Modelling river flood risk for the whole continental US

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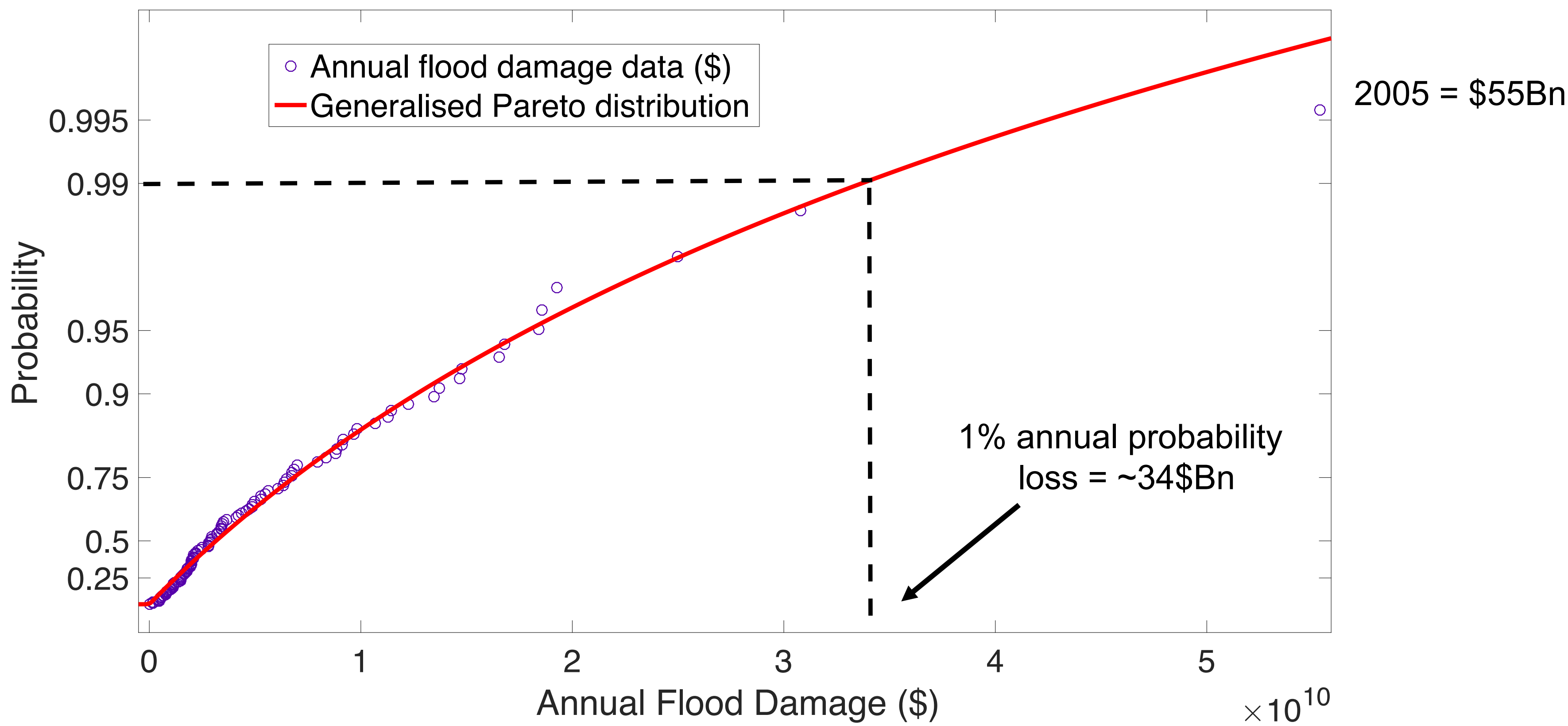
(With lots and lots of help from Niall Quinn, Chris Sampson, Andy Smith, Ollie Wing and Jeff Neal)

www.fathom.global

The problem – US flood river risk

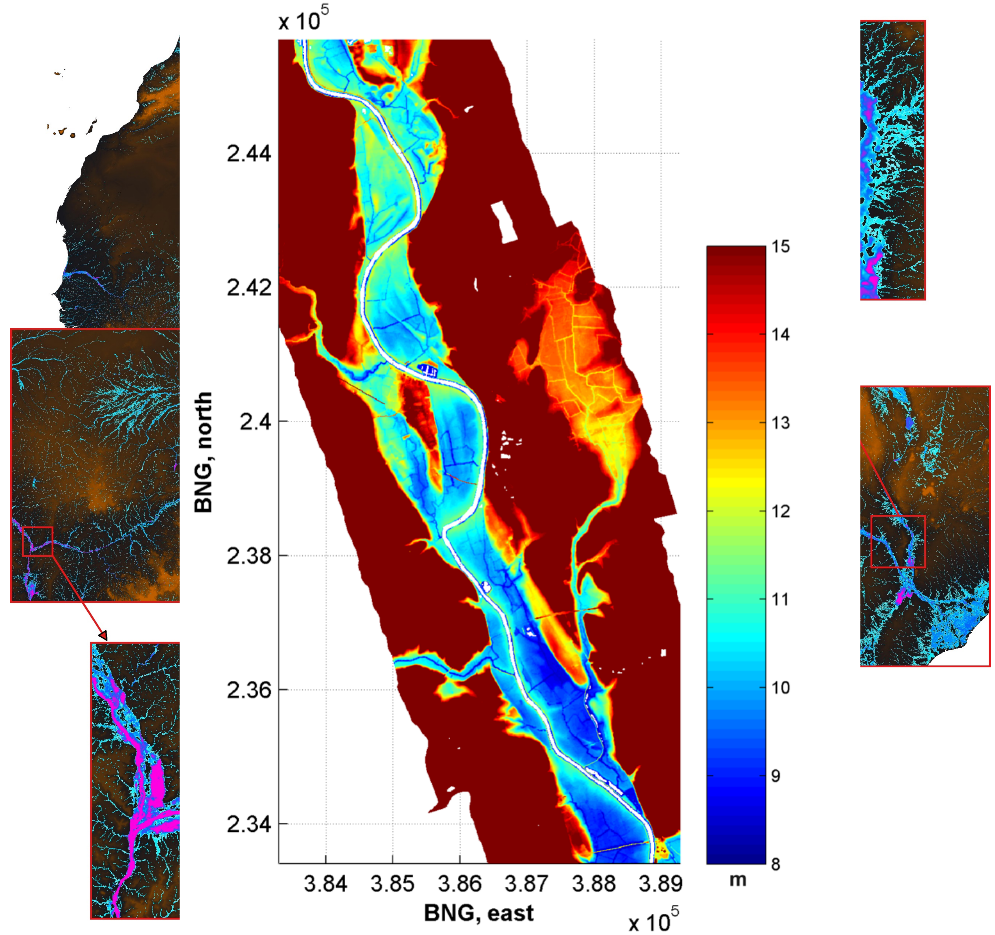
- **Substantial losses each year**
  - Average annual damage 1903-2014 = ~$5Bn
    - (NWS data for river flood, not including coastal events, actual losses at 2014 prices)
  - ~100 fatalities a year on average, with no trend over the same time
  - Significant social disruption
- **National Flood Insurance Programme costs $190M p.a. and is $25Bn in debt**
- **Recent events have raised public awareness of the issue**

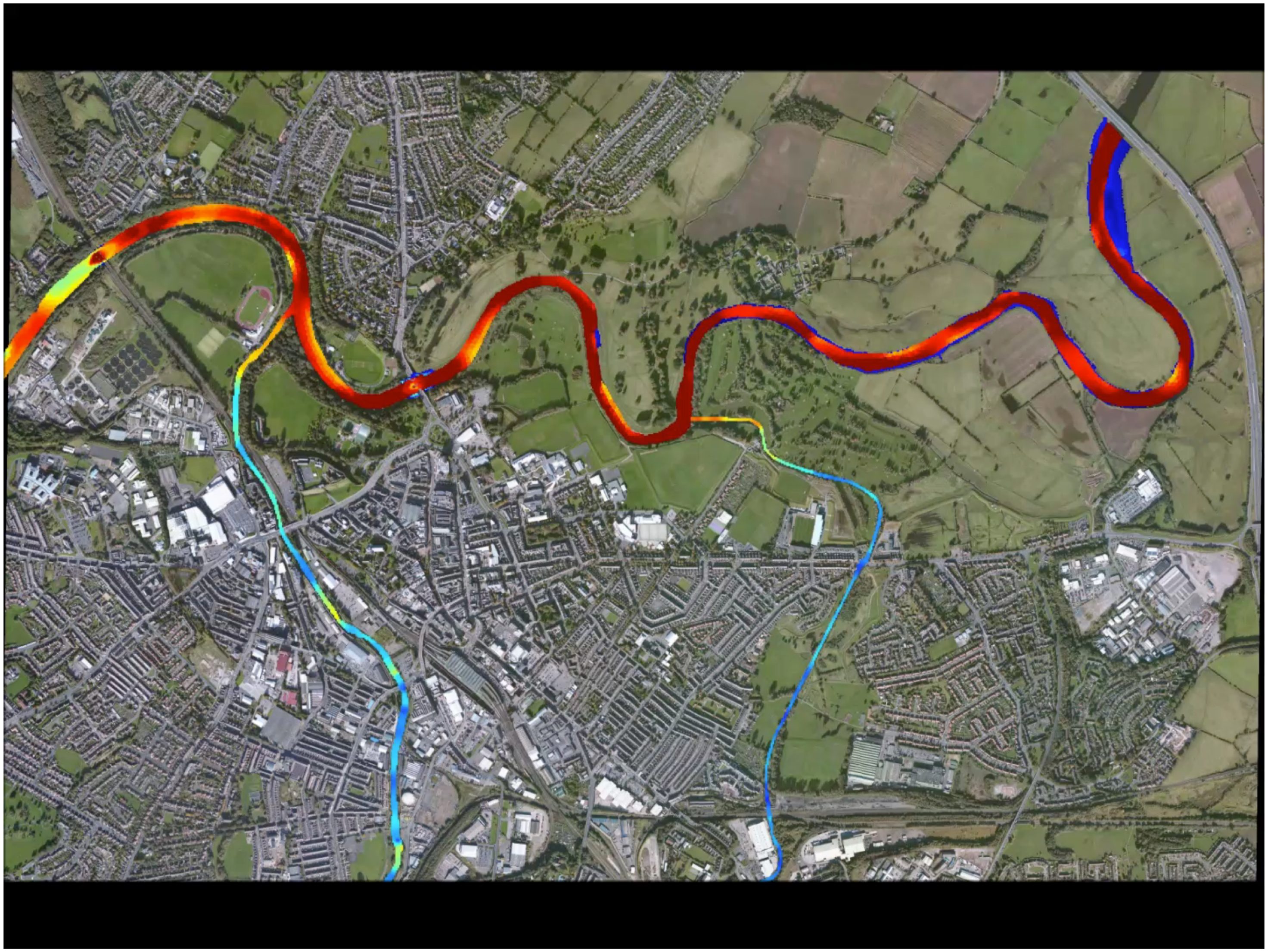
US Flood losses – National Weather Service data



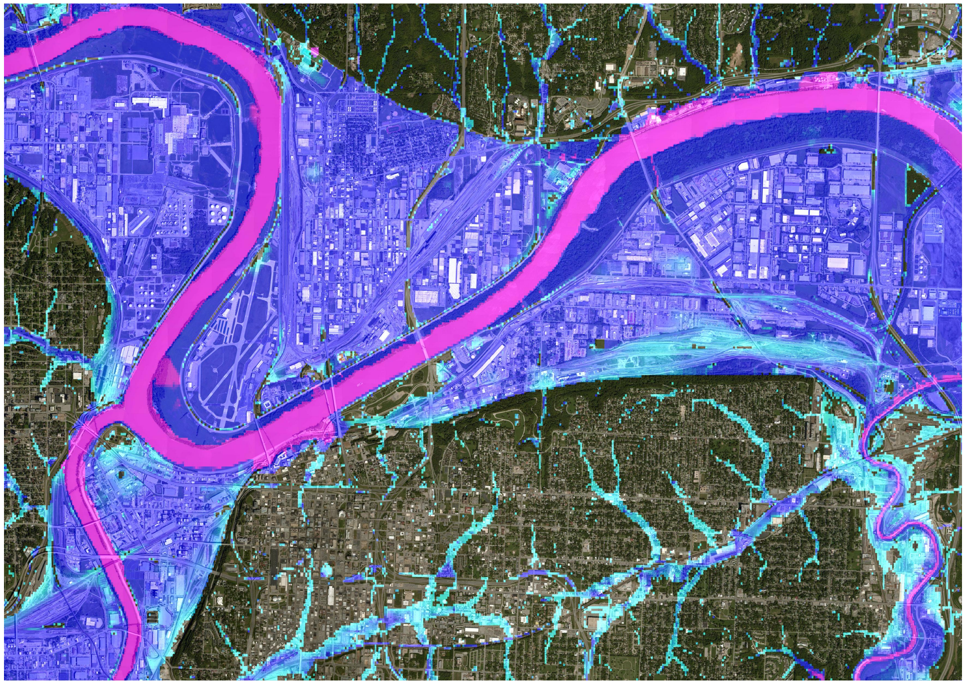
Flood modelling

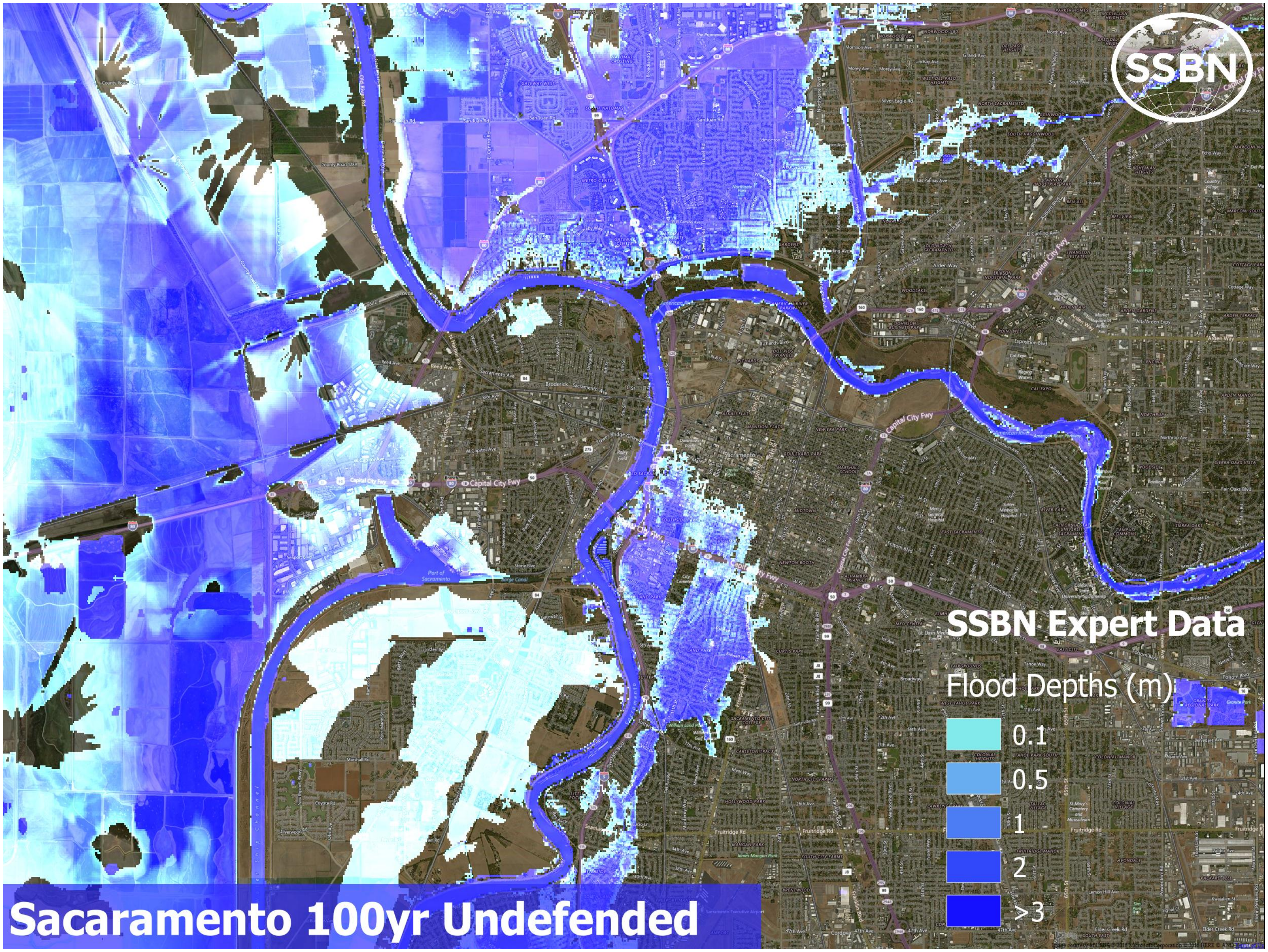
- Over the last 20 years remote sensing has revolutionized flood modelling
  - From early work at reach scales with LiDAR data ….
  - to global data sets enabling continental and global models at <100m resolution

