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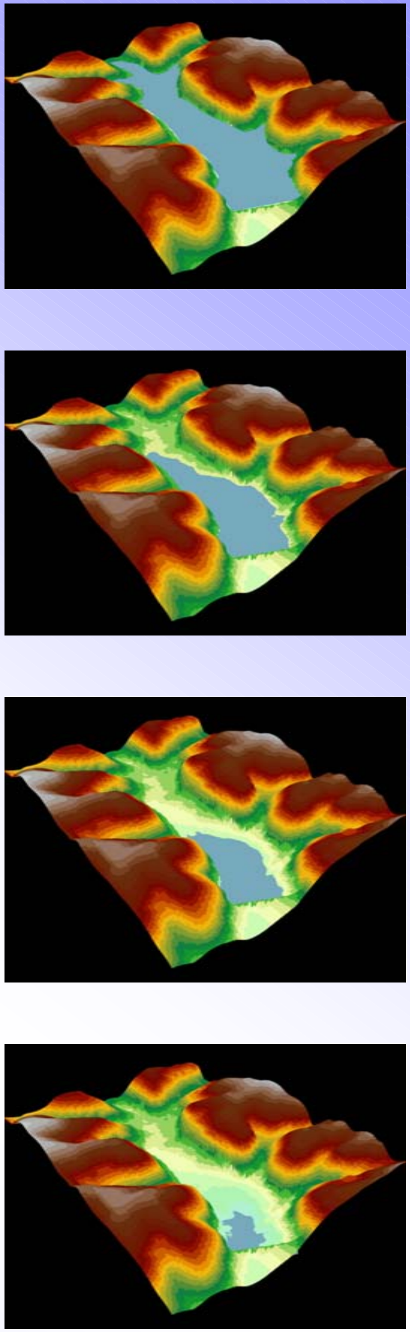
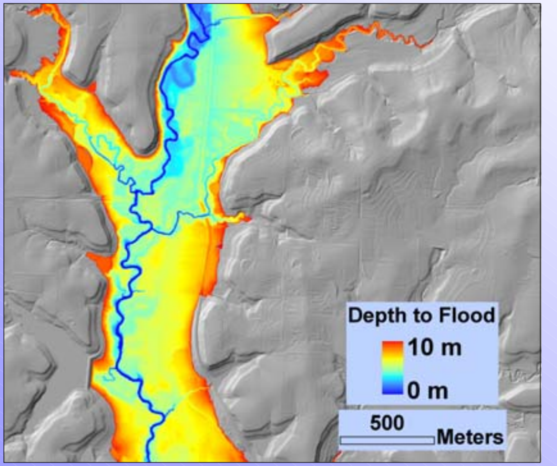
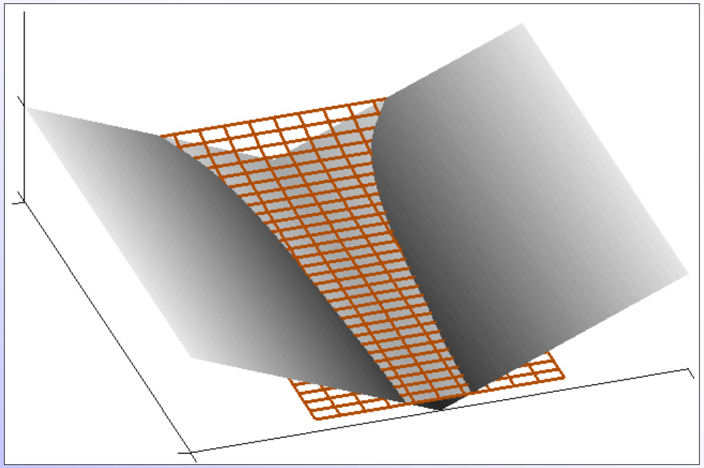
Using Digital Elevation Data for Applications in Floodplain Mapping

Jude H. Kastens (jkastens@ku.edu)







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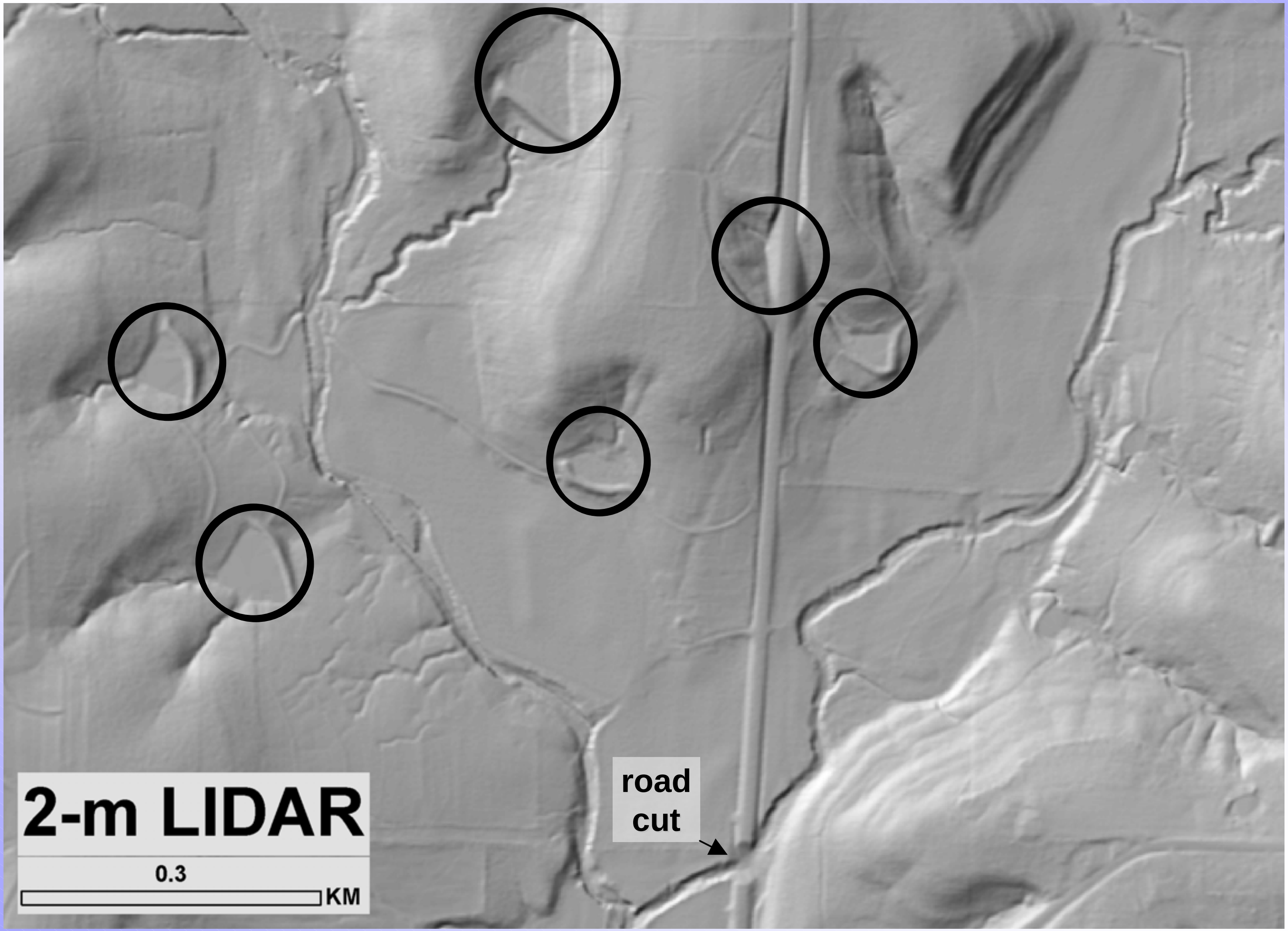
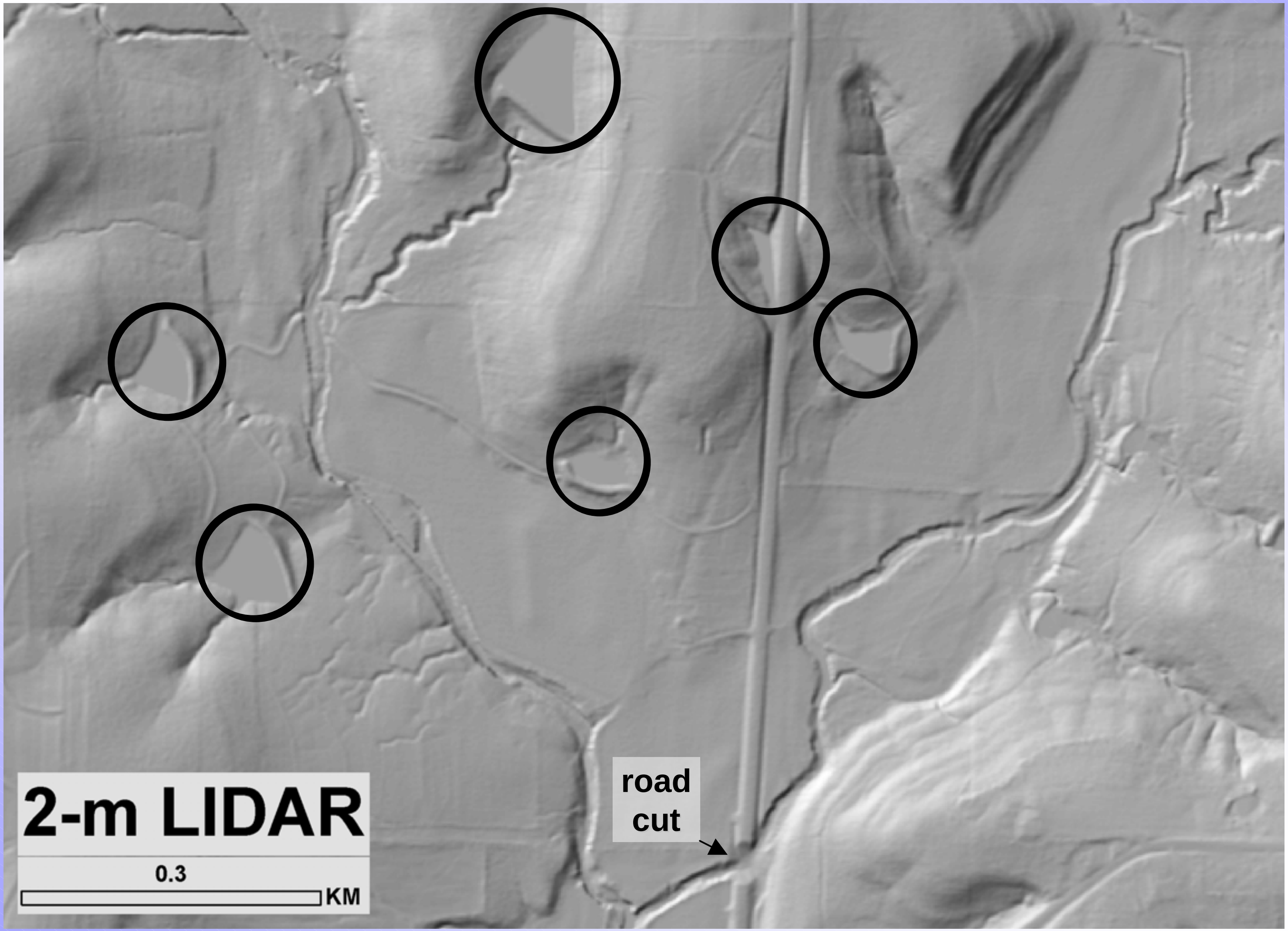
Background Examples: Sink Filling



