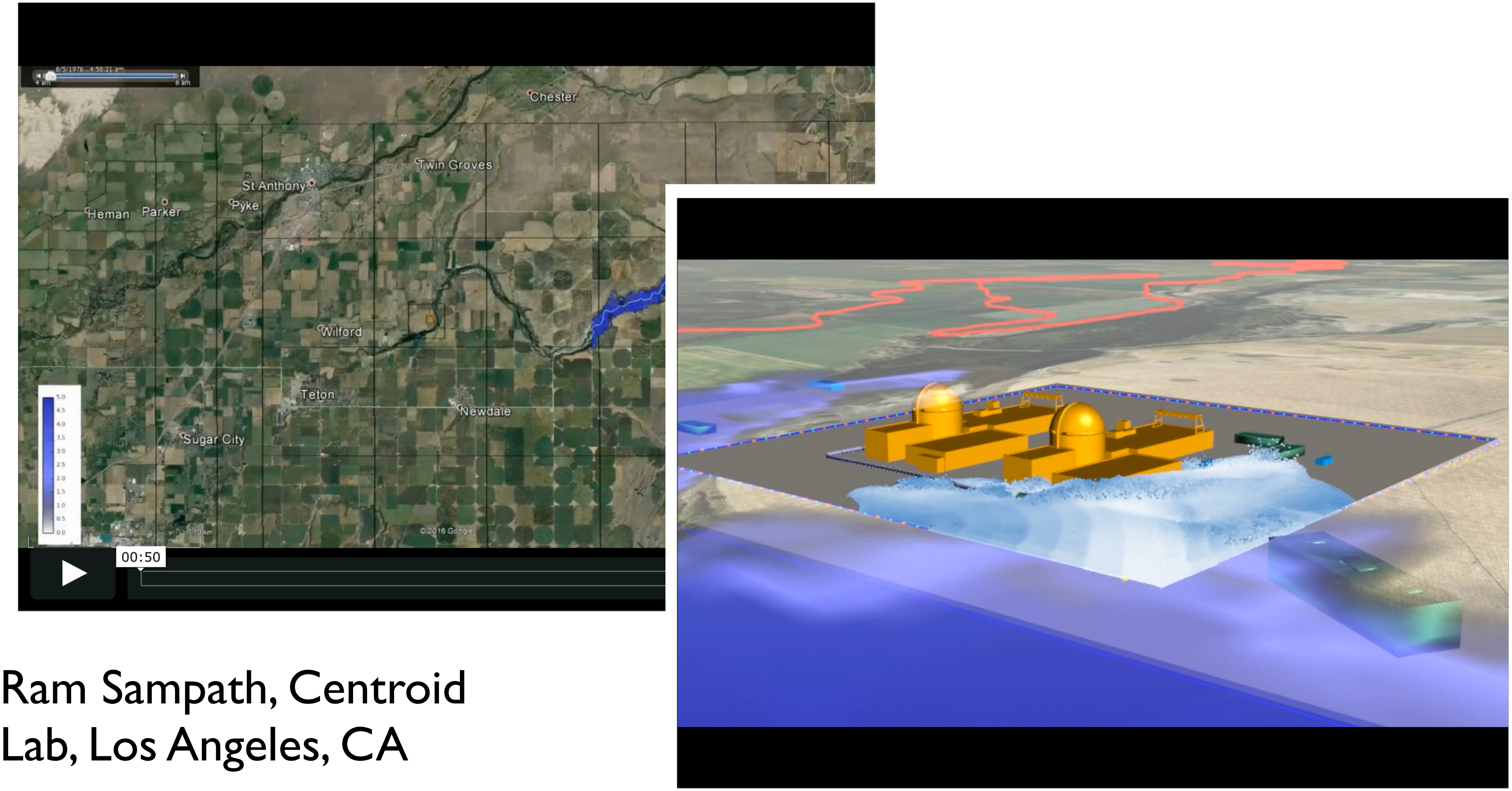
- Better modeling of dam failure to get initial outflow correct
- Use numerical "gauges" to compare with historical depth records
- Multi-rate time stepping (tricky with SWE, since wave speed depends on depth)
- Other dam failure scenarios, i.e. Malpassat, France.