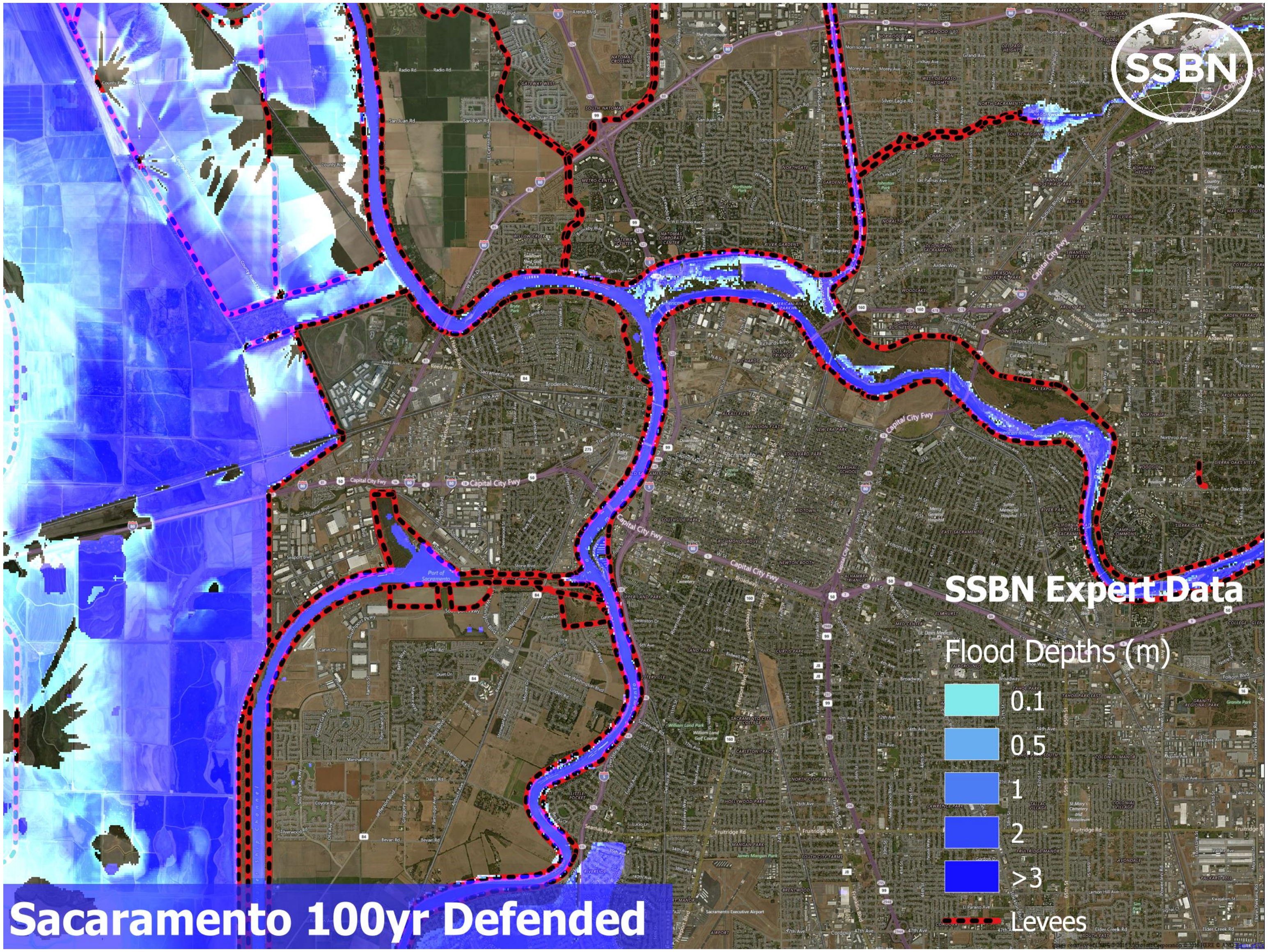




- Whole US model
  - DEM from US National Elevation Dataset (NED)
  - 30m resolution
  - All river channels explicitly represented
  - Boundary conditions from regional flood frequency analysis of rainfall and flow
  - Includes US Army National Levee Dataset
  - 10 return periods from 5 to 1000 years




SSBN
SSBN Expert Data
Flood Depths (m)
0.1
0.5
1
2
>3
Sacaramento 100yr Undefended
Capital City Fwy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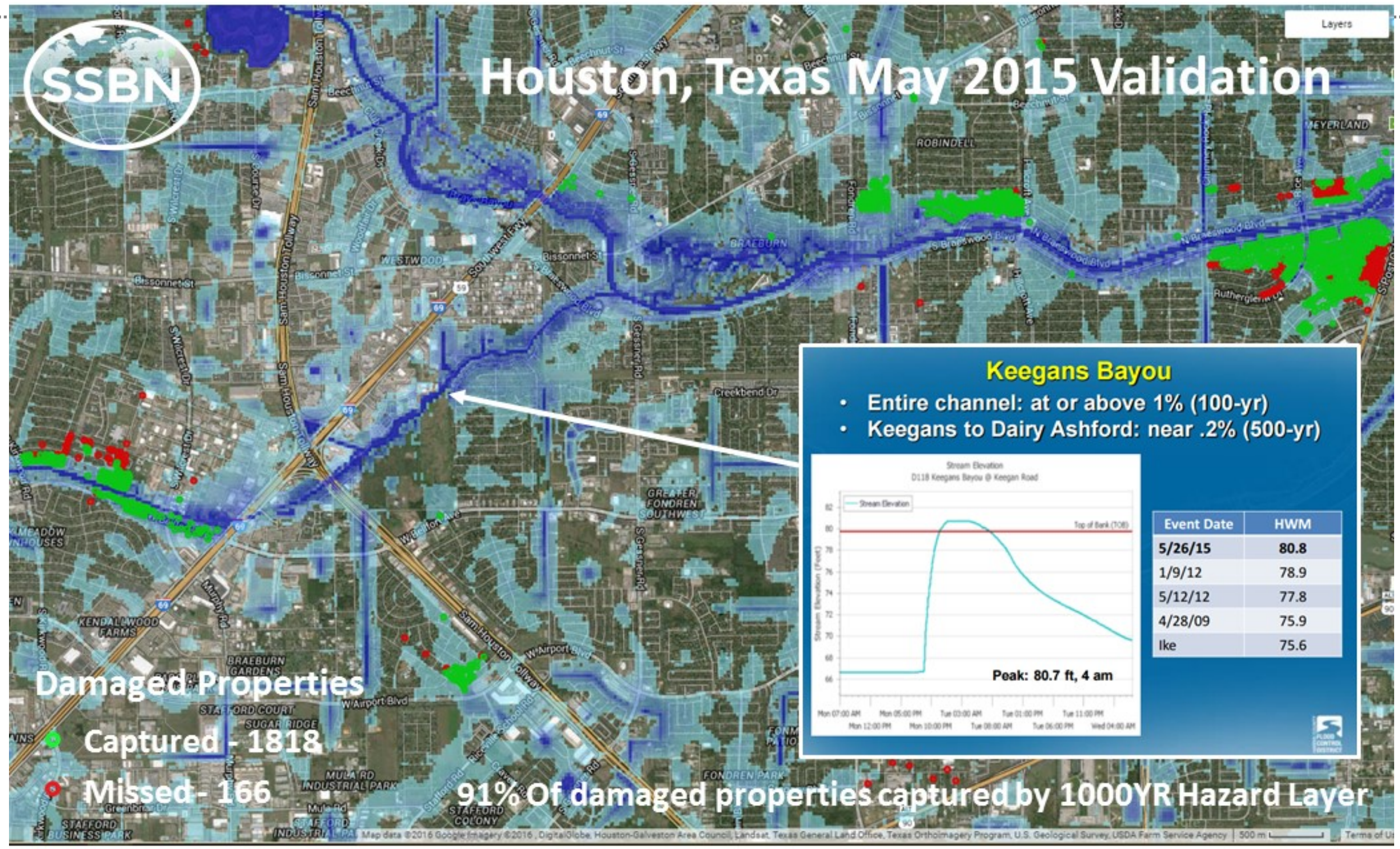
Validation – Memorial day, Houston 2015



- 1984 properties defined as being inundated with flood waters.
- Event magnitude estimates range from 100-500 year event depending on exact location.
- Hit rate of 70% and 91% for the 100 year and 1000 year hazard layers respectively.

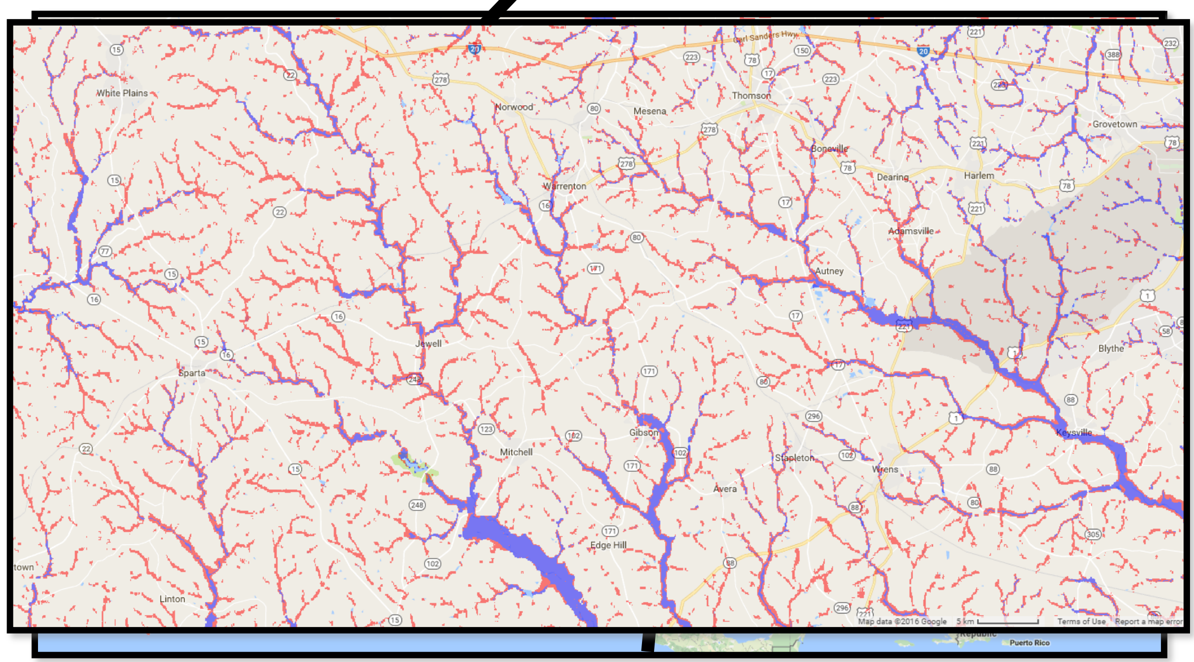
Layer	Captured	Missed	Hit Rate %
20YR	683	1301	34
100YR	1391	593	70
1000YR	1818	166	91

100-500YR observed event magnitude

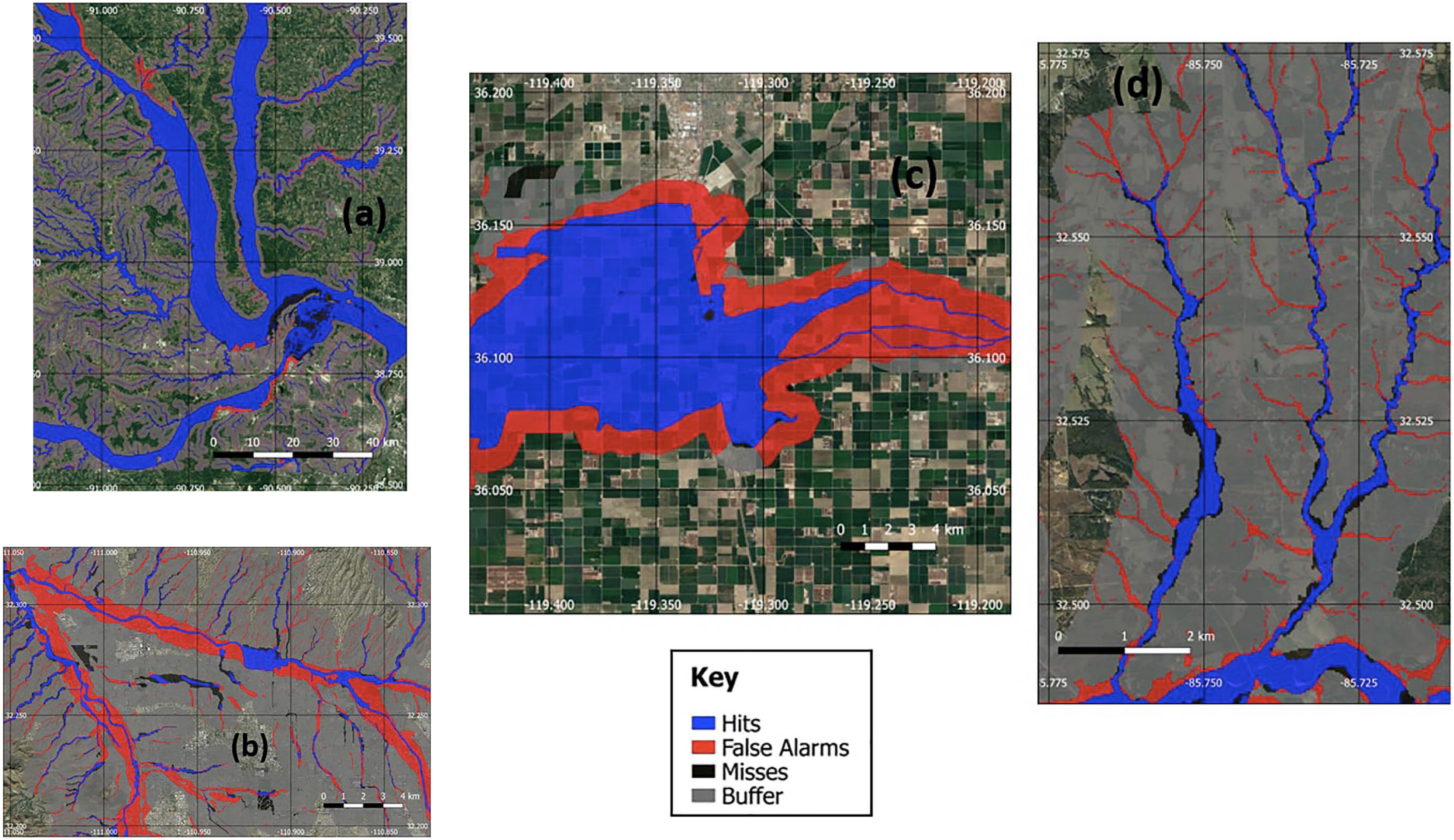
Global model validation: FEMA

- An amalgamation of local studies carried out by FEMA to determine the 1 in 100-year flood extent
- Re-sampled to 90m resolution
- Unexamined areas: both declared and undeclared
- Lack of headwater area coverage problematic
- Analysis performed in Google Earth Engine

No data ?



Over prediction ?


(a)
0 10 20 30 40 km
(b)
0 1 2 3 4 km
(c)
-119.400 -119.350 -119.300 -119.250 -119.200
36.200
36.150
36.100
36.050
0 1 2 3 4 km
(d)
-85.750 -85.725
32.575
32.550
32.525
32.500
0 1 2 km
Key
Hits
False Alarms
Misses
Buffer