Digital Elevation Model (DEM)

Background Examples: Sink Filling



DEM with sinks filled (*depressionless DEM*)

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Background Examples: Big River

30-m DEM from the National Elevation Database (NED)

An ~850 km segment of the Missouri River is shown in blue.

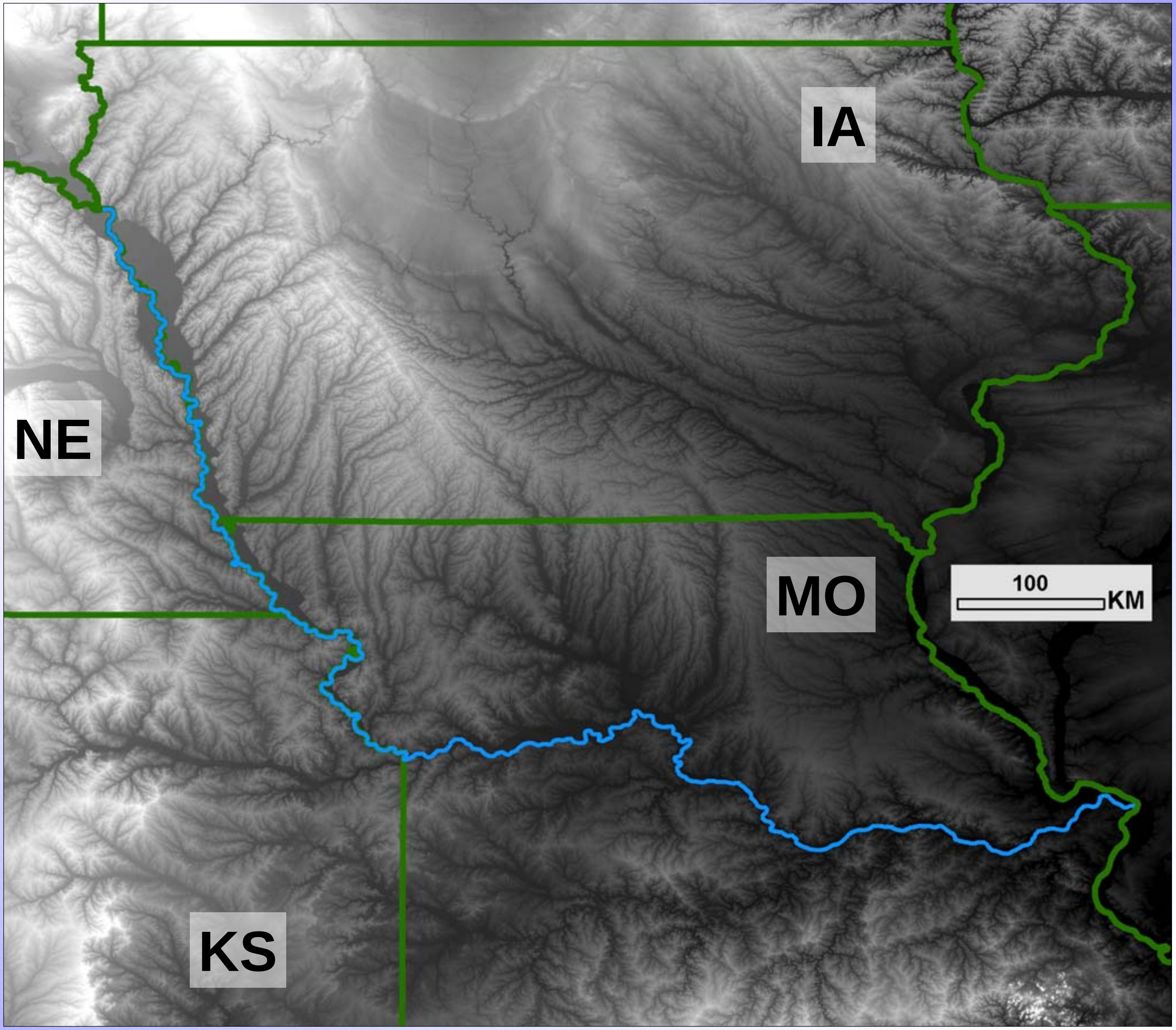
DEM @ start: 329.4 m

DEM @ end: 122.8 m

Matrix Size:

(r,c) = (22948,27275)

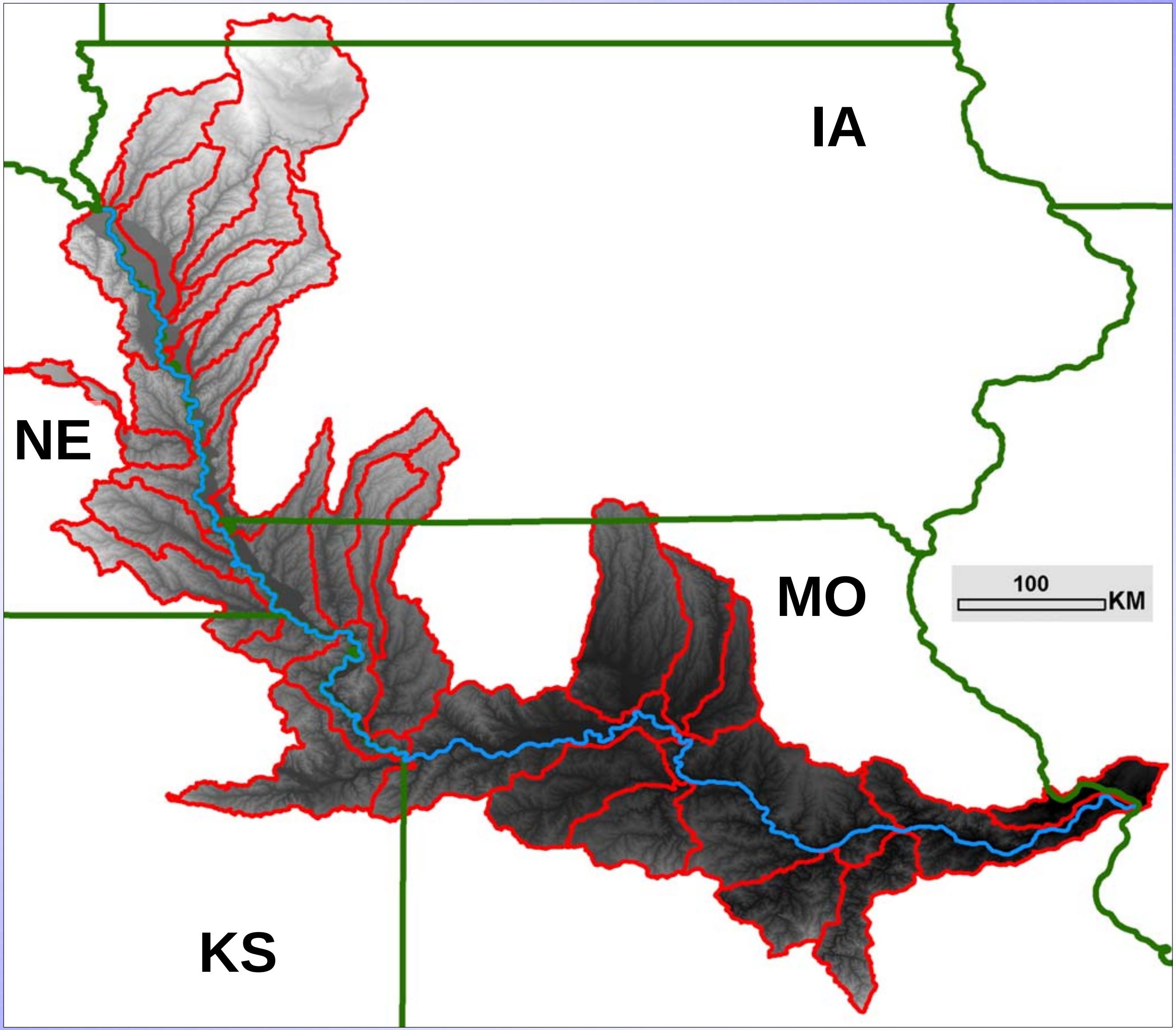
Over 625 million pixels!



Background Examples: Big River

8-digit hydrologic unit code (HUC8) boundaries are shown in red.