Future?

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

Interested students are always welcome!

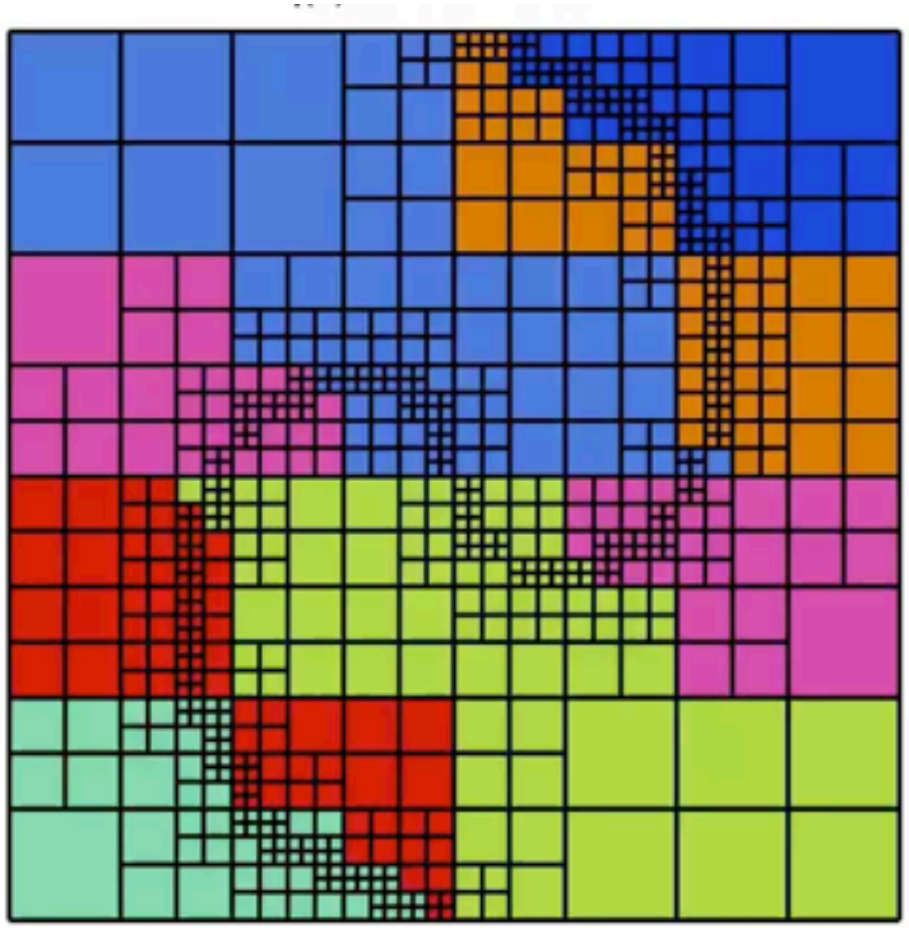
Teton Dam Failure, June 5, 1976



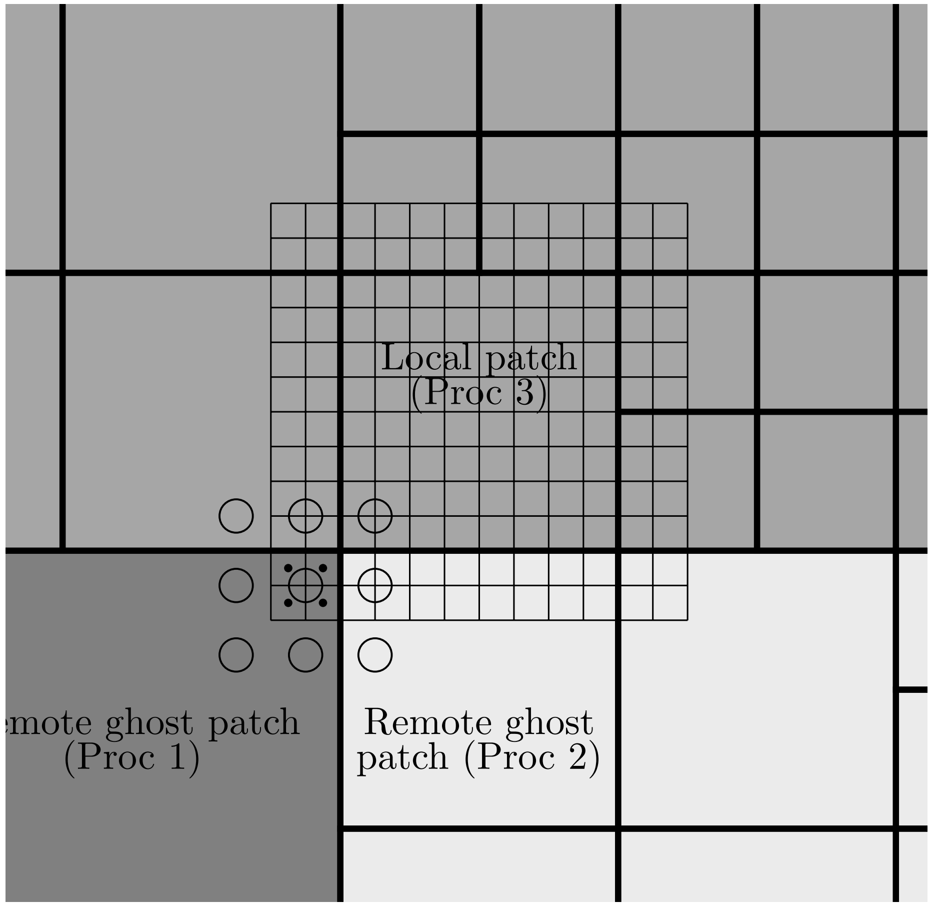