Global model validation: FEMA

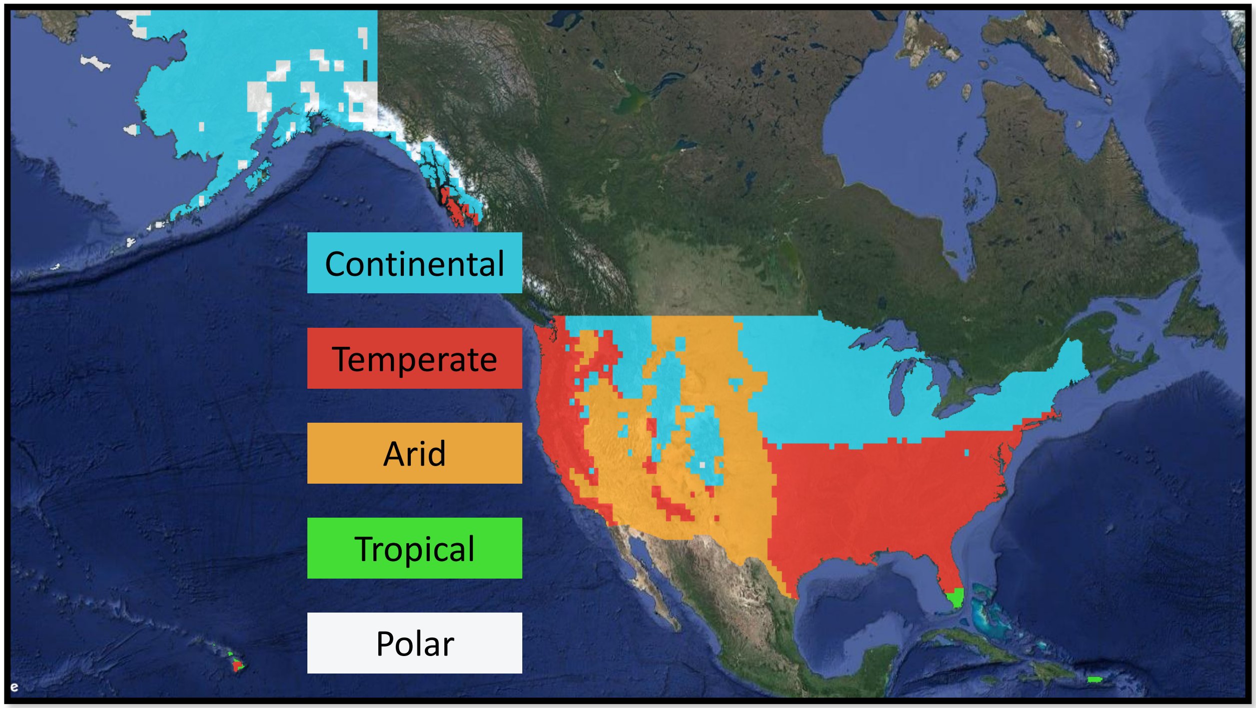
Hite Rate = 81%

- 84% for catchments >80 km^2
- 86% for 'high quality' FEMA data at all scales

CSI = 59%

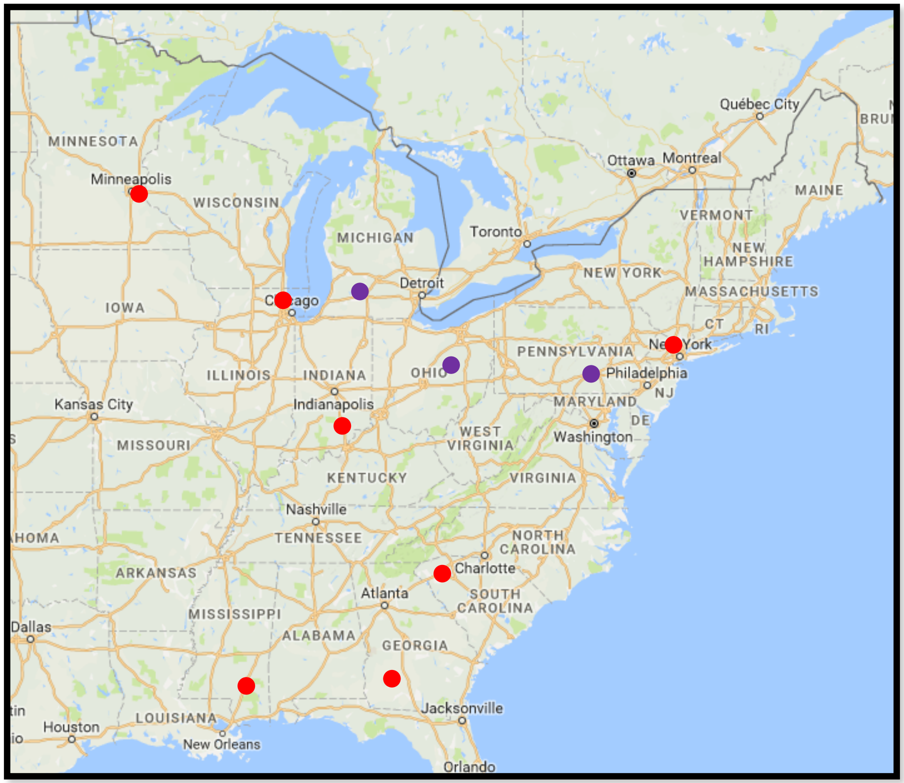
Köppen-Geiger zones

- Temperate = 84%
- Arid = 73%
- Continental = 78%

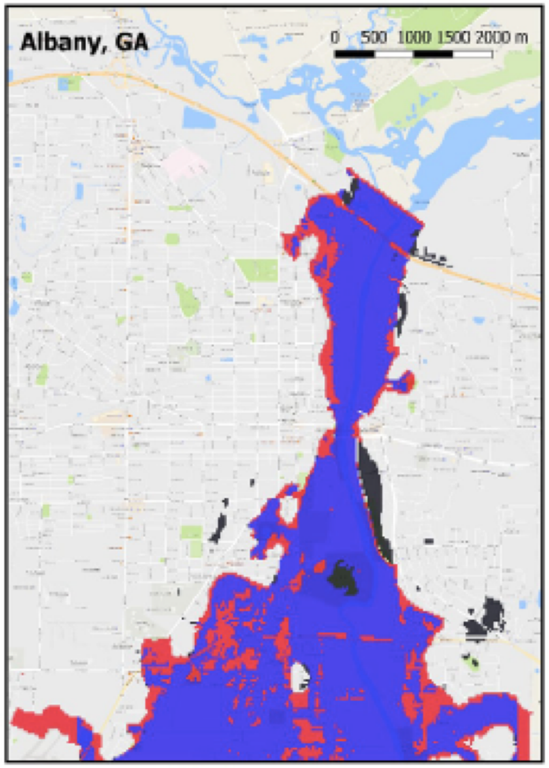


Catchment-scale validation: USGS 1D models

- Isolated local modelling studies – usually a few kilometres of a single stream
- 10 sites with 100-year simulations
- 3 further sites with events of varying magnitude



LOCATION	HIT RATE (%)
Albany, GA	**93.8**
Columbus, IN	**83.3**
Greenville, SC	**99.7**
Hattiesburg, MS	**93.7**
Lincolnshire, IL	**81.8**
Minneapolis, MN	**91.0**
Ridgewood, NJ	**88.6**



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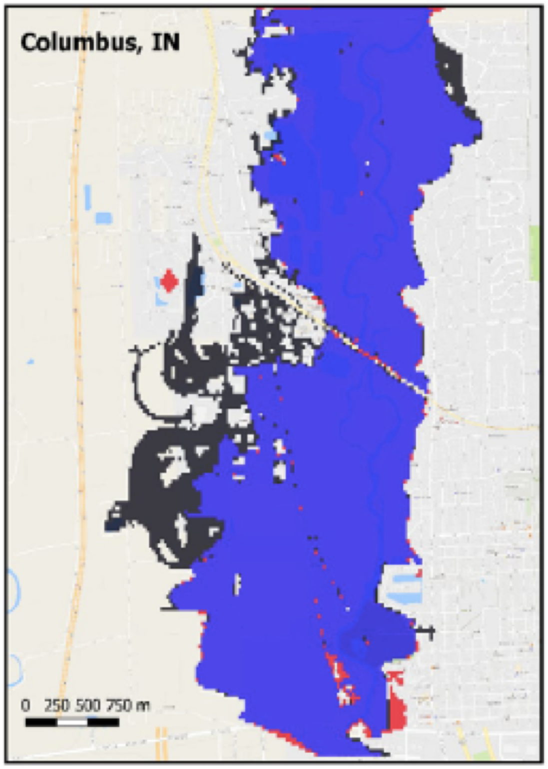

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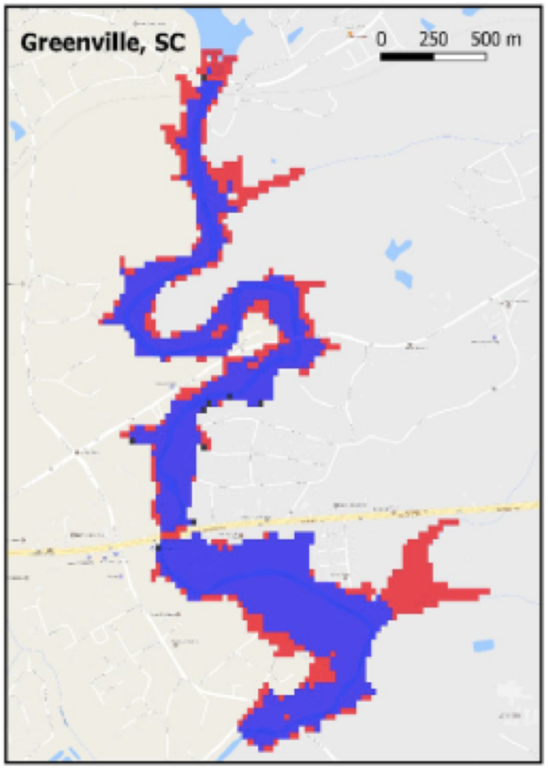

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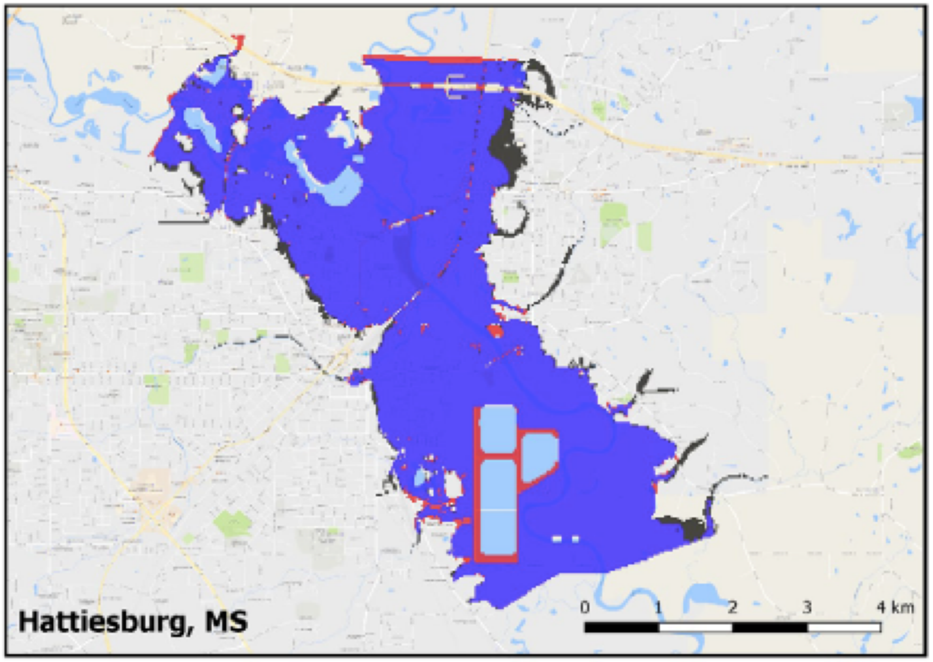

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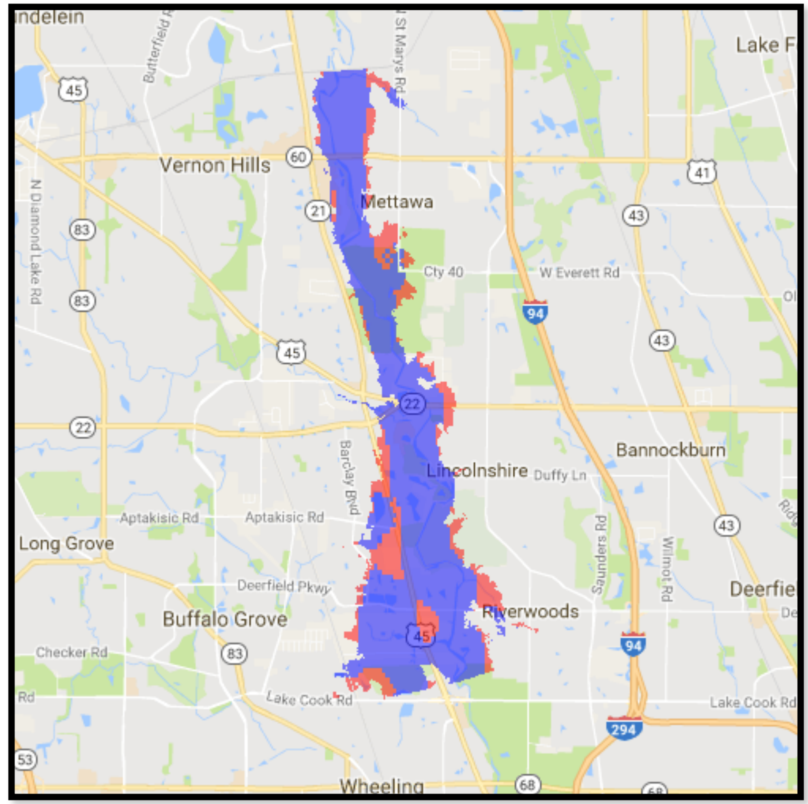

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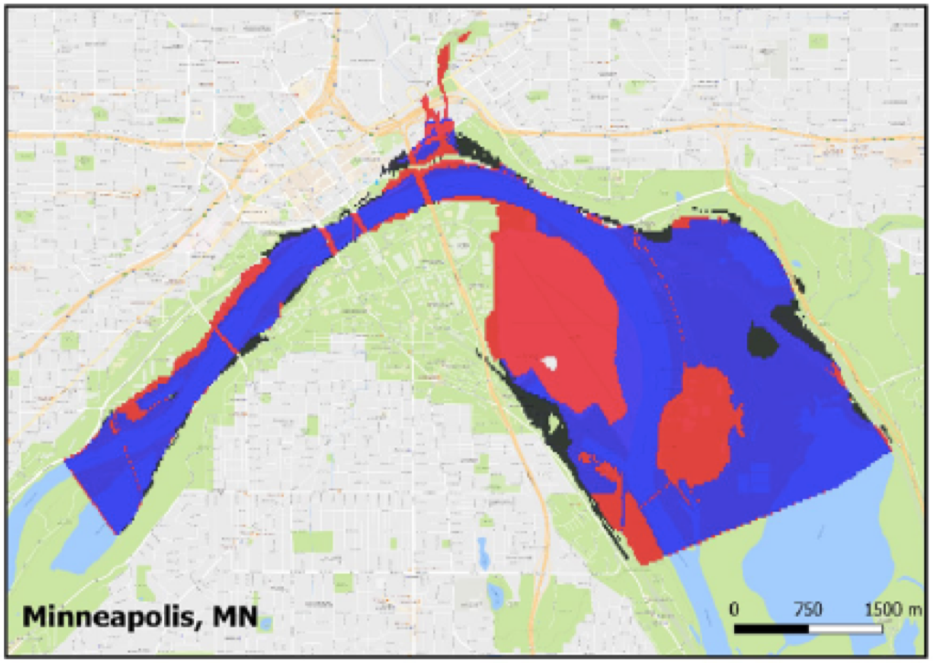

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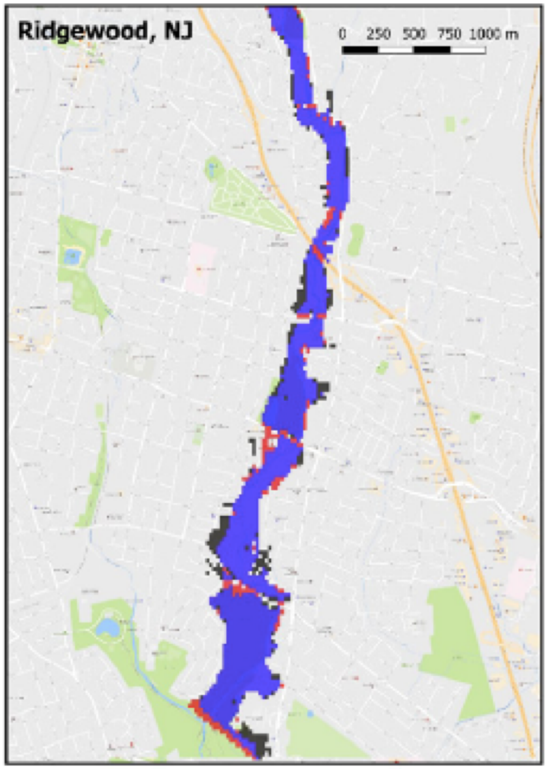
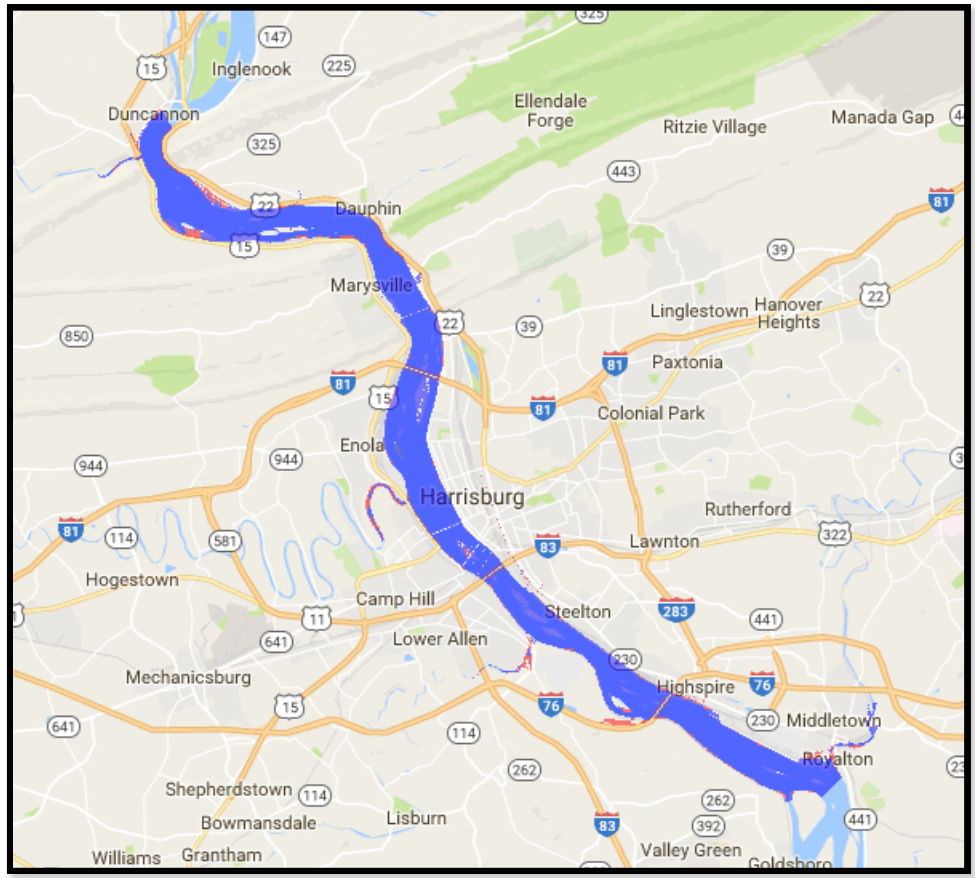
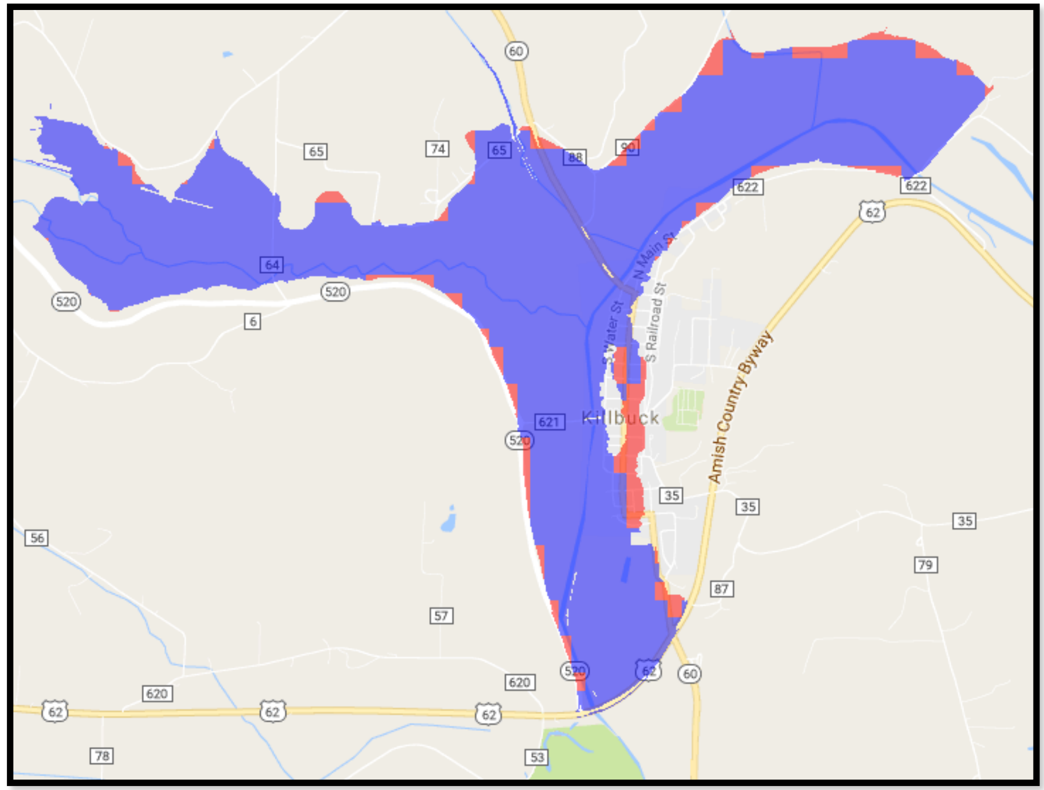