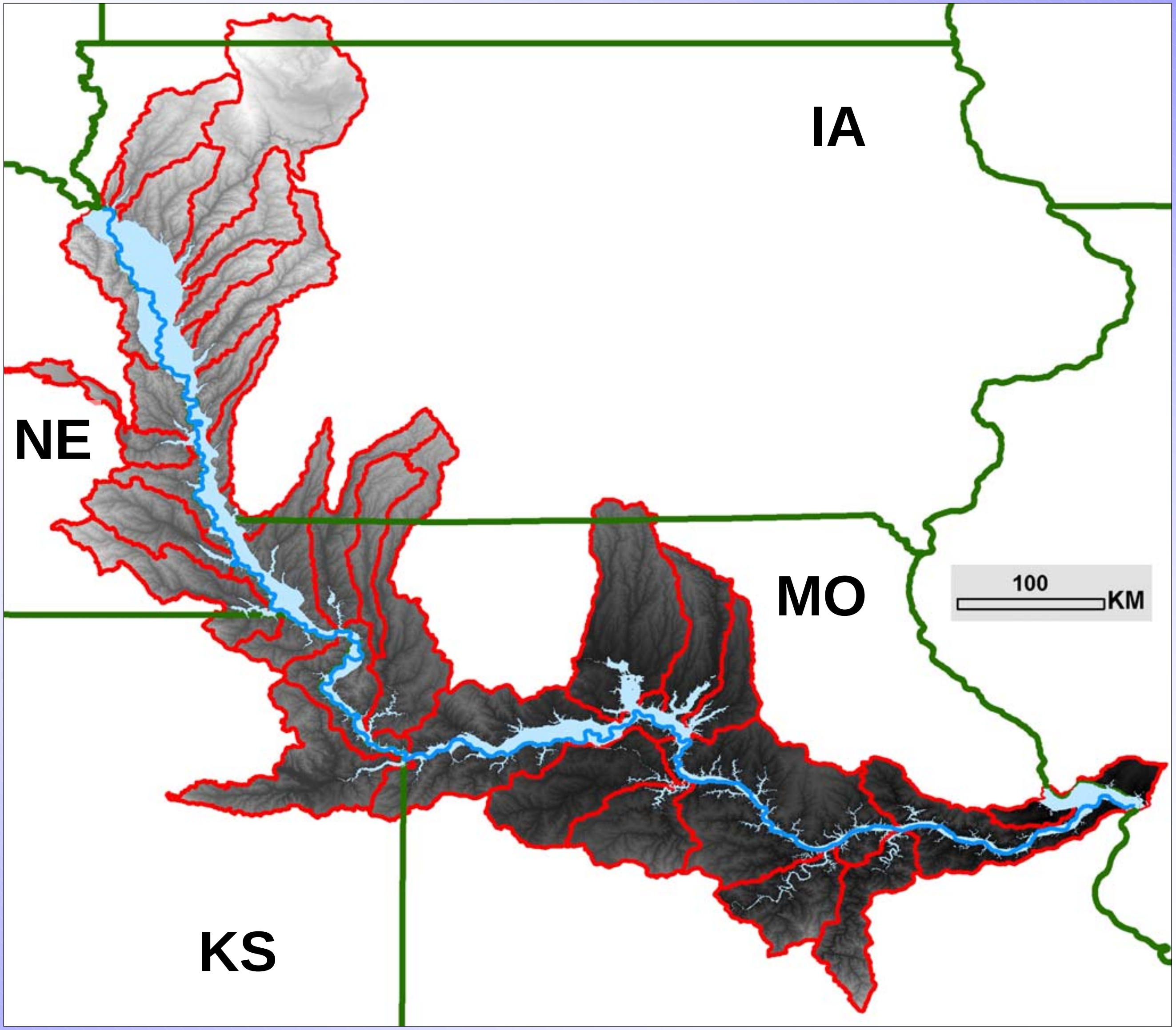
These quasi-watersheds depict local catchments.



Background Examples: Big River

The 16-m floodplain is shown in light blue.

This particular example was used to identify wetlands for research.



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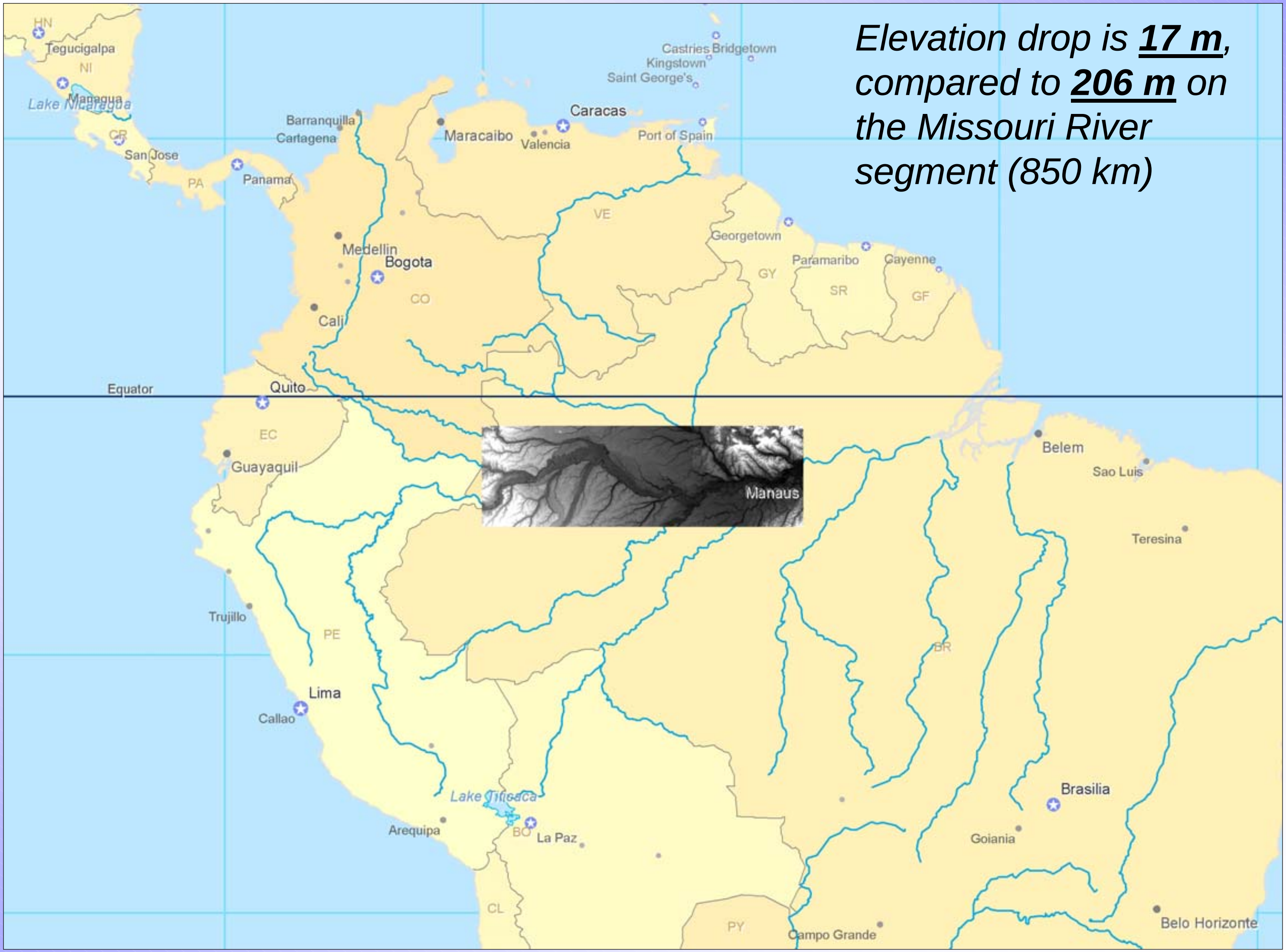
Background Examples: Really Big River

90-m DEM from NED is shown for ~1700 km of the **Amazon River** in South America.

Matrix Size:

(r,c) = (4676,14940)