Ram Sampath, Centroid Lab, Los Angeles, CA

http://neutrinodynamics.com//portfolio-riverflood.html

ForestClaw - Parallelism



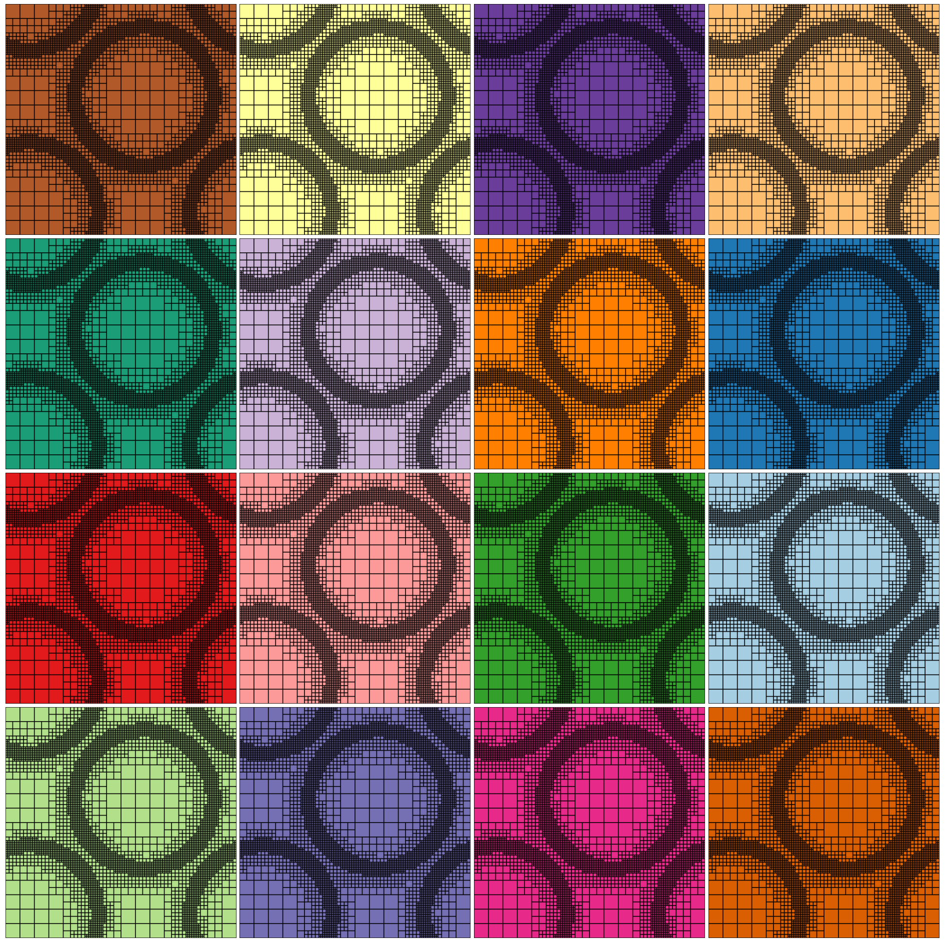
p4est : Load balancing using a space filling curve