LOCATION	HIT RATE (%) 1 in 500
Battle Creek, MI	**90.7**

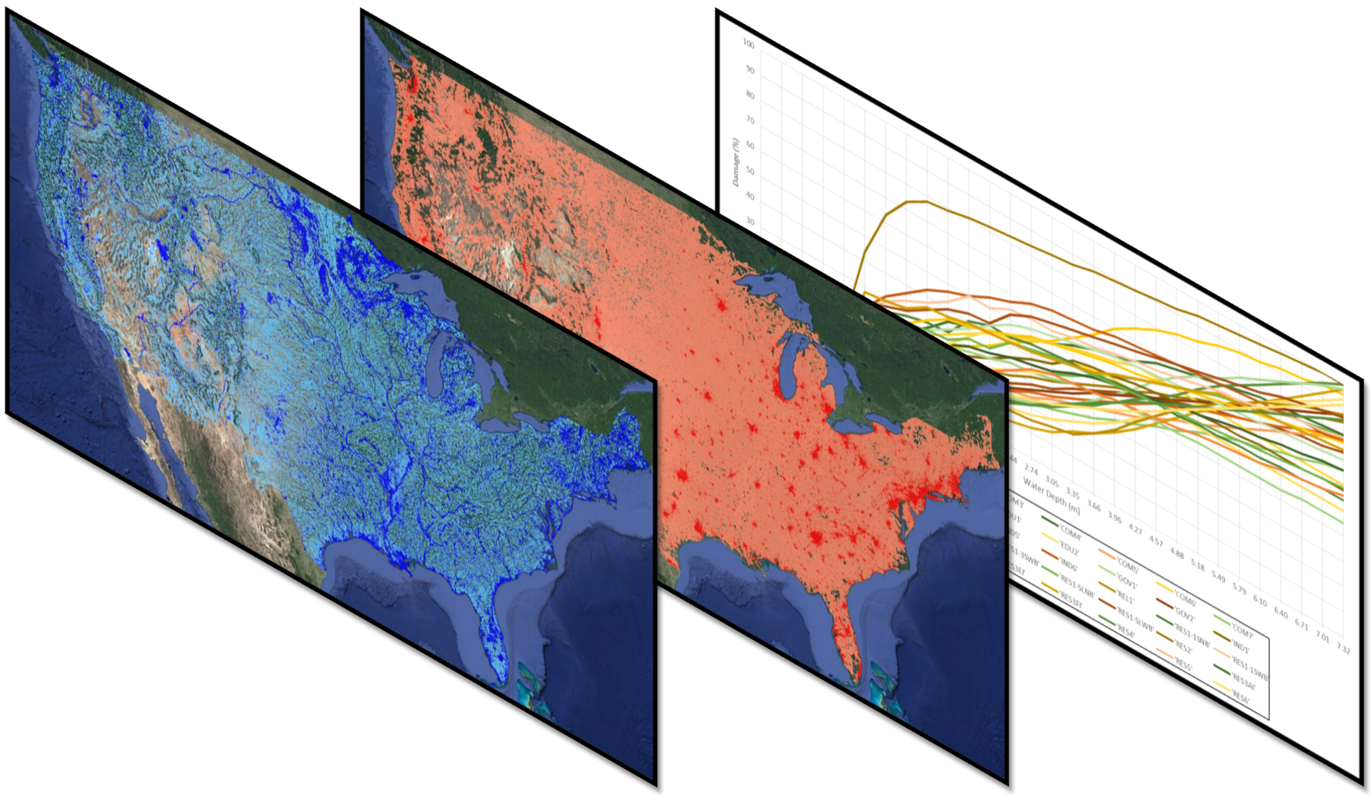
LOCATION	HIT RATE (%) 1 in 10
Harrisburg, PA	**95.1**



LOCATION	HIT RATE (%) 1 in 500
Killbuck, OH	**94.3**

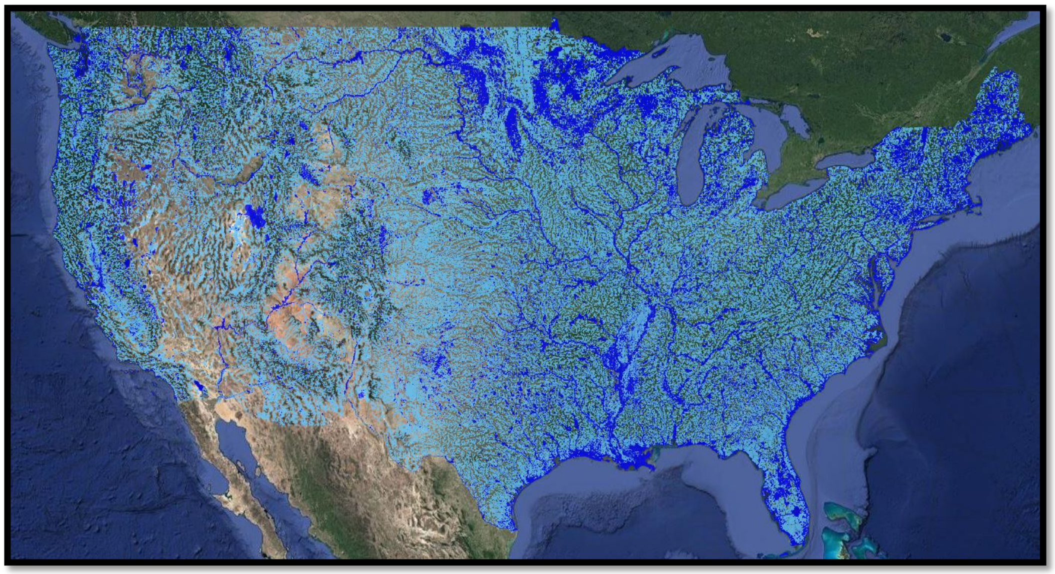


Basics of risk calculation



- Hazard
    - Flooded area
- Exposure
    - Value of buildings within floodplain
    - Number of people within floodplain
- Vulnerability
    - Potential damages

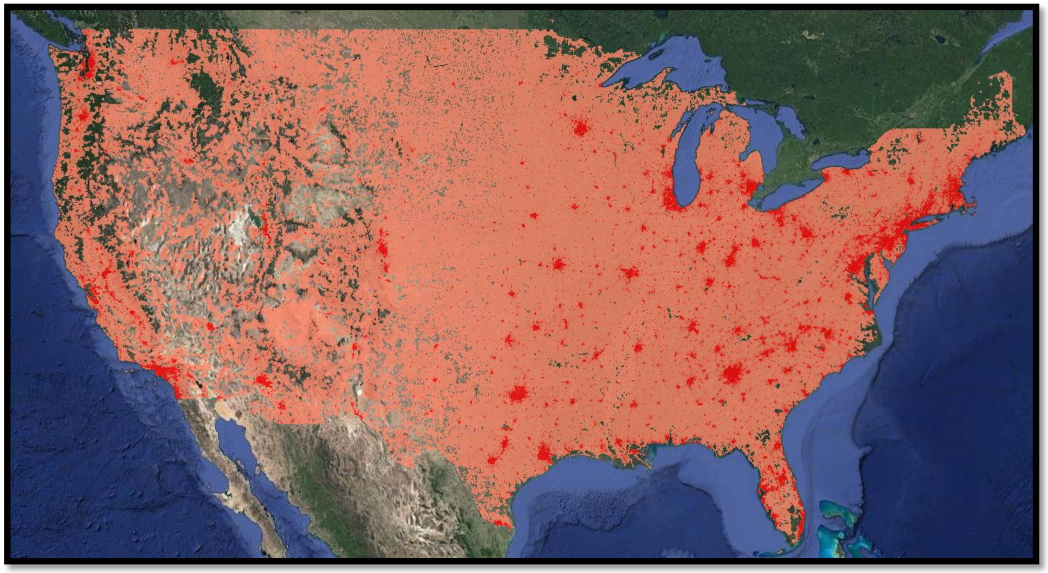
Hazard data



- ~30m resolution flood hazard model of CONUS (Wing *et al.*, 2017)

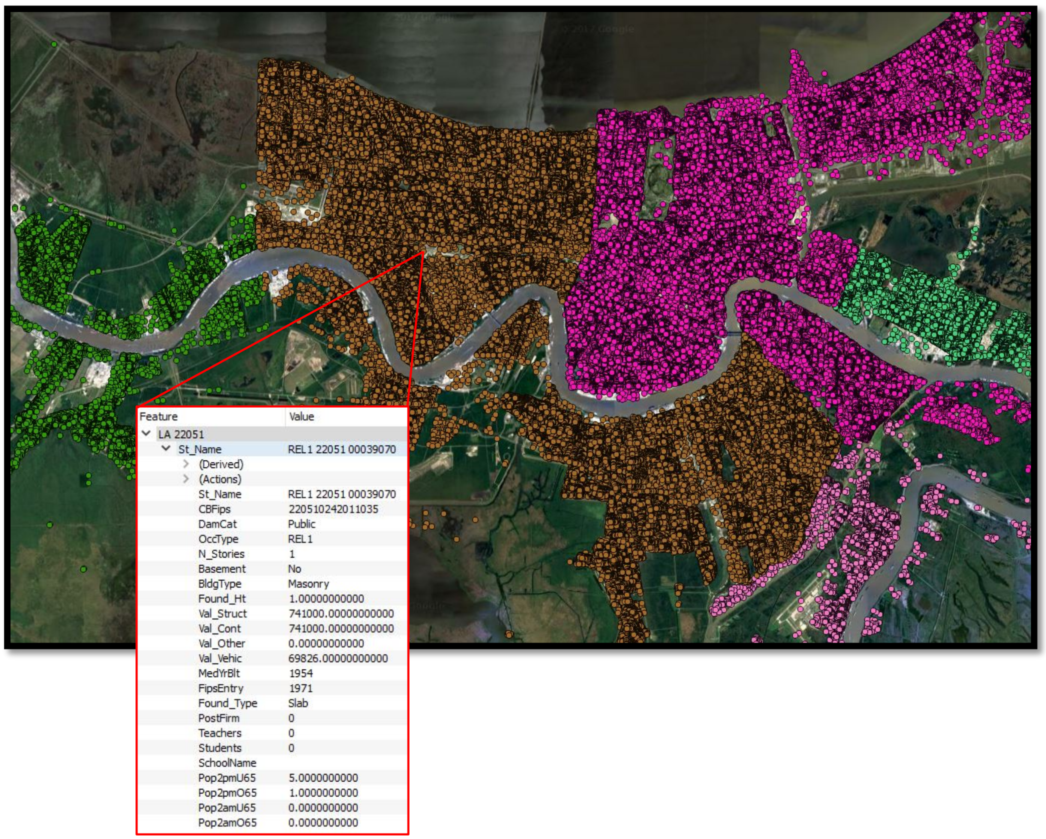
Wing, O. E. J. *et al.* (2017), Validation of a 30 m resolution flood hazard model of the conterminous United States, *Water Resour. Res.*, 53, 7968–7986, doi:10.1002/2017WR020917.

Socio-economic data



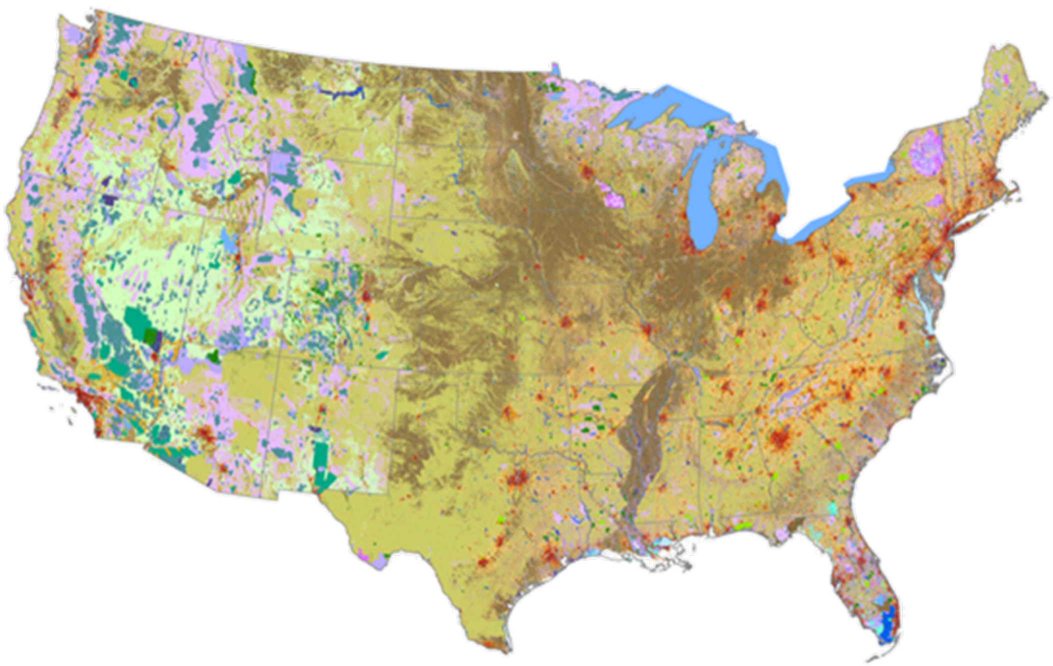
- EPA EnviroAtlas dasymetric population map
- Assigns 2010 census populations to 30m pixels based on land-use and slope

Socio-economic data



- FEMA National Structure Inventory
- Information on over 100M buildings in the CONUS:
  - Location
  - Value
  - Type
  - Number of storeys
  - Presence of basement

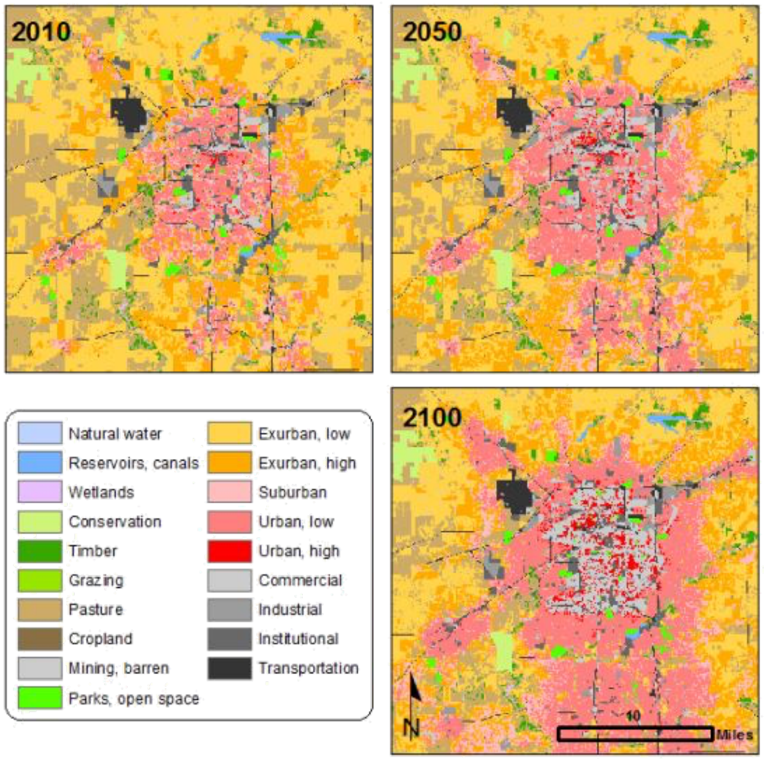
Socio-economic data



- National Land Use Database (Theobold, 2014)
- Indicates developed areas across the CONUS

Theobold, D. M. (2014), Development and Applications of a Comprehensive Land Use Classification and Map for the US, *PLOS ONE*, 9(4), e94628, doi:10.1371/journal.pone.0094628.