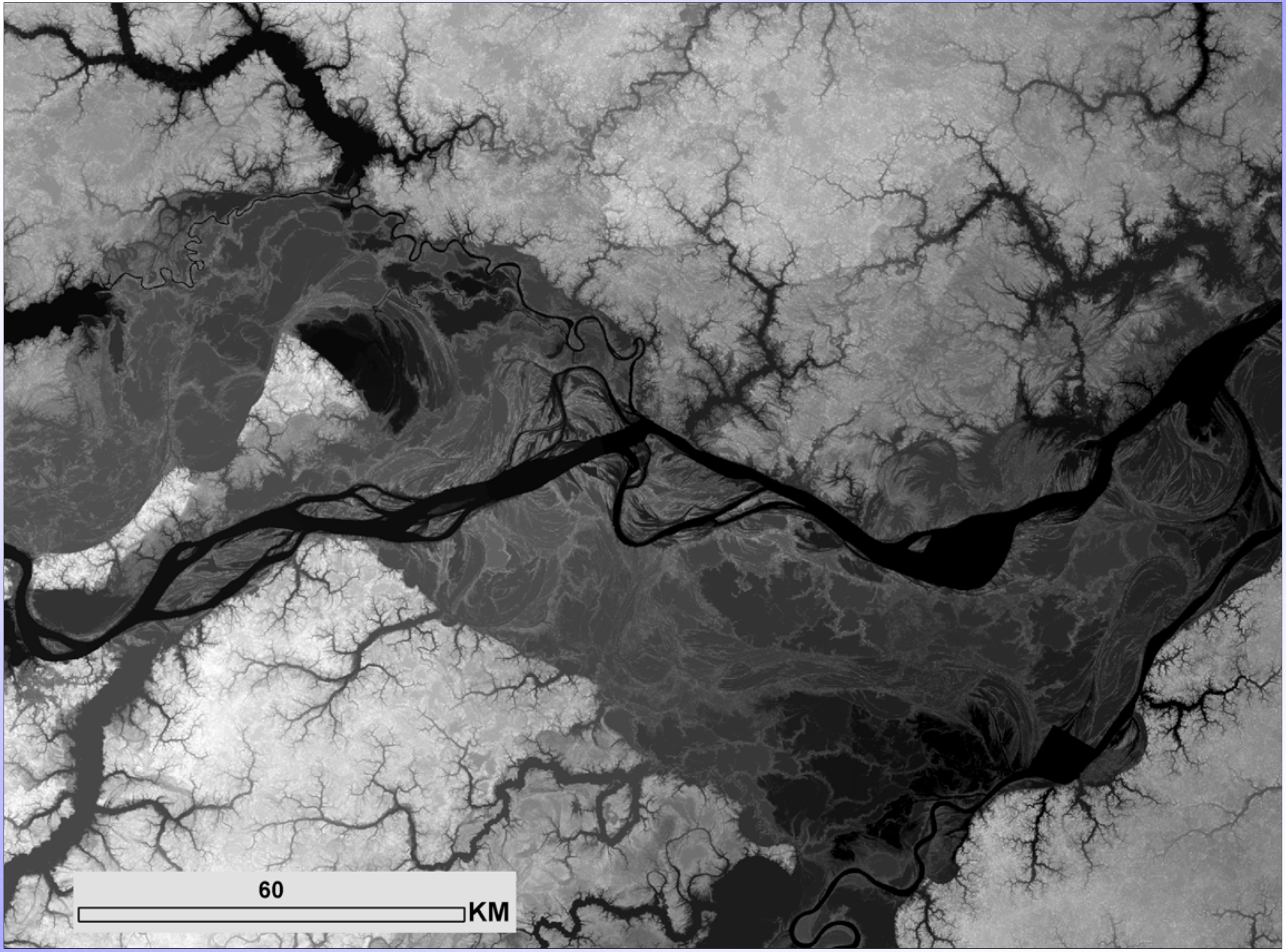
Elevation drop is ***17 m****, compared to* ***206 m*** *on the Missouri River segment (850 km)*

Background Examples: Really Big River

Amazon subset:

Filled DEM

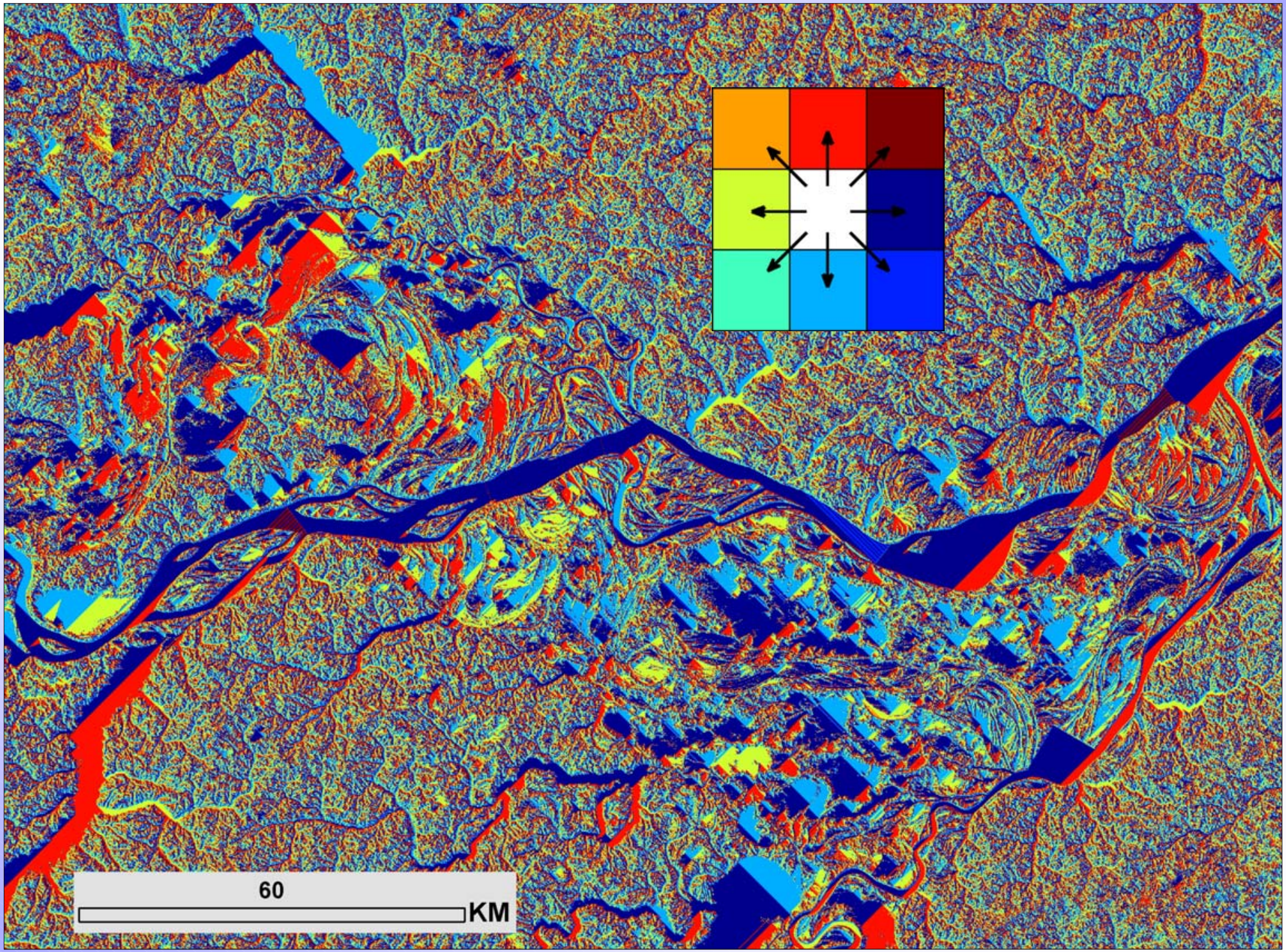
- ***90-m NED data have one meter vertical resolution***



Background Examples: Really Big River

Amazon subset:

Flow Direction



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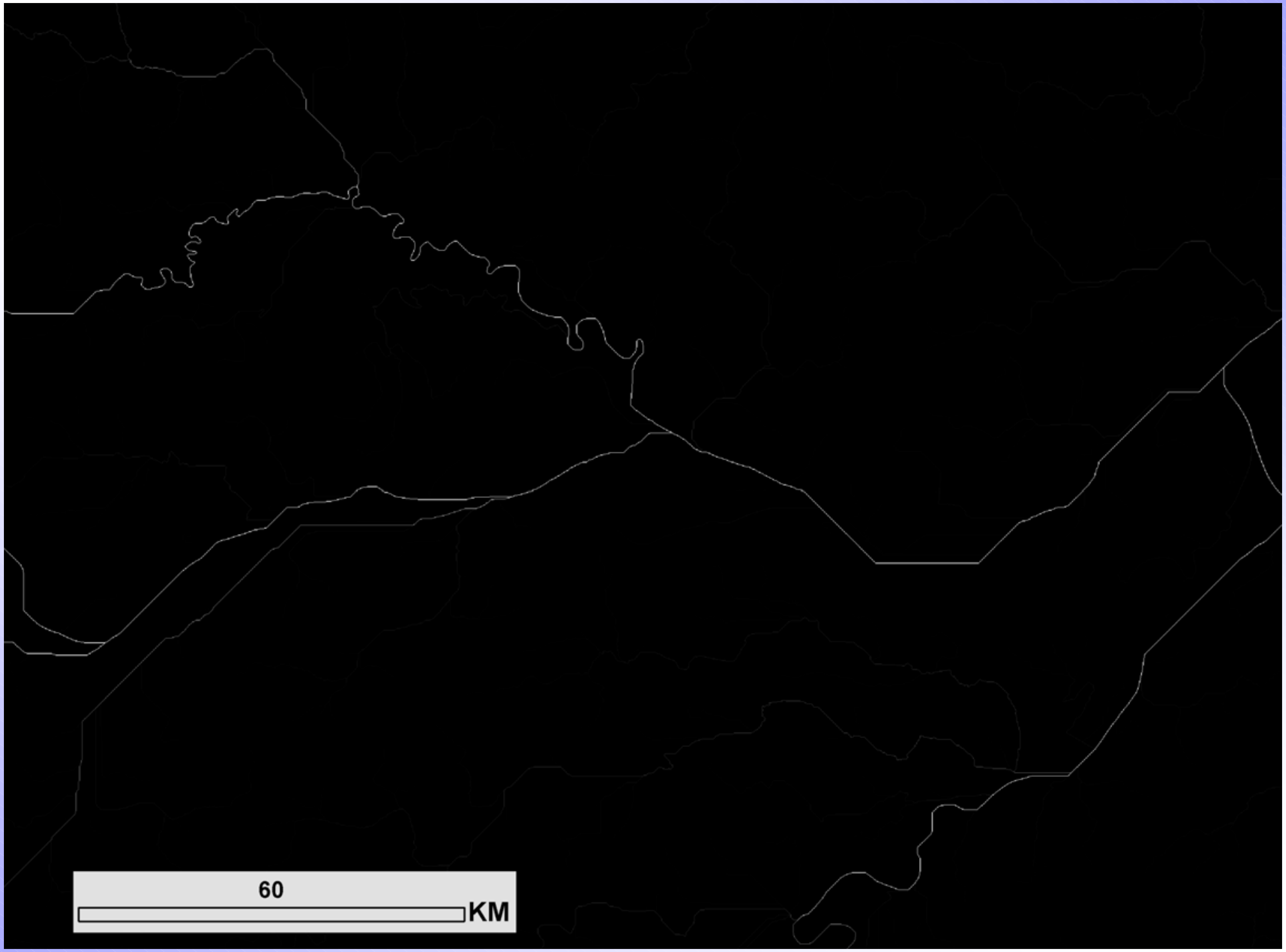
Background Examples: Really Big River