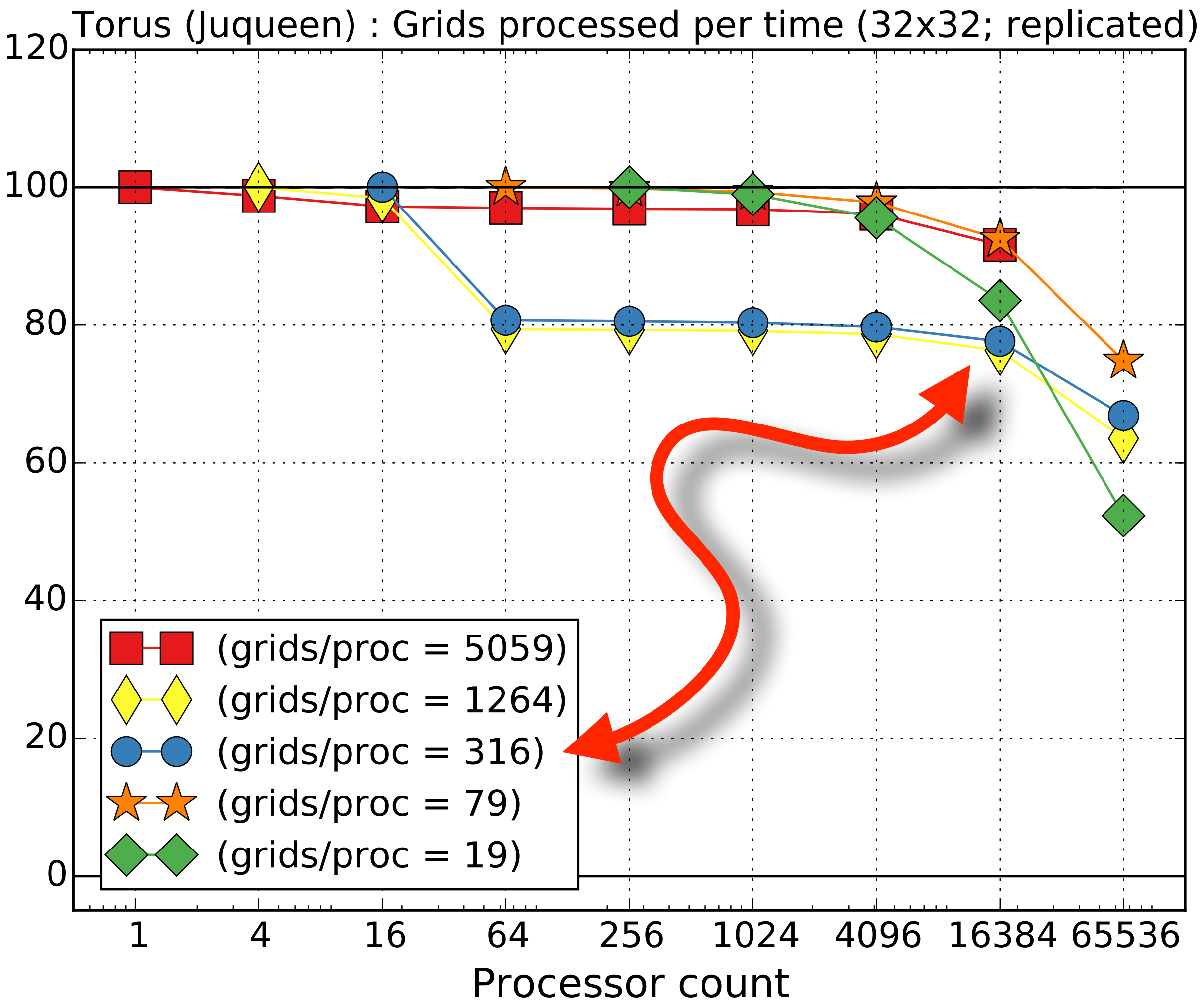
Fine grid corner ghost cells at corners where 3 or more processors meet