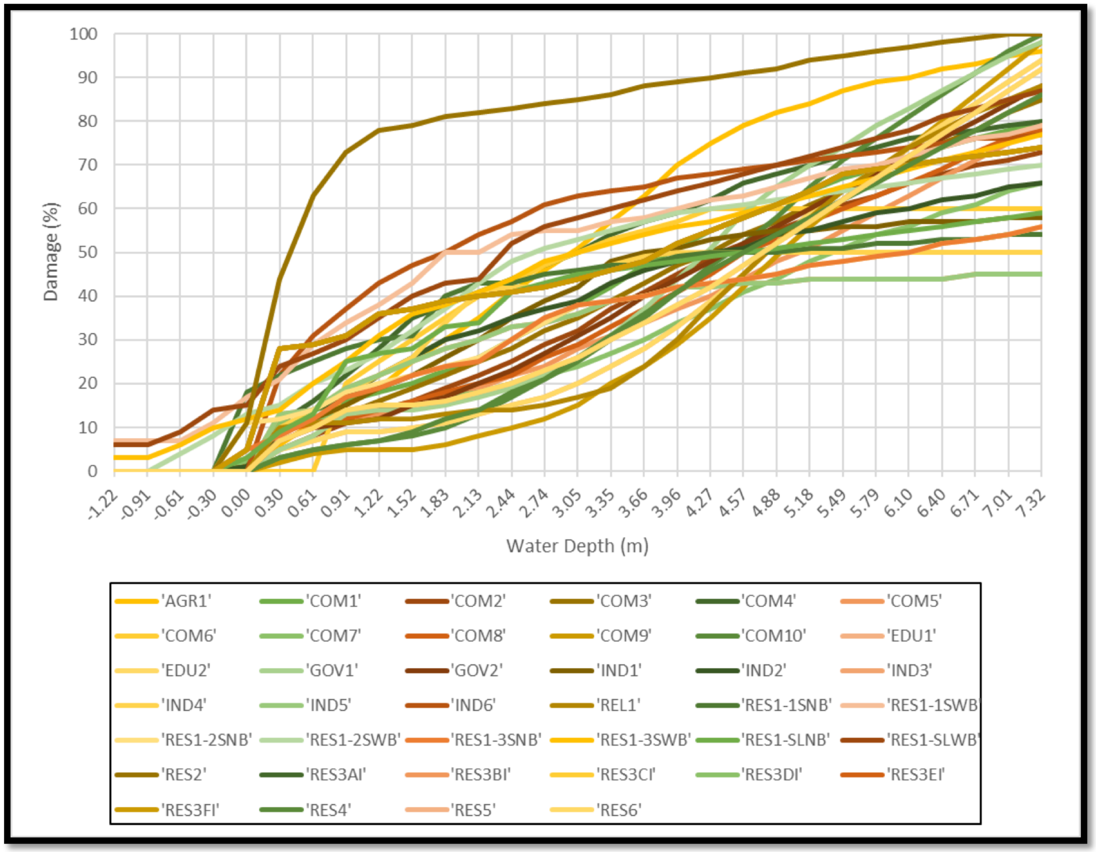
Future projections



EPA (2016), Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) Version 2. EPA/600/R-16/366F, National Center for Environmental Assessment, Washington, DC.

- EPA Integrated Climate and Land Use Scenarios (ICLUS) project
- Projects population and land use change up to 2100:
  - SSP2 = tracks US census projection
  - SSP5 = high growth case

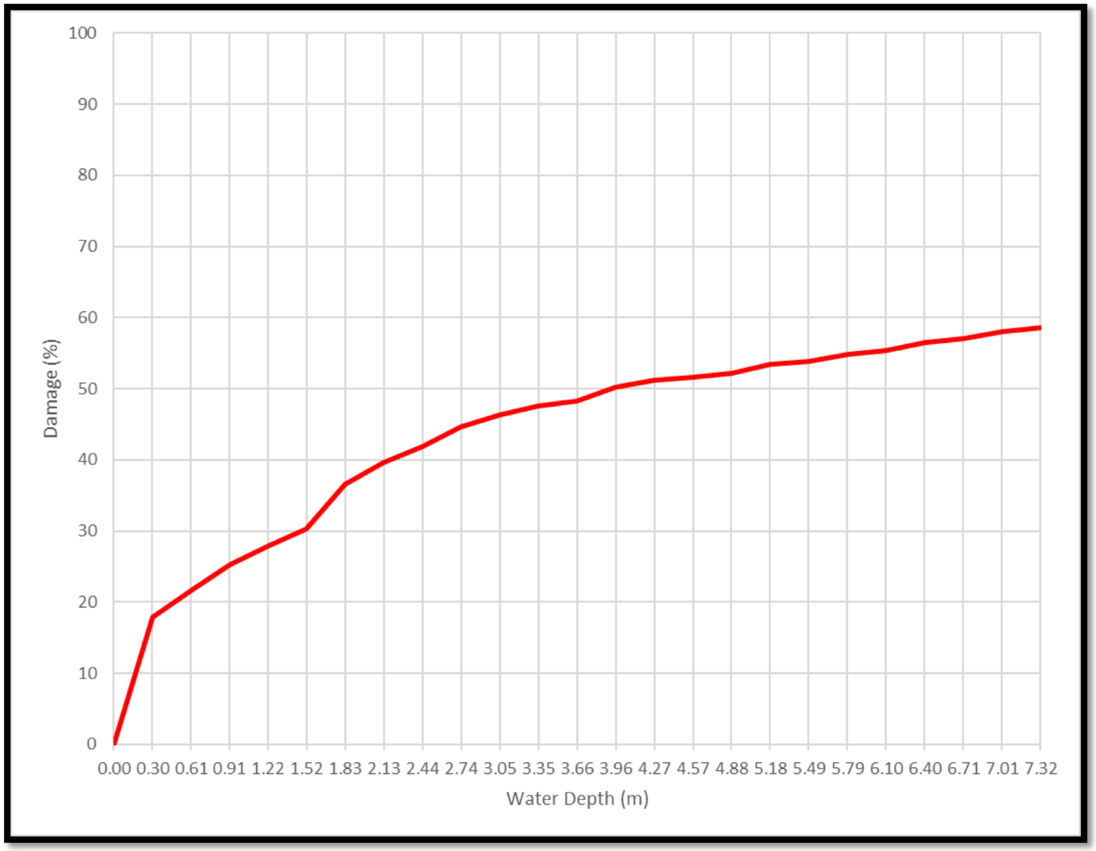
Vulnerability functions



- Simple relationship between water depth and % damage to an asset obtained from USACE

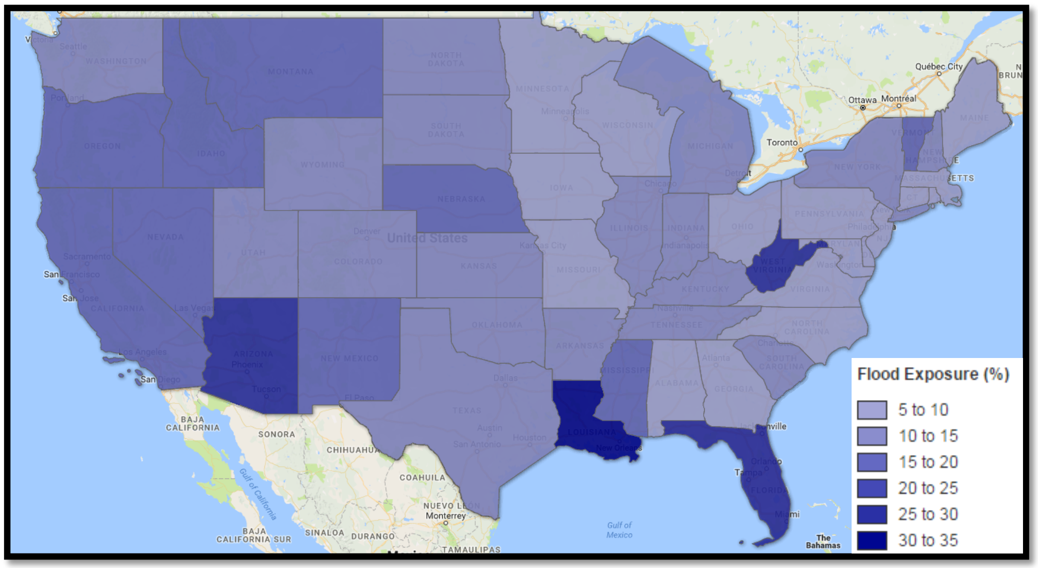
- Specific function for each building type when used with FEMA NSI

Future vulnerability functions



- Simple relationship between water depth and % damage to an asset obtained from USACE
- Generalised curve used for ICLUS projections

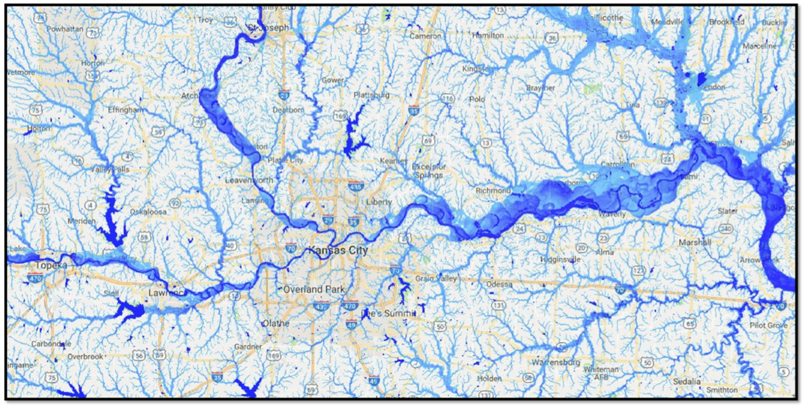
Population exposure

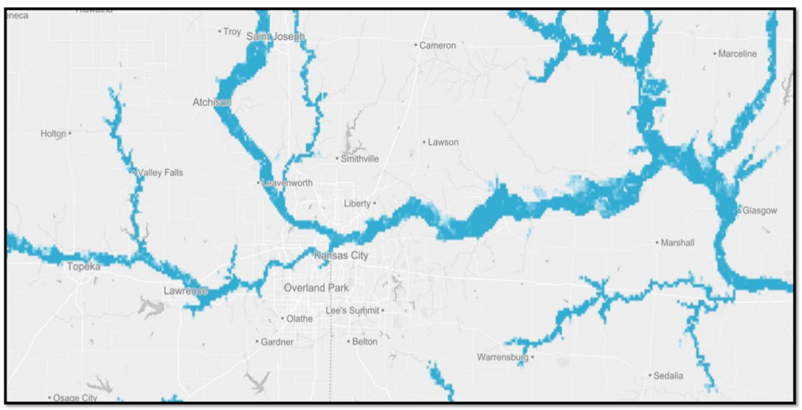


- Present-day

Return Period	Exposure (millions)	Exposure (%)
1 in 50	33.5	11.0
1 in 100	**40.8**	**13.3**
1 in 500	61.4	20.0
FEMA (1 in 100)	13.0	4.2
Aqueduct (1 in 100)	15.7	5.1

Population exposure





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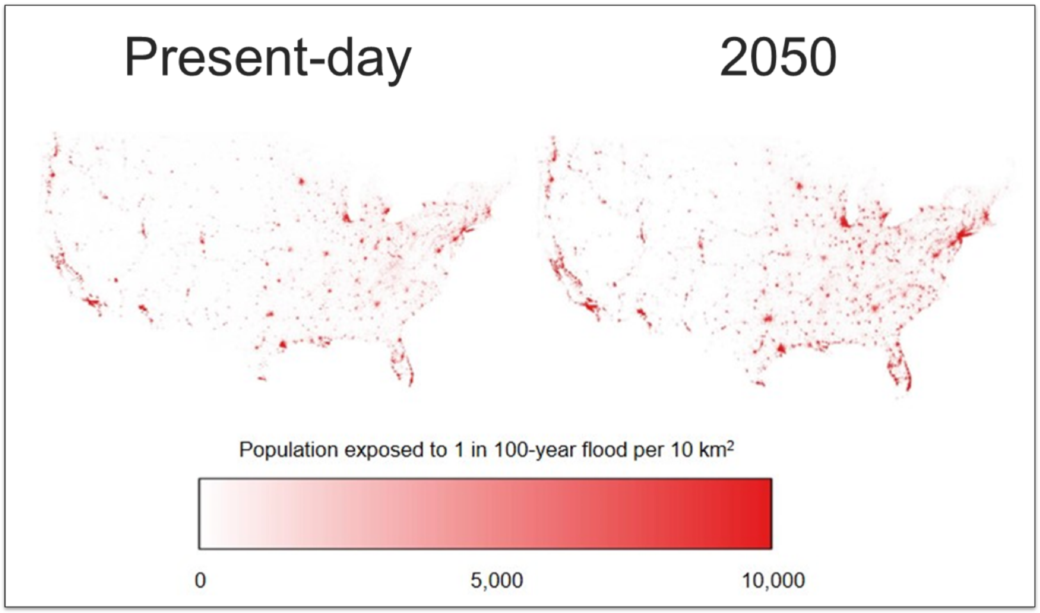
www.floods.wri.org

Winsemius, H. C. *et al.* (2013), A framework for global river flood risk assessments, *Hydrol. Earth Syst. Sci.*, 17, 1871–1892, doi:10.5194/hess-17-1871-2013.

Ward, P. J. *et al.* (2013), Assessing flood risk at the global scale: model setup, results, and sensitivity, *Environ. Res. Lett.*, 8, doi:10.1088/1748-9326/8/4/044019.

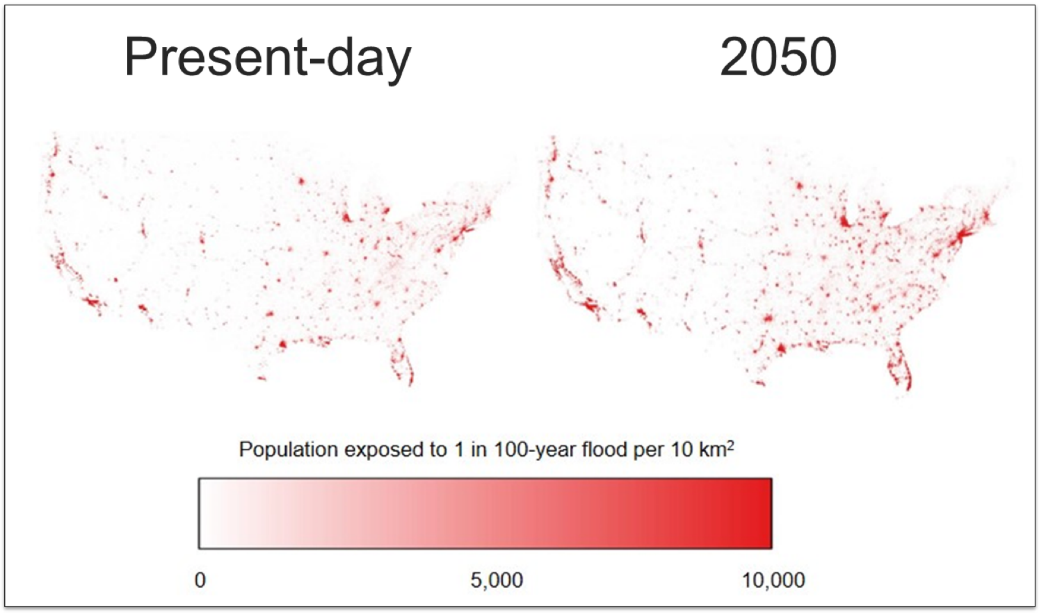
Population exposure



- SSP2 2050

Return Period	Exposure (millions)	Exposure (%)
1 in 50	51.3	13.1
1 in 100	**61.2**	**15.6**
1 in 500	86.8	22.2

Population exposure



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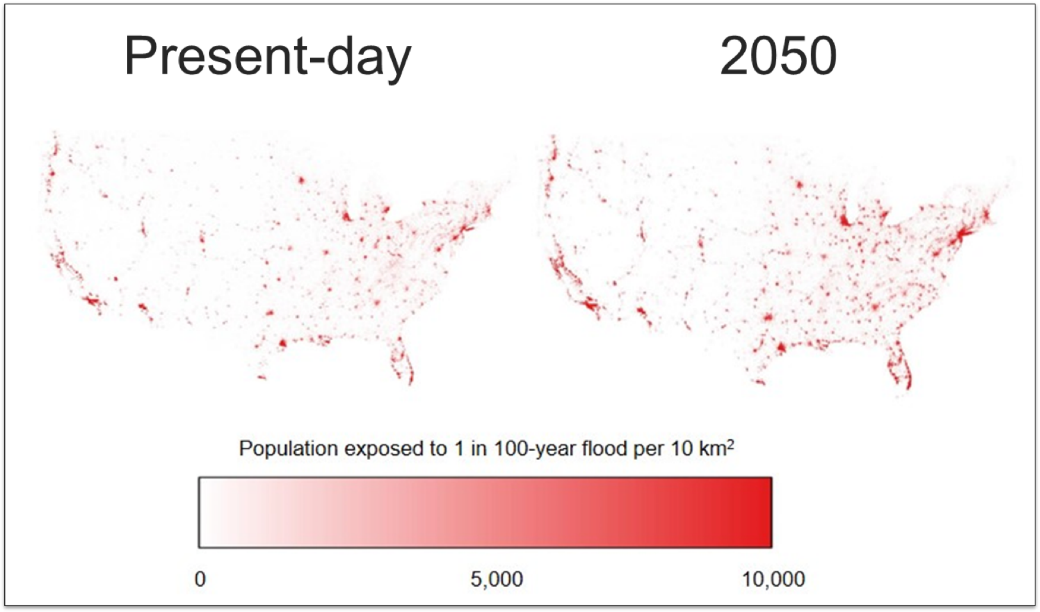
Return Period	Exposure (millions)	Exposure (%)
1 in 50	51.3	13.1
1 in 100	**61.2**	**15.6**
1 in 500	86.8	22.2

- Changes from present-day (100-year floodplain)
  - 20.4M (↑ 50%)