Amazon subset:

Flow Accumulation



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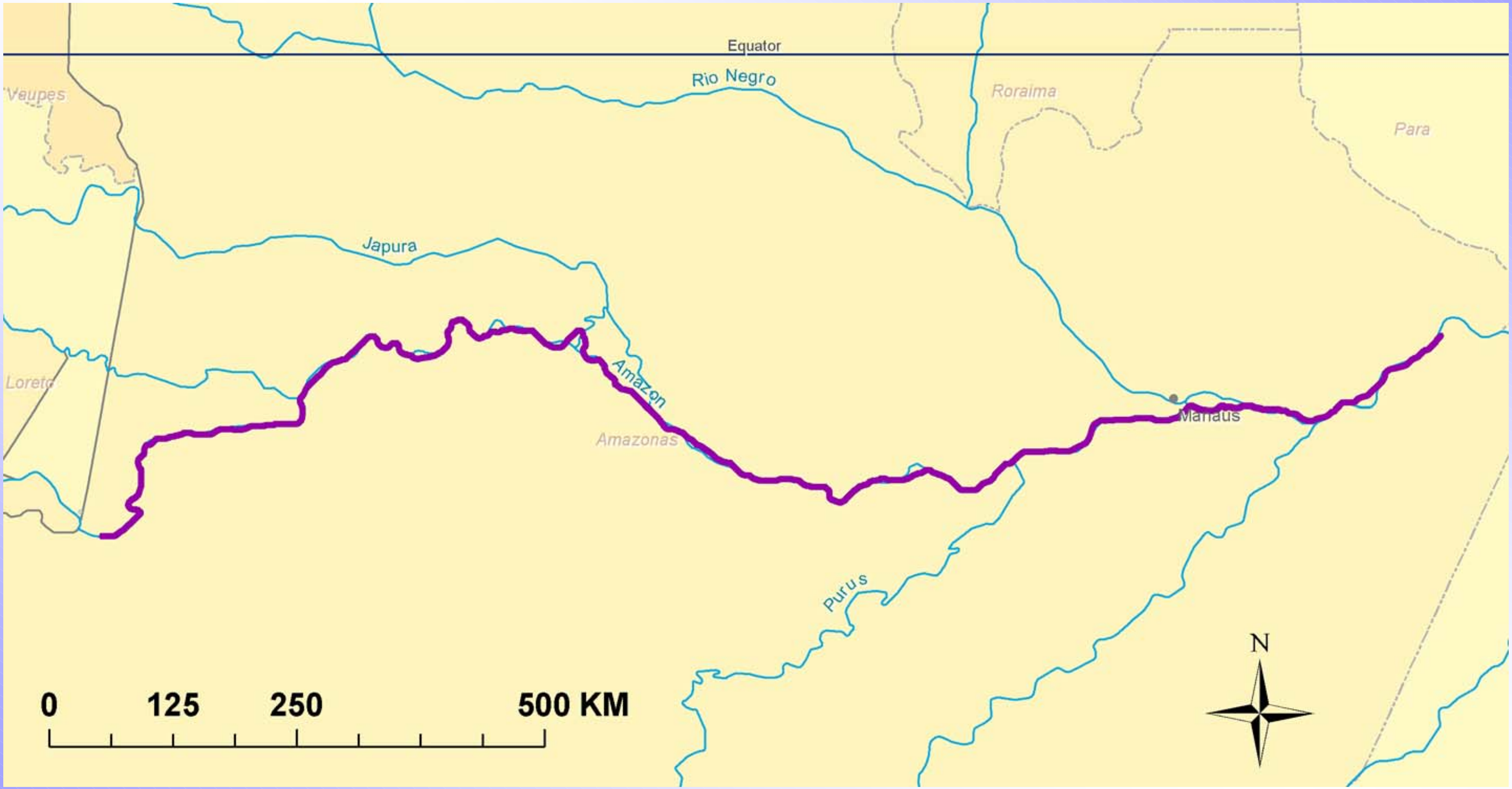
Background Examples: Really Big River



DEM-based Amazon River arc

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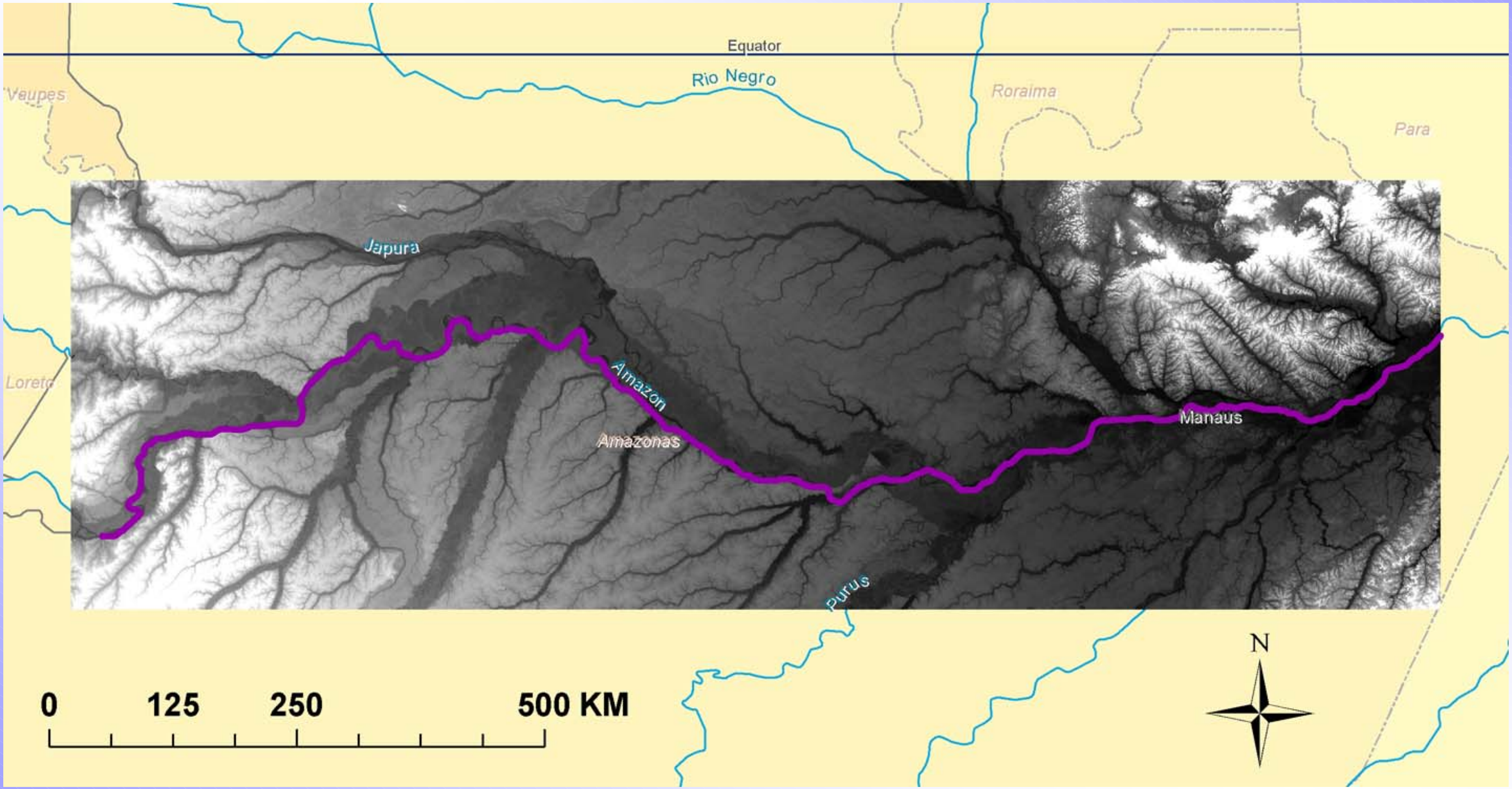
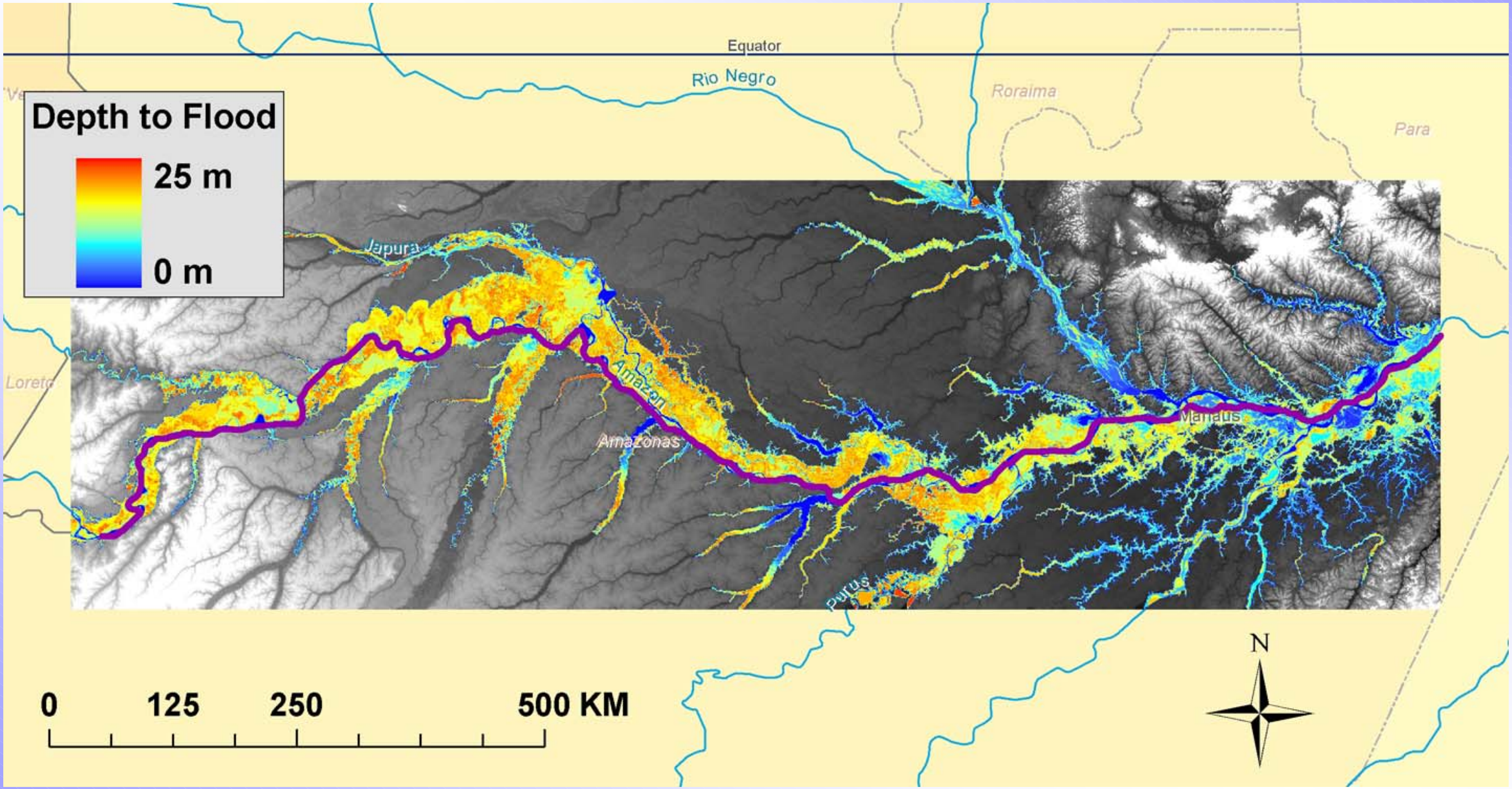
Background Examples: Really Big River