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)



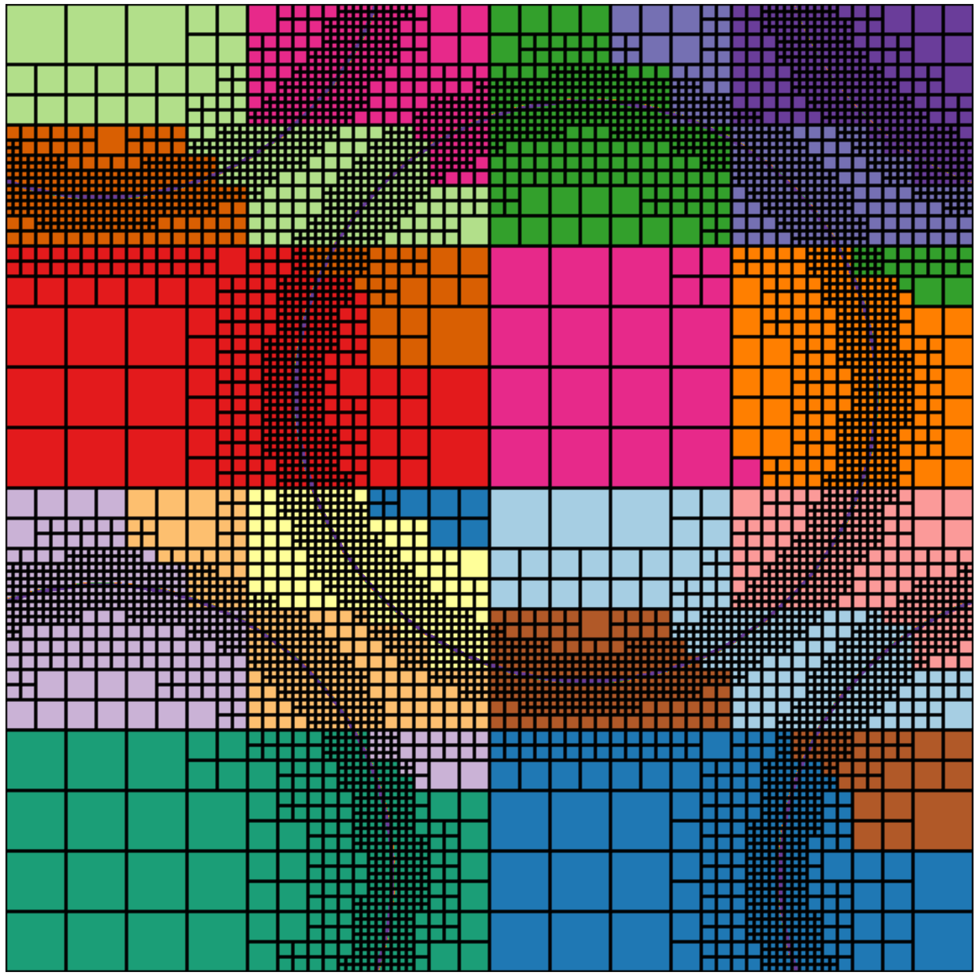
Scalar advection on replicated domain using 32x32 patches