Population exposure



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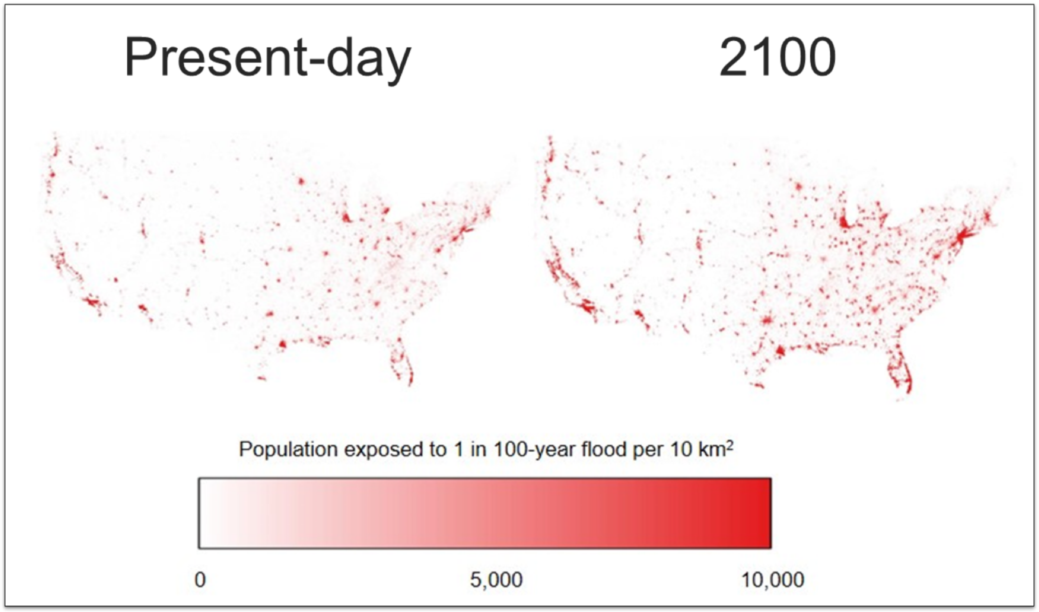
1 in 50	51.3	13.1
1 in 100	**61.2**	**15.6**
1 in 500	86.8	22.2

- Changes from present-day (100-year floodplain)
  - 2.3pp ↑ in proportion of total population

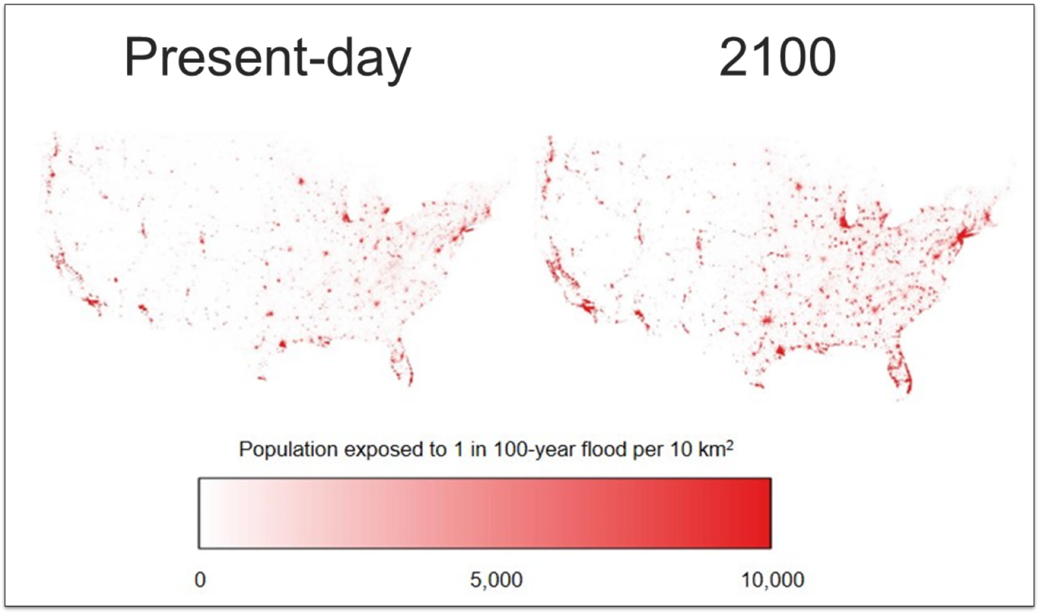
Population exposure



- SSP2 2100

Return Period	Exposure (millions)	Exposure (%)
1 in 50	63.1	13.9
1 in 100	**74.8**	**16.4**
1 in 500	104.5	23.0

Population exposure

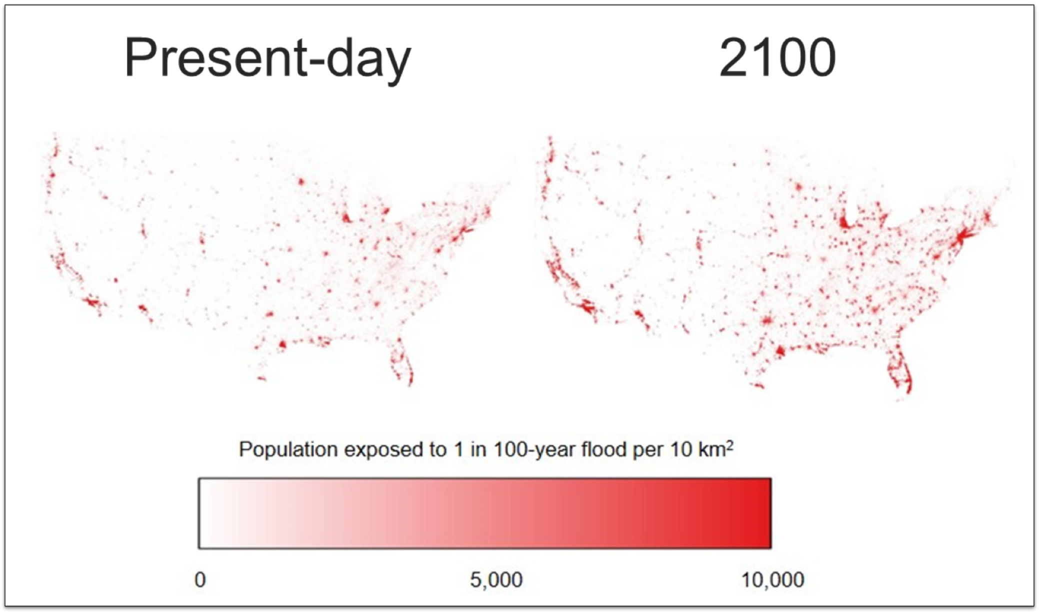


- SSP2 2100

Return Period	Exposure (millions)	Exposure (%)
1 in 50	63.1	13.9
1 in 100	**74.8**	**16.4**
1 in 500	104.5	23.0

- Changes from present-day (100-year floodplain)
  - 34.0M (↑ 83%)

Population exposure



- SSP2 2100

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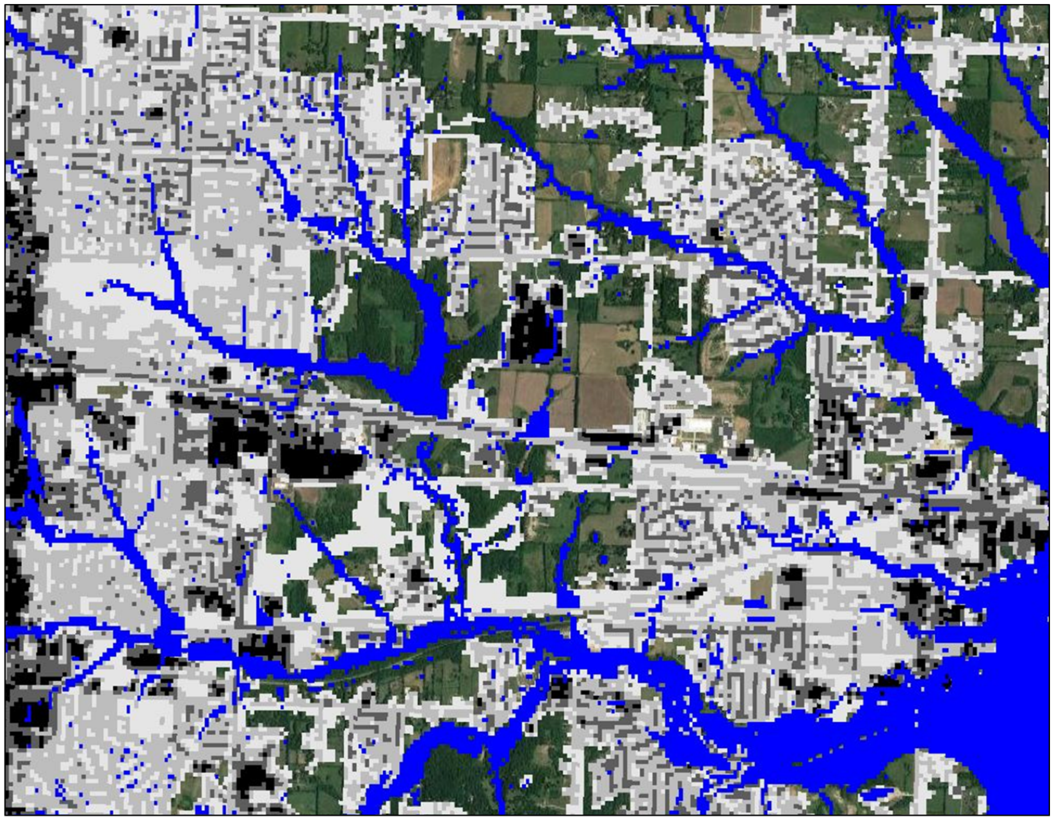
1 in 50	63.1	13.9
1 in 100	**74.8**	**16.4**
1 in 500	104.5	23.0

- Changes from present-day (100-year floodplain)
  - 3.1pp ↑ in proportion of total population

Asset exposure and risk

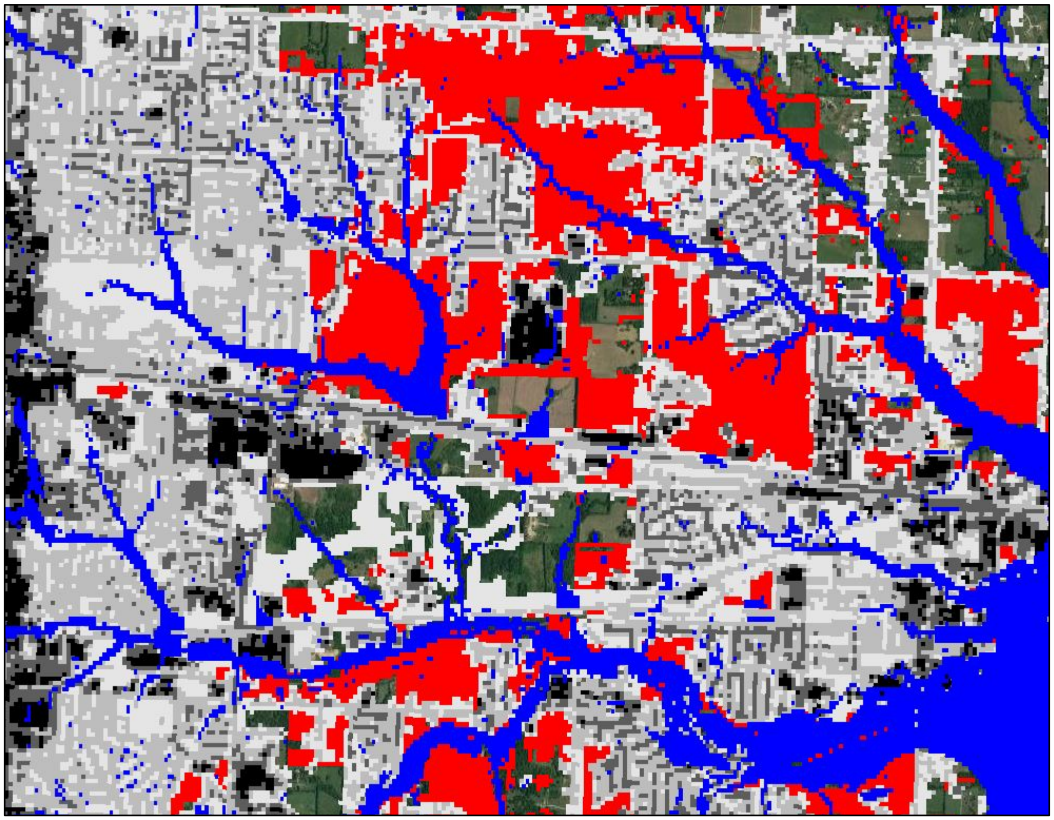


- Present-day

Return Period	Dev. Area (km^2)	Exposed assets ($tn)	Potential dmg ($tn)
1 in 50	140,657	4.6	0.9
1 in 100	**157,430**	**5.5**	**1.2**
1 in 500	203,775	8.2	1.9

- 100-year developed floodplain = approx. the land area of **Georgia**

Asset exposure and risk

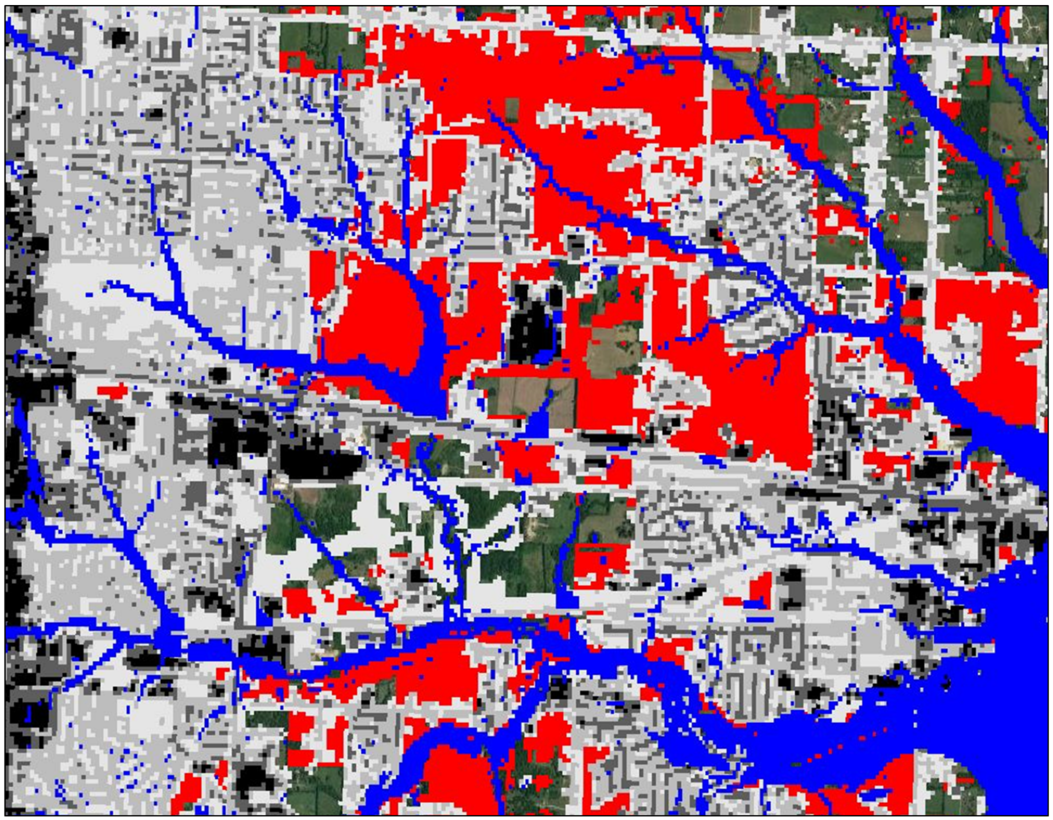


- SSP2 2050

Return Period	Dev. Area (km²)	Exposed assets ($tn)	Potential dmg ($tn)
1 in 50	174,989	6.9	1.5
1 in 100	**195,981**	**8.1**	**1.7**
1 in 500	251,702	11.3	2.7

- 100-year developed floodplain = approx. the land area of **S. Dakota**

Asset exposure and risk

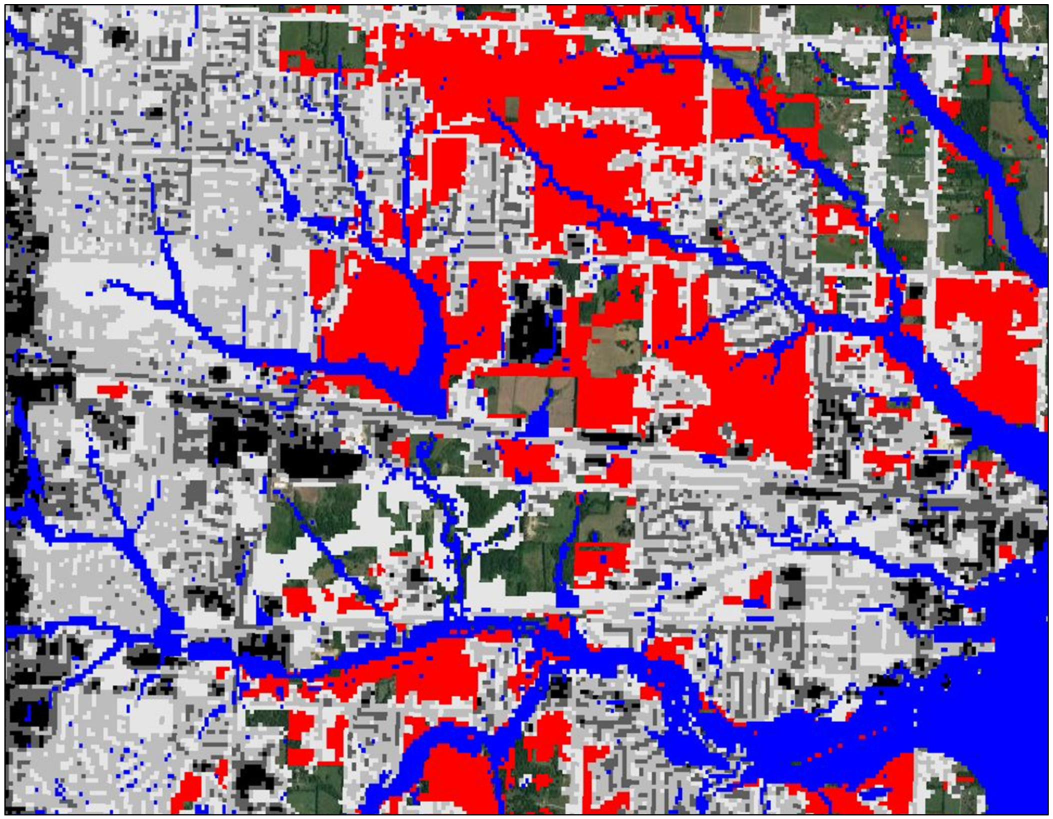


- SSP2 2100

Return Period	Dev. Area (km^2)	Exposed assets ($tn)	Potential dmg ($tn)
1 in 50	192,417	8.3	1.7
1 in 100	**215,900**	**9.8**	**2.1**
1 in 500	276,956	13.6	3.2