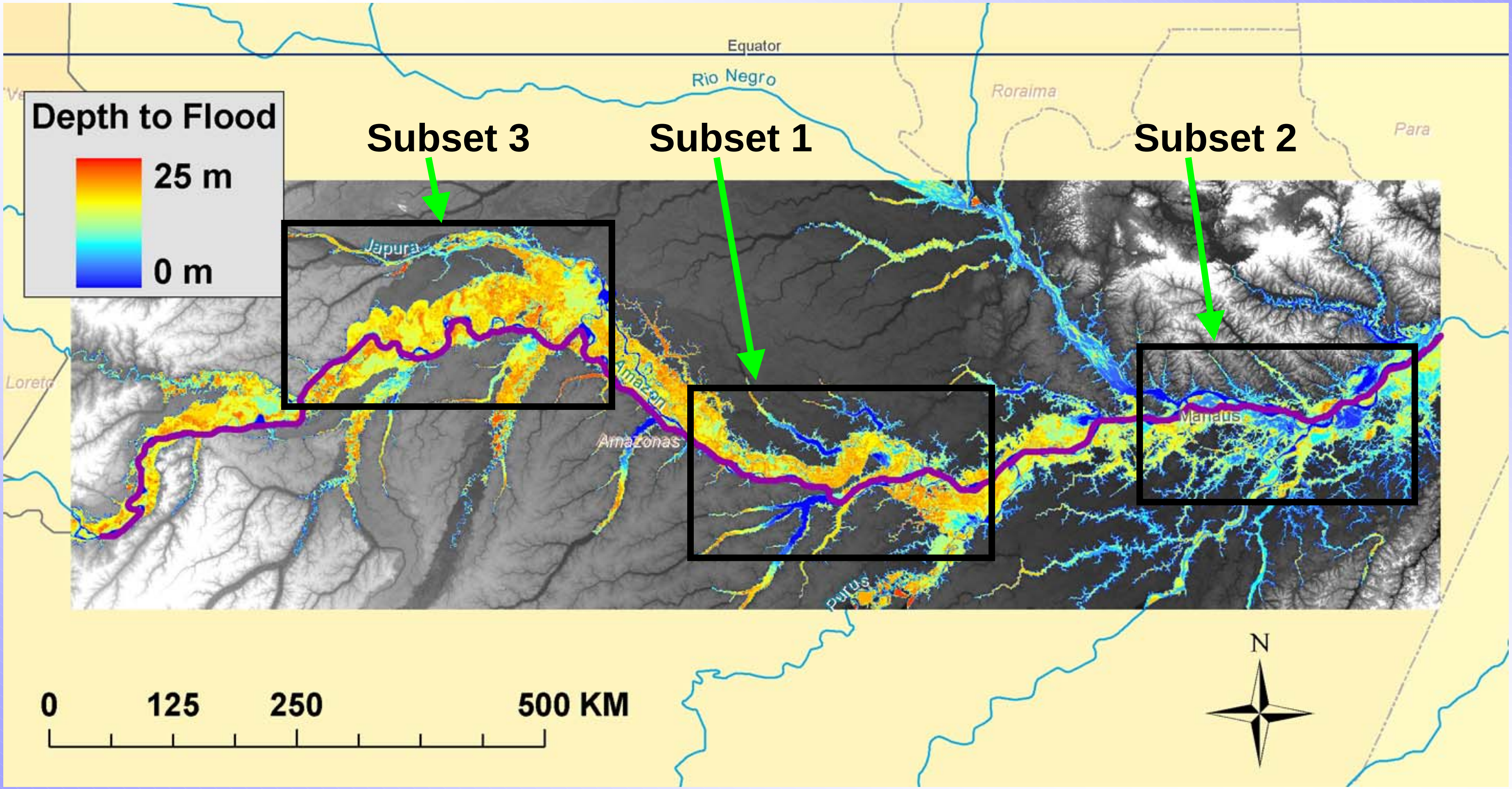
Amazon River arc overlaid on the filled DEM

Background Examples: Really Big River



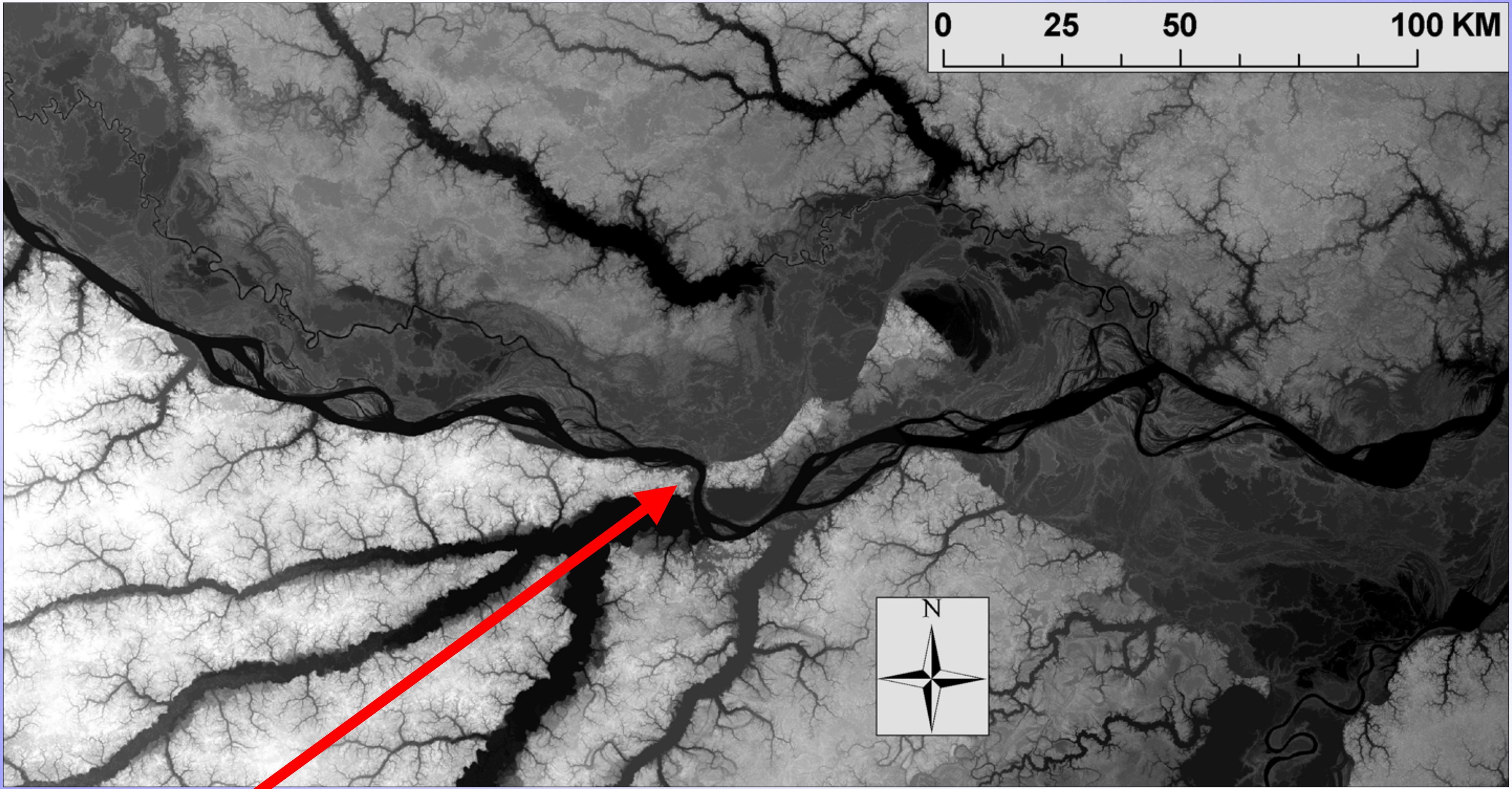
Amazon River, the filled DEM, and the 25-m Floodplain

Background Examples: Really Big River



Taking a closer look….