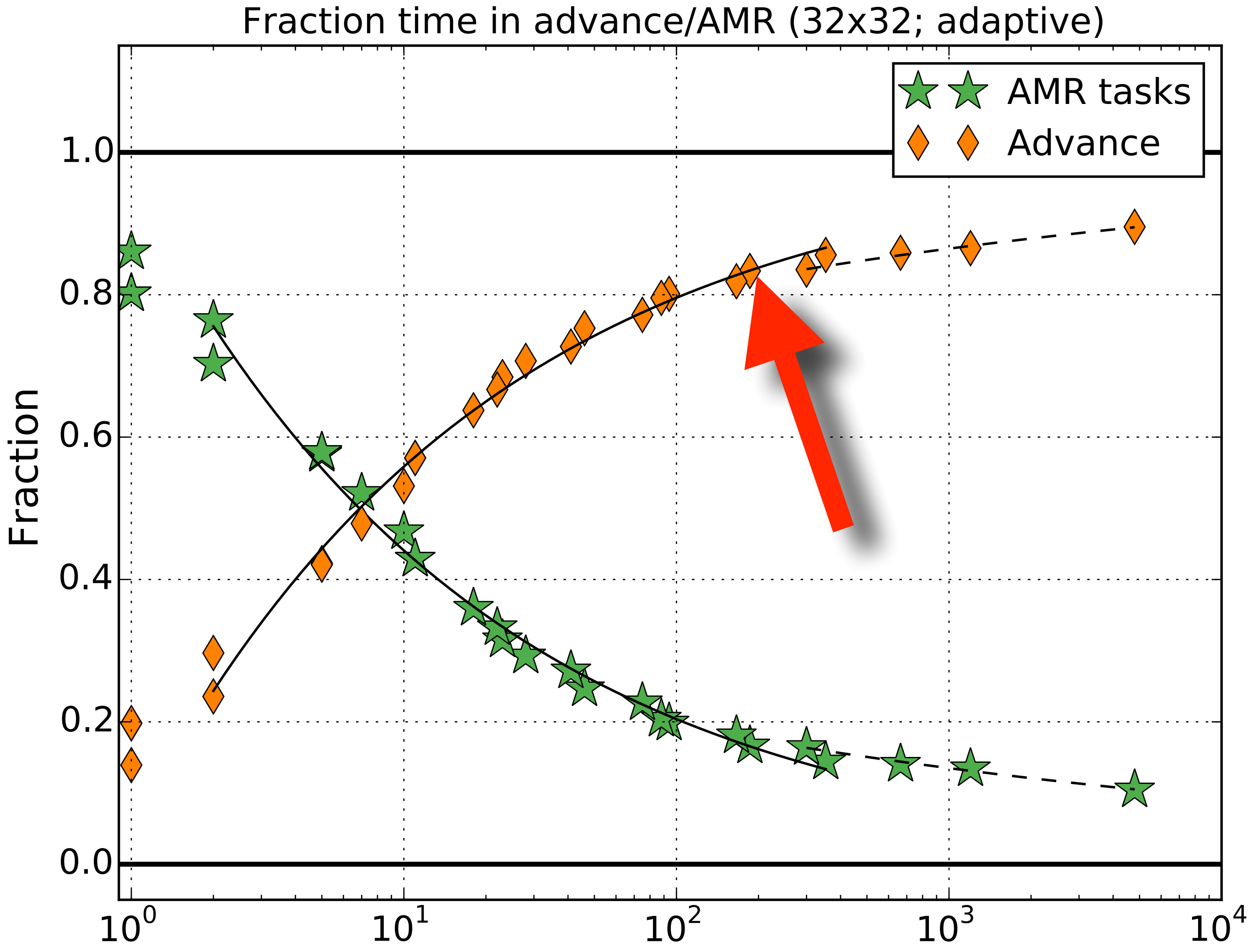
90% (or better) efficiency at 16K cores

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)