- 100-year developed floodplain = approx. the land area of **Kansas**

Asset exposure and risk



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1 in 100	**215,900**	**9.8**	**2.1**
1 in 500	276,956	13.6	3.2

- 100-year newly developed floodplain = approx. the land area of **W. Virginia**

Conclusions

- Developed a whole US flood inundation model with skill approaching that local bespoke simulations
- Intersecting simulations with high resolution population data shows exposed population and assets are ~3x higher than previous estimates
- Socio-economic change alone will increase the proportion of US population at risk during the C21st
- Climate change will undoubtedly amplify these effects further
- Now need to move away from ‘constant return period in space’ hazard layers to properly estimate flood risk

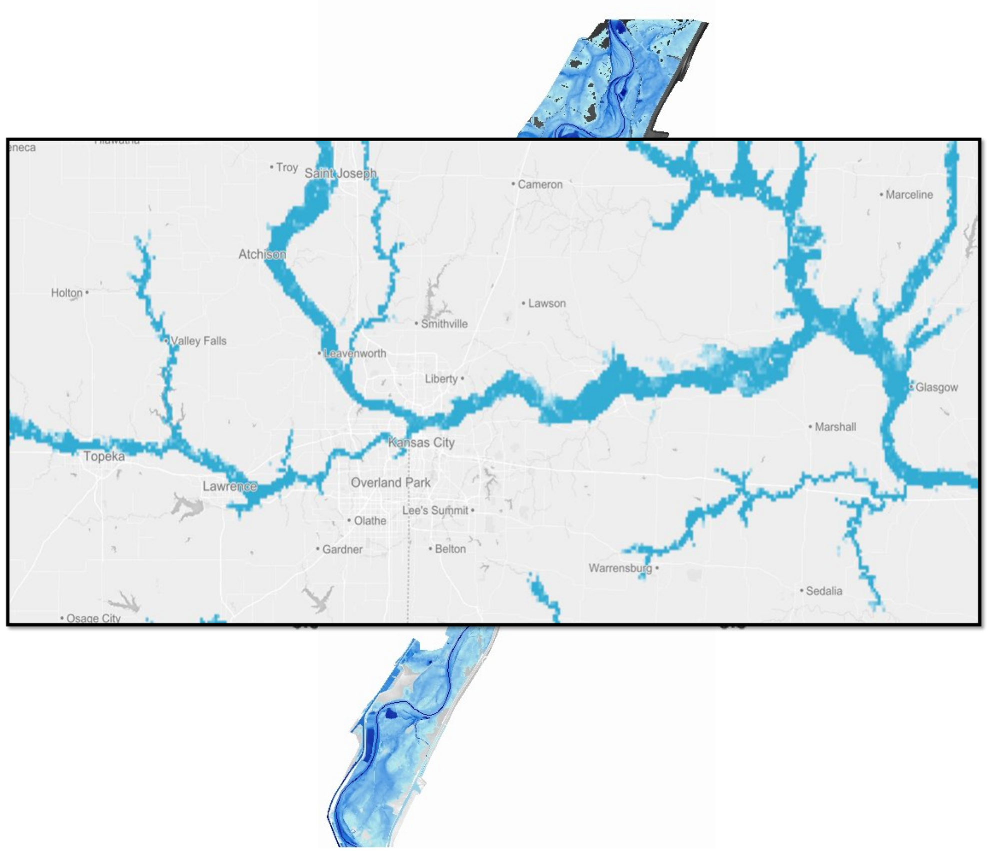
Spare slides

Catchment-scale validation: USGS 1D models

LOCATION	HIT RATE (%)				
	1 in 5	1 in 10	1 in 50	1 in 100	1 in 500
Battle Creek, MI	**-**	**81.9**	**84.3**	**88.1**	**90.7**
Harrisburg, PA	**-**	**95.1**	**92.3**	**88.7**	**86.1**
Killbuck, OH	**78.1**	**81.8**	**90.2**	**91.9**	**94.3**

Traditional flood hazard assessment

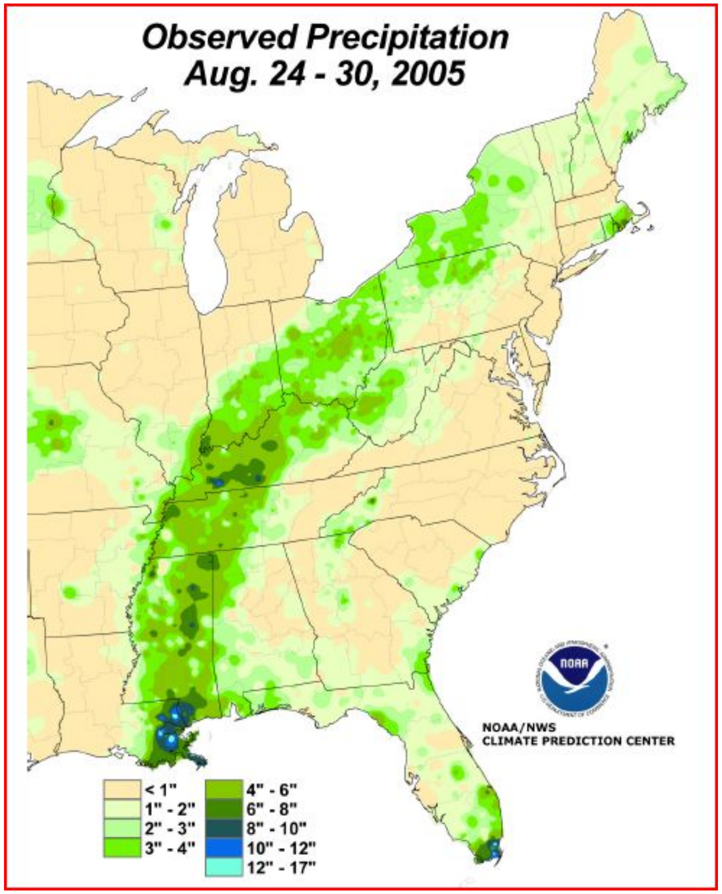
- Return period flows from gauge data
- Reach scale hydraulic models
- Large scale hazard maps then ‘stitch together’ the results of many local studies
  - E.g. FEMA Special Flood Hazard Areas



- Spatially invariant return period assumption breaks down at large scales

Event footprints

- Over large scales the event return period varies in space
  - Known as the ‘flood footprint’
- Often ignored in many large scale analyses
- Gauge time series not long enough to sample all possible footprints
- Use conditional stochastic simulation to generate a bigger sample of plausible event footprints

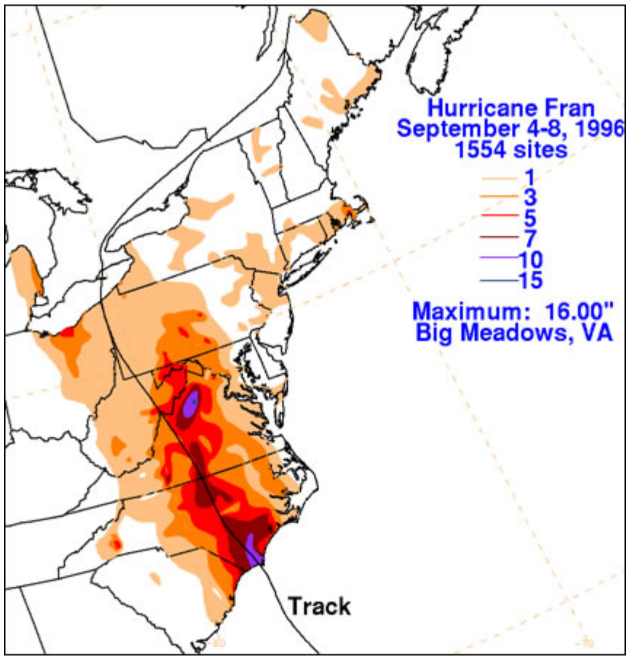


The problem

- For a T year return period flow at gauging site X, Q_X^T, what is the probability distribution of flow at gauge Y, i.e. $Pr(Q_y | Q_X^T)$ for all $Y_{1,2 \ldots\ldots n}$

- Multi-site conditional probability statistical methods are well known, but not previously applied at continental scales for thousands of gauges
  - Cross-correlation between all gauges gives a large compute problem
  - Large climatic differences at continental scales
  - Multiple flood generating mechanisms

Method



Heffernan, J.E. and Tawn, J.A. (2004). A conditional approach for multivariate extreme values. J. *R. Statist. Soc. B*, **66**, Part 3, 497–546.

Gauge Preparation

Import gauges

QC gauges

Infill missing data

Filter gauges

Spatio-temporal dependence

Marginal thresholds

- Define threshold
- Produce semi-parametric distribution

Dependence thresholds

- Define threshold
- Define multivariate dependence structure

Generate event catalogues

Define expected number of events per year within region

Utilise dependence information to simulate *N* event footprints

- Likelihood of a given gauge being the largest is used to define the number of times of condition upon that gauge

Generate areal flood depths and losses

Interpolation

- Point data to accumulation units

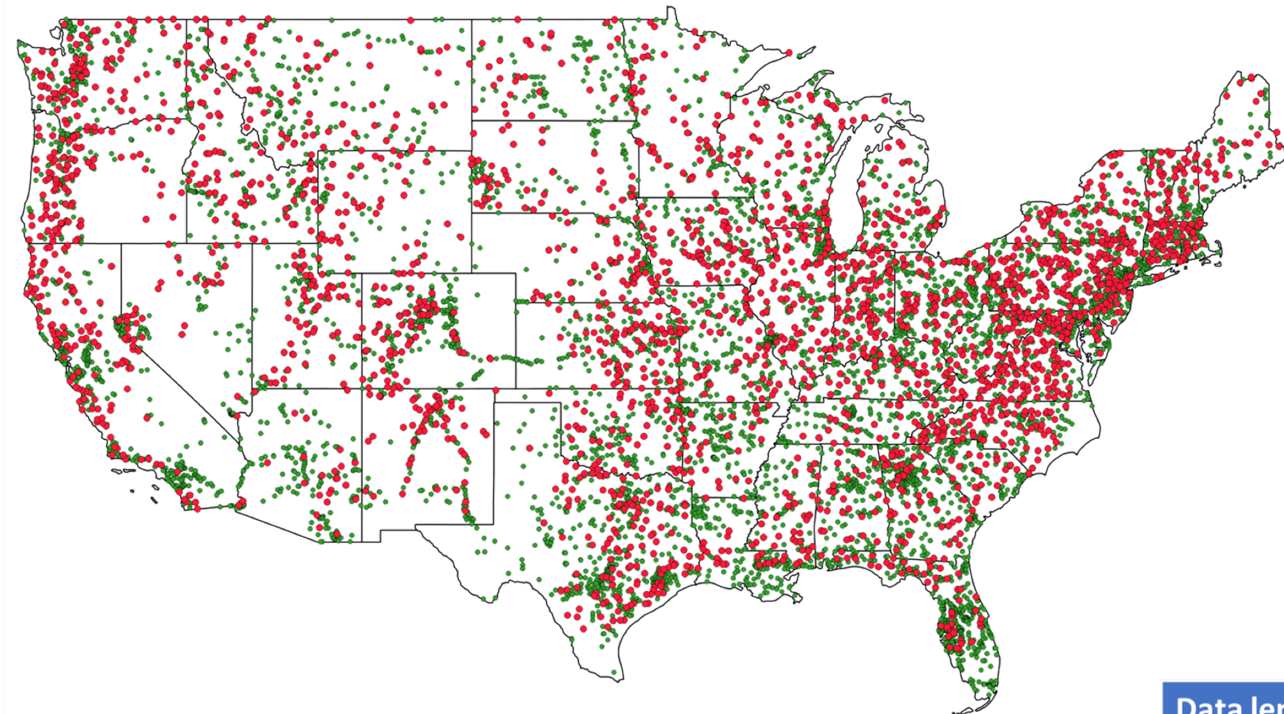
Extract Fathom hazard layers

- Corresponding to interpolated R period surfaces

Extract economic losses

- USA asset information and depth damage functions
- Overlay with extracted inundation extend / depth

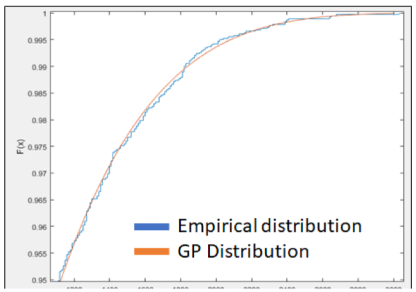
Gauge preparation

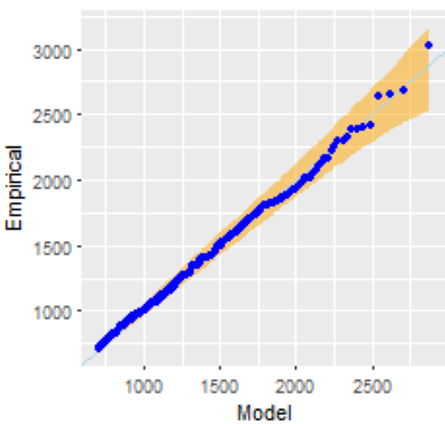


Data length (years)	# Suitable Gauges
>30	4450
>40	3625
>50 ✓	2800

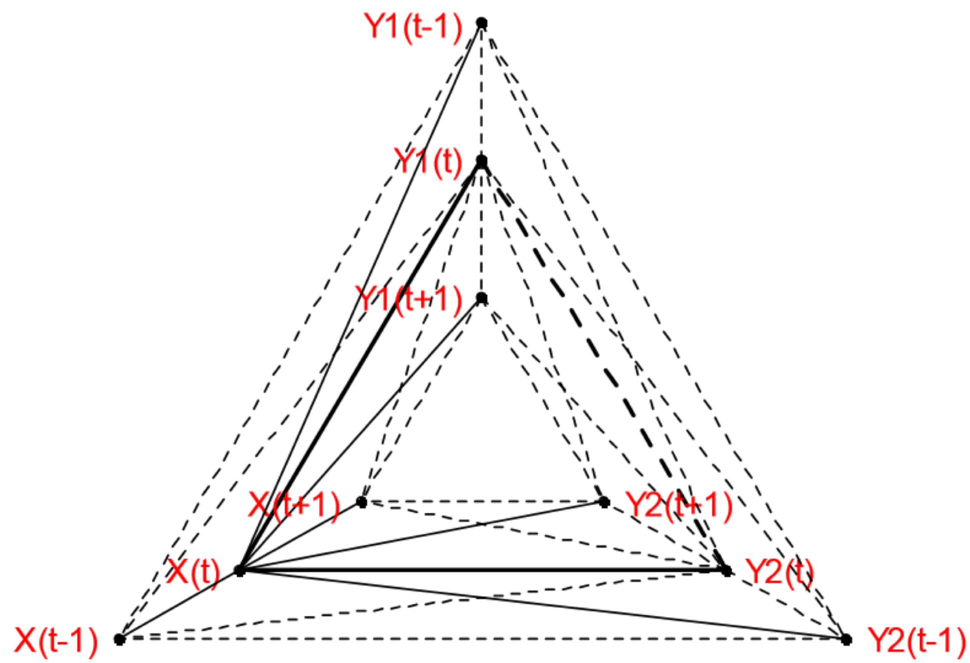
Spatio-temporal dependence

a. Define marginals at each gauge





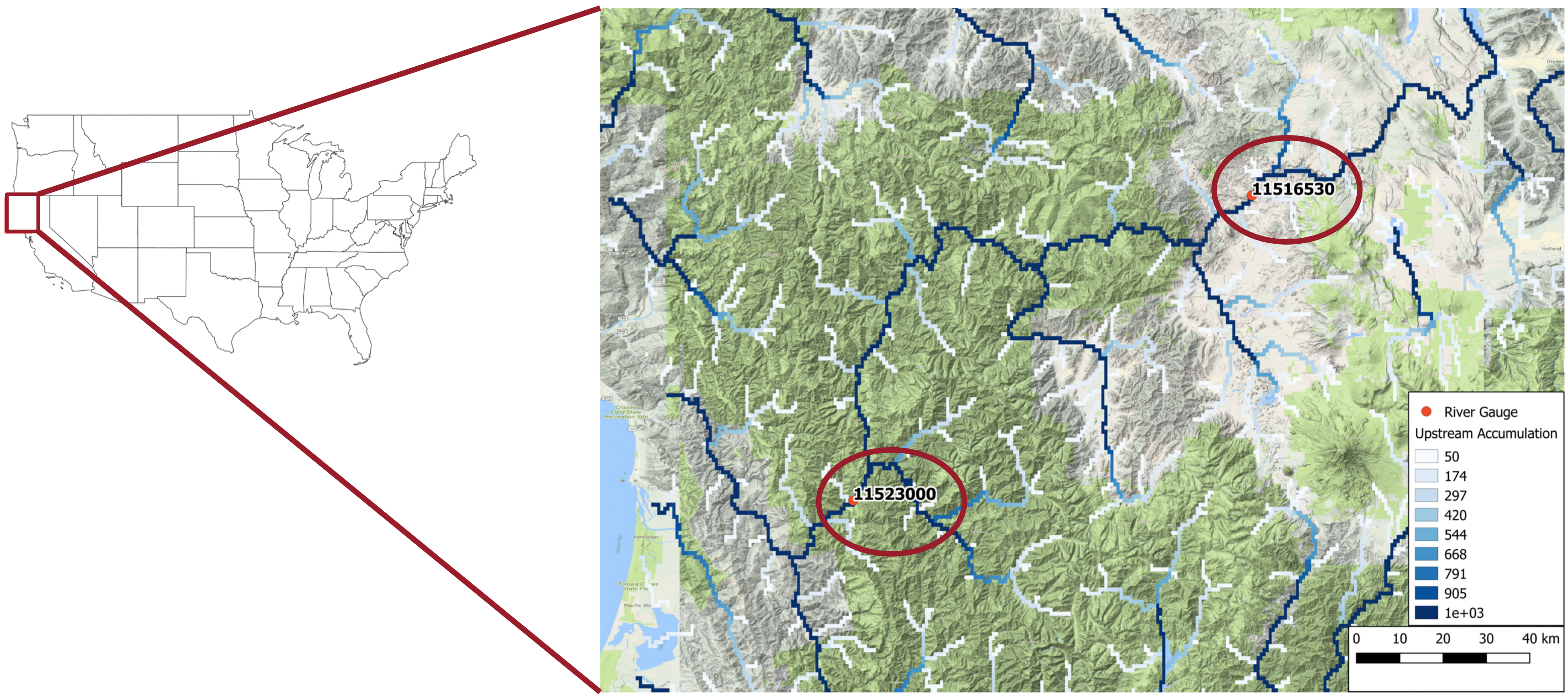
b. Compute spatio-temporal connections between gauges for flows Above Q99 threshold