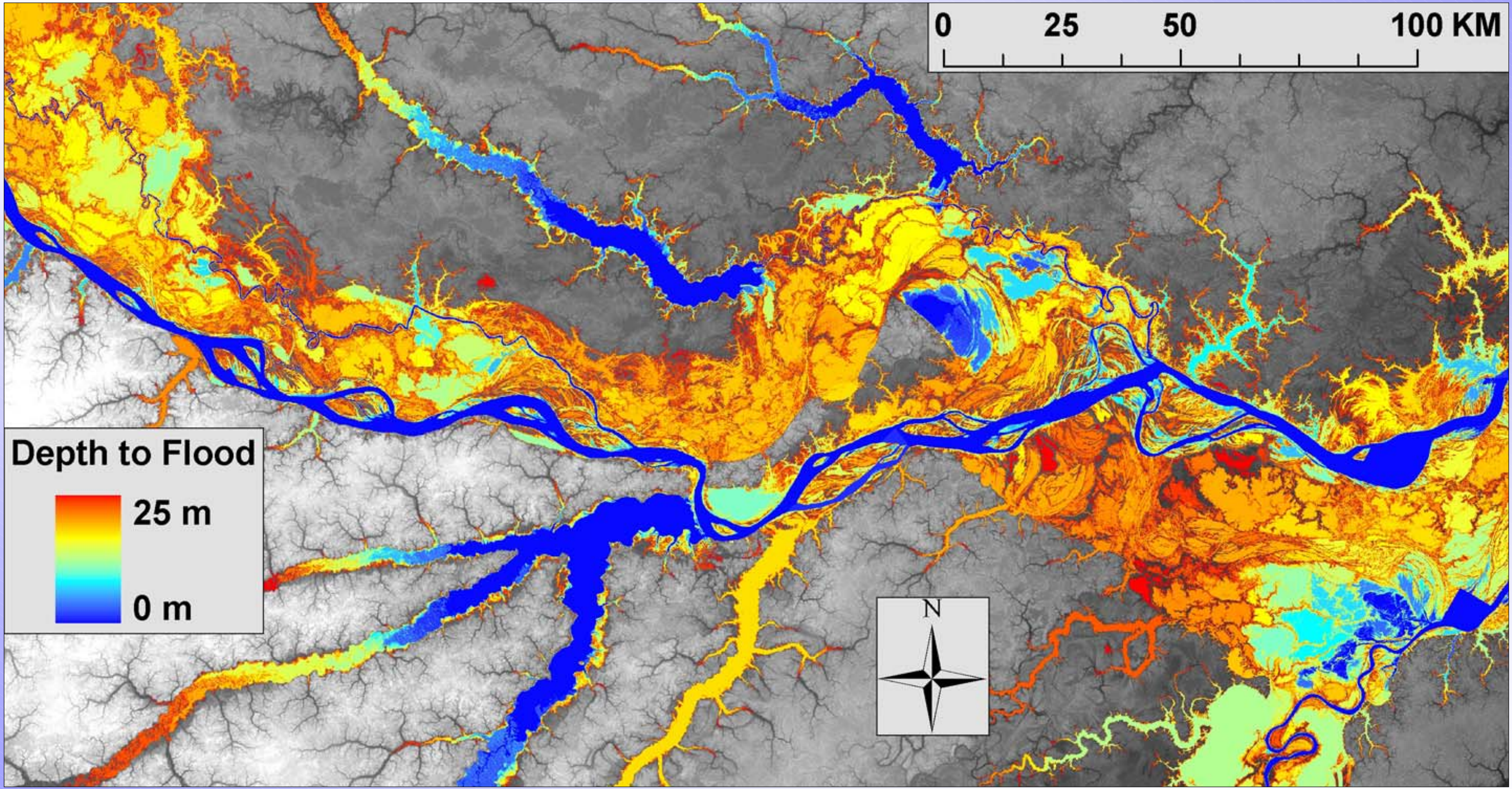
Background Examples: Really Big River



Subset 1: Filled DEM

Note that the river jumped out of the floodplain at some point

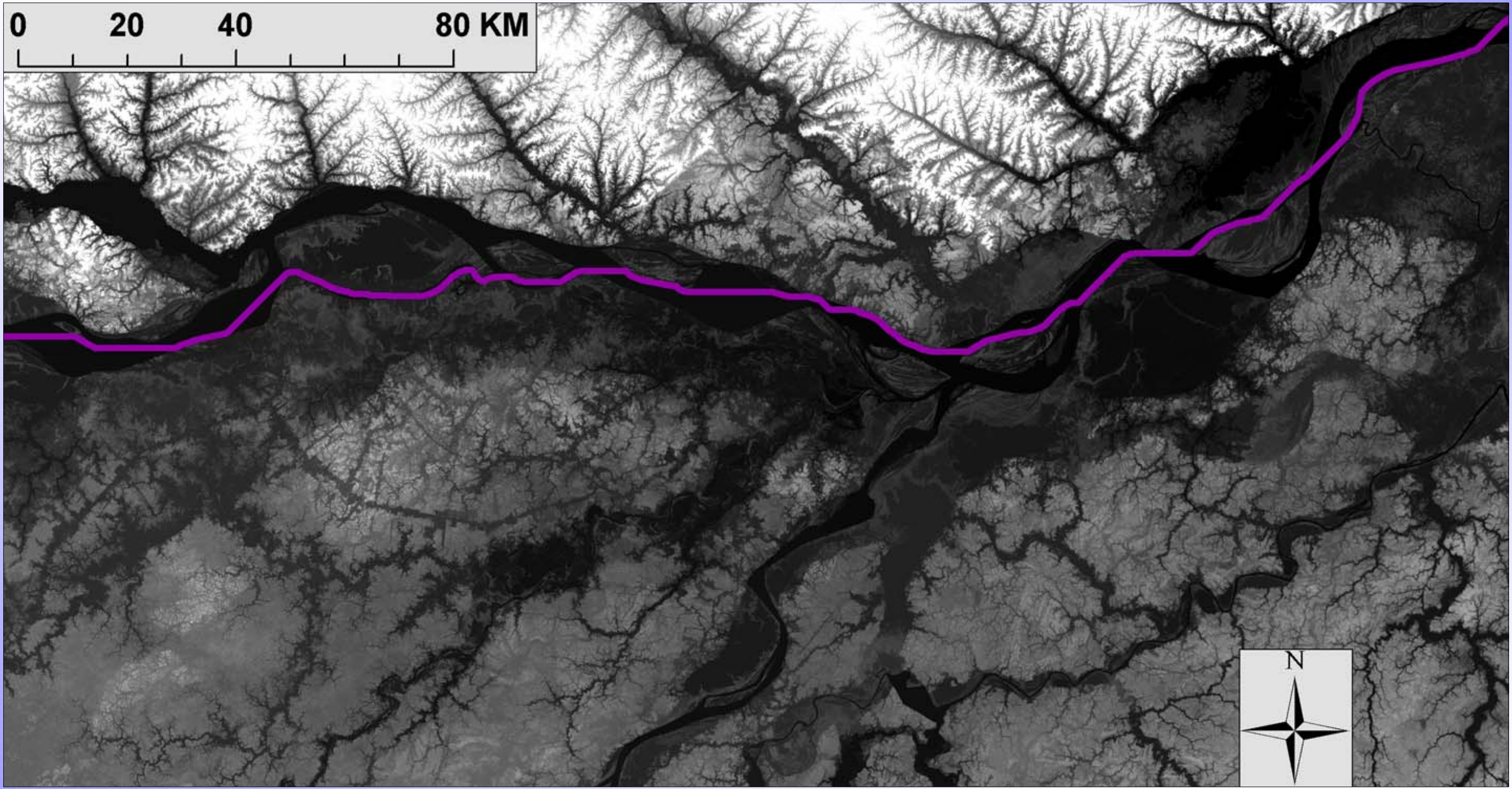
Background Examples: Really Big River



Subset 1: Filled DEM and 25-m Floodplain

Acuity and precision are limited by the V & H resolution

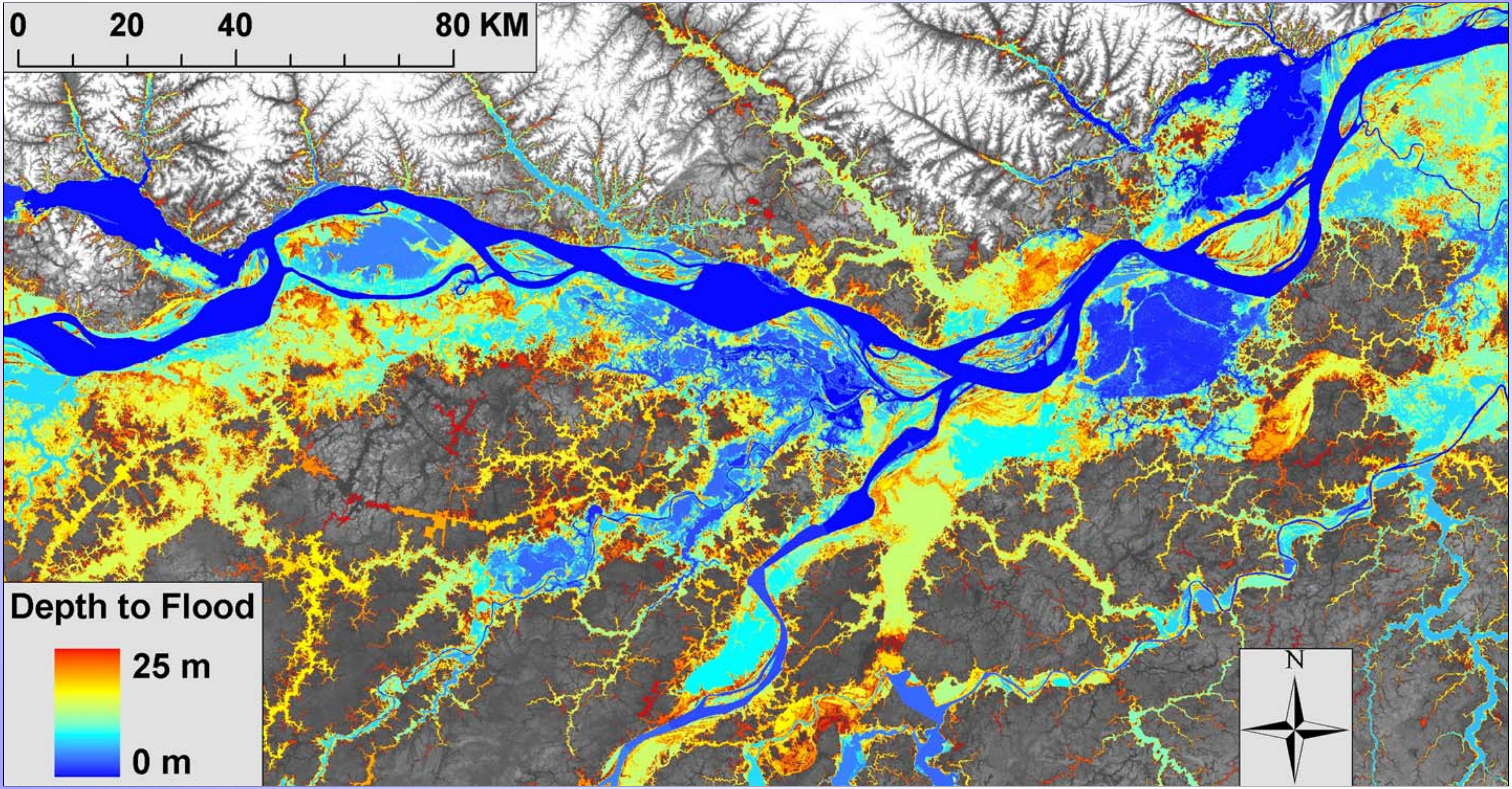
Background Examples: Really Big River



Subset 2: Filled DEM

Business to the North, Party to the South

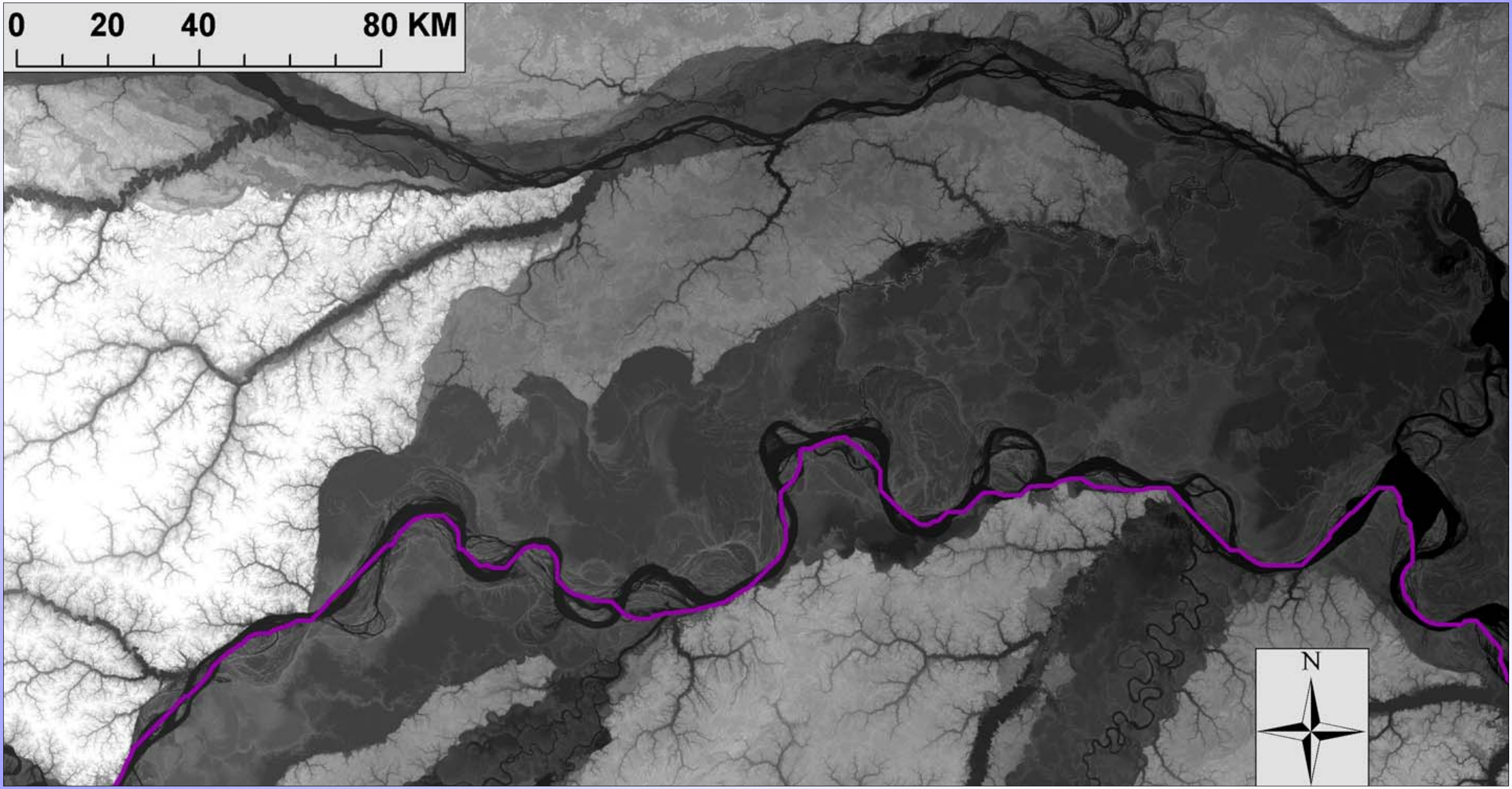
Background Examples: Really Big River



Subset 2: Filled DEM and 25-m Floodplain

Automation is a good thing

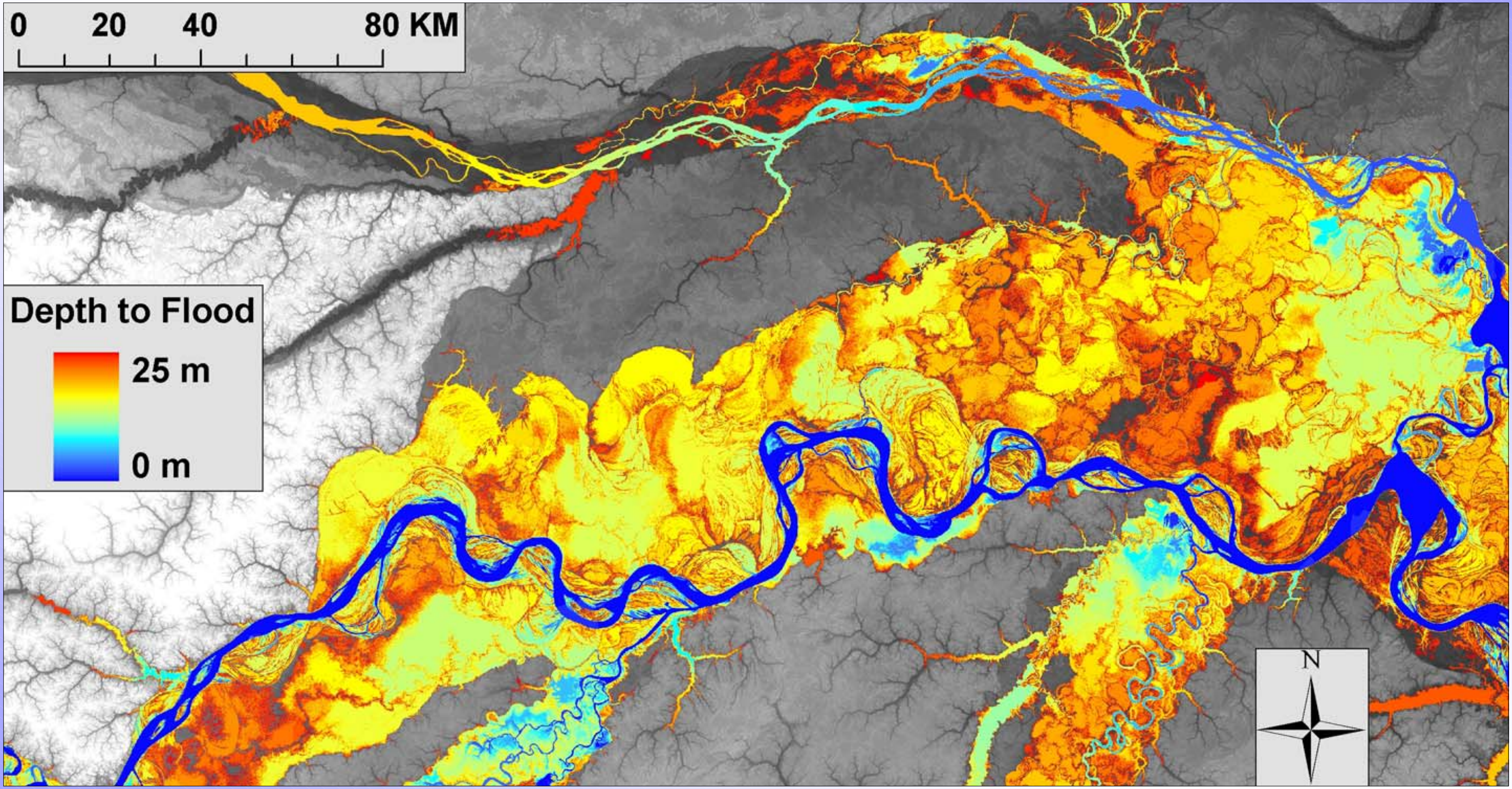
Background Examples: Really Big River



Subset 3: Filled DEM

Floodplain terracing: Nature's Flood Zones