See also poster H21J-1615 by Quinn et al

Spatio-temporal dependence

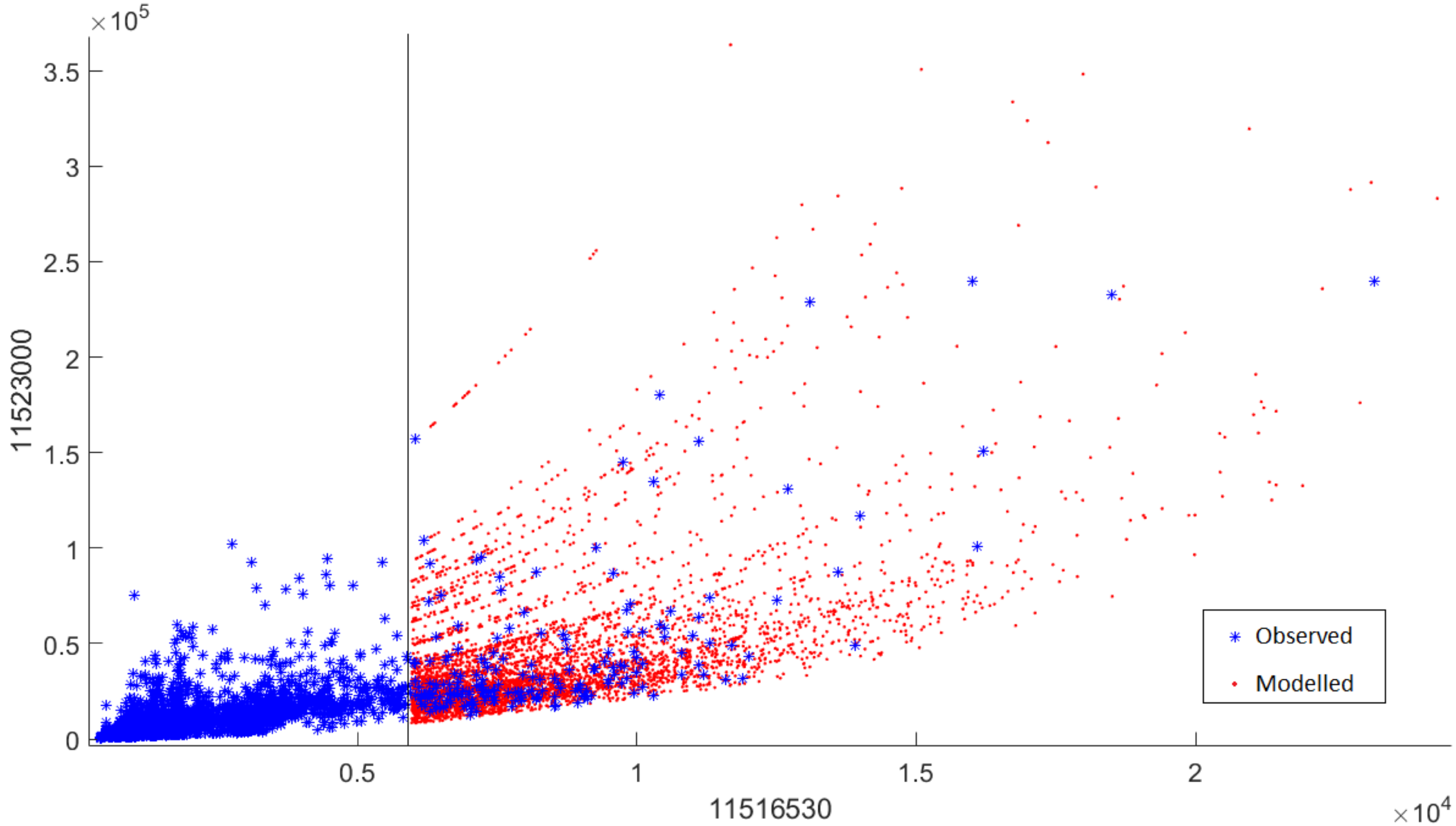
c. Define dependence structure



See also poster H21J-1615 by Quinn et al

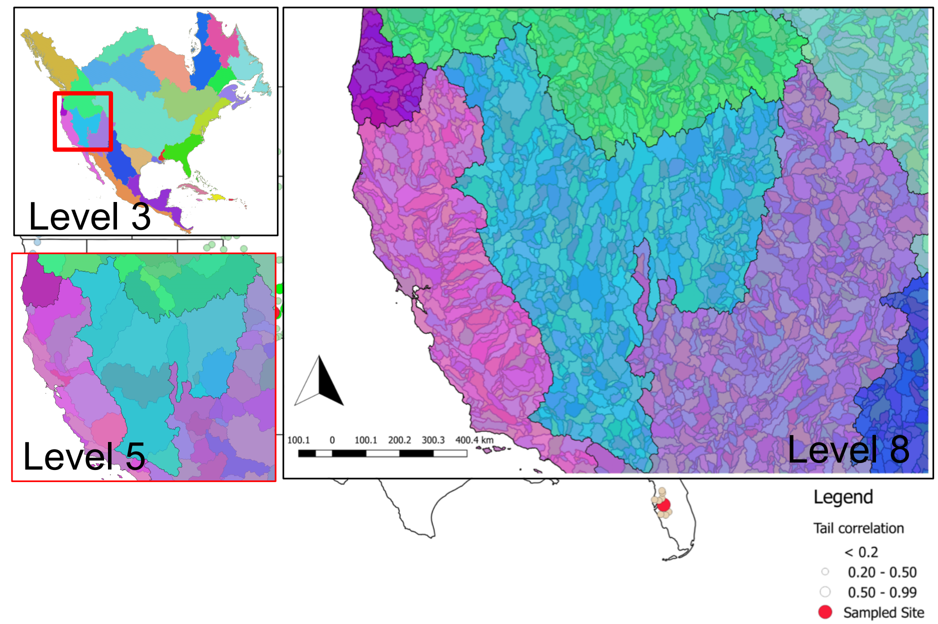
Spatio-temporal dependence

c. Define dependence structure

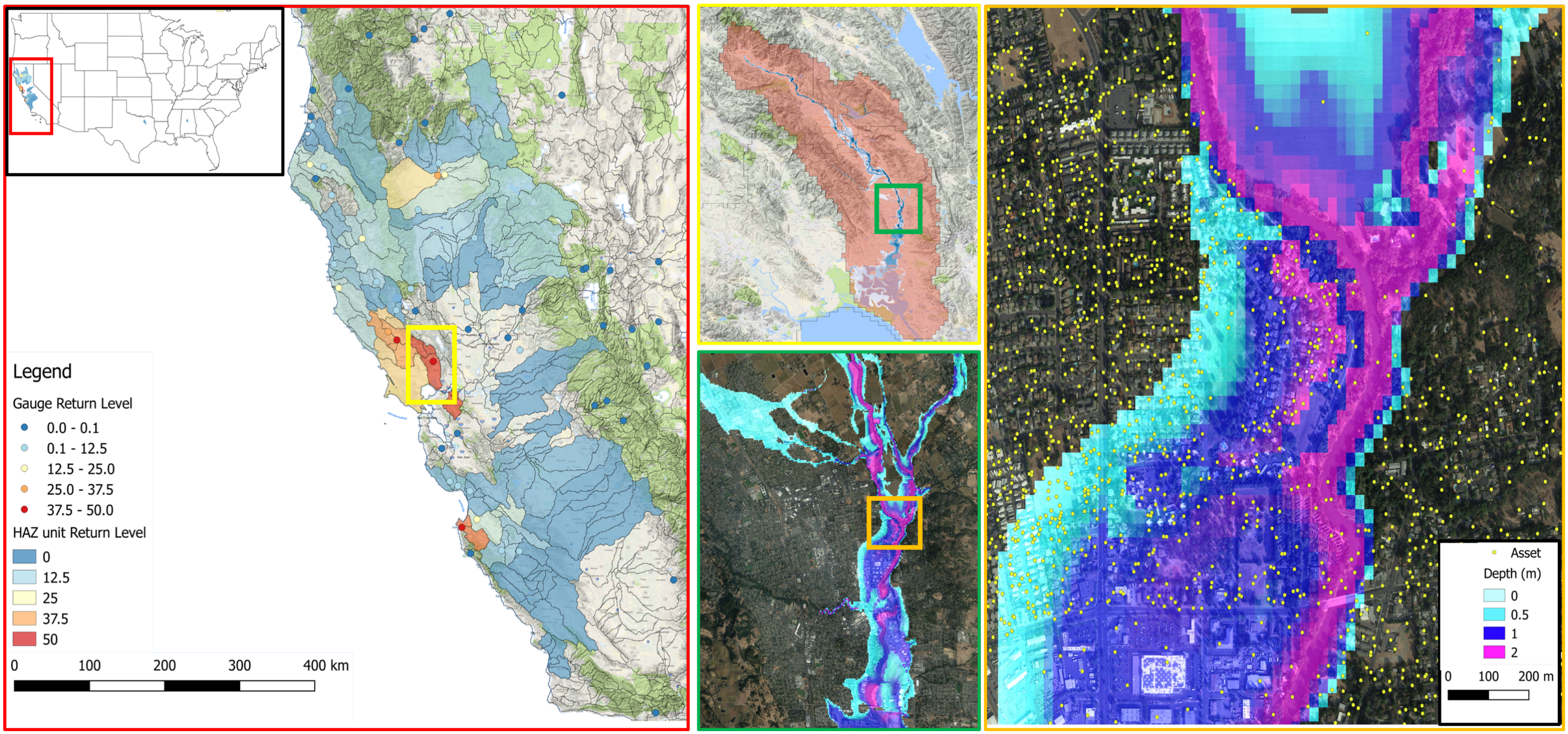


Generate event catalogues

- Given gauge dependence structure we can simulate event footprints at any given conditioning site
- Need a structure to interpolate over
  - Use HydroBasins Level 8 and 10 units
  - Interpolate gauge return period values to these units
  - Build footprint using pre-computed set of return period hazard layers from the Fathom Global US 30m hydraulic model

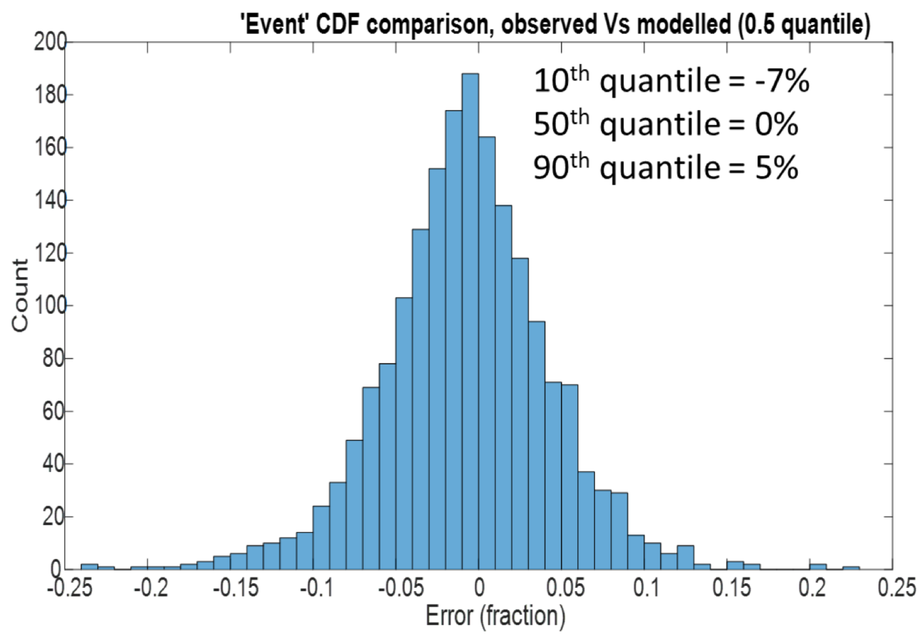


Example event footprint



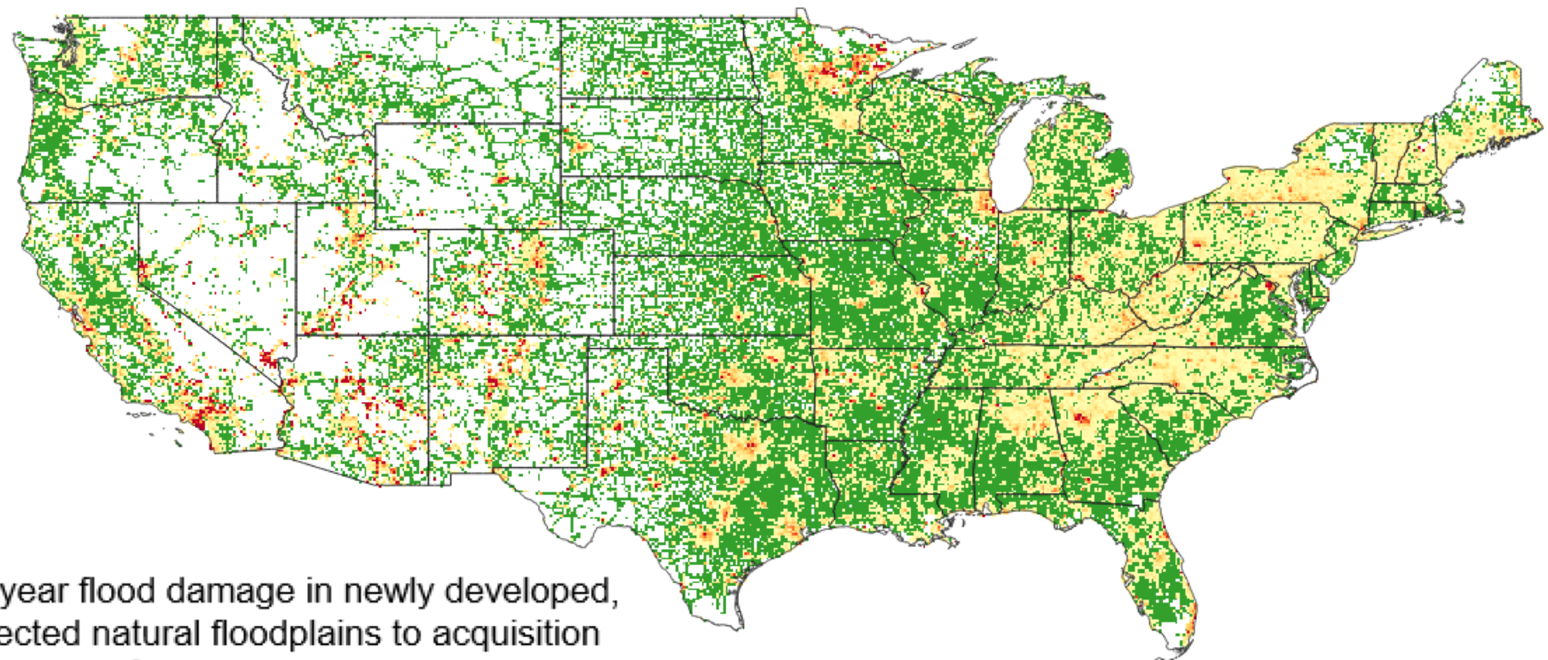
Validation

- Test 1: observed vs. modelled extreme value CDFs
  - For a given CDF quantile (0.5 in this case) does the dependence structure in the synthetic event ensemble match the observations?
- Test 2: Independent events
  - Extract all independent events > 1 in 5 year return period in USGS record
  - Simulate same record length many times using the stochastic method
  - Mean error in no. of events and no. of gauges hit is <5%



Event animation

Costs of avoidance



Ratio of 1 in 100-year flood damage in newly developed, currently unprotected natural floodplains to acquisition cost per 100 km² in 2050 under SSP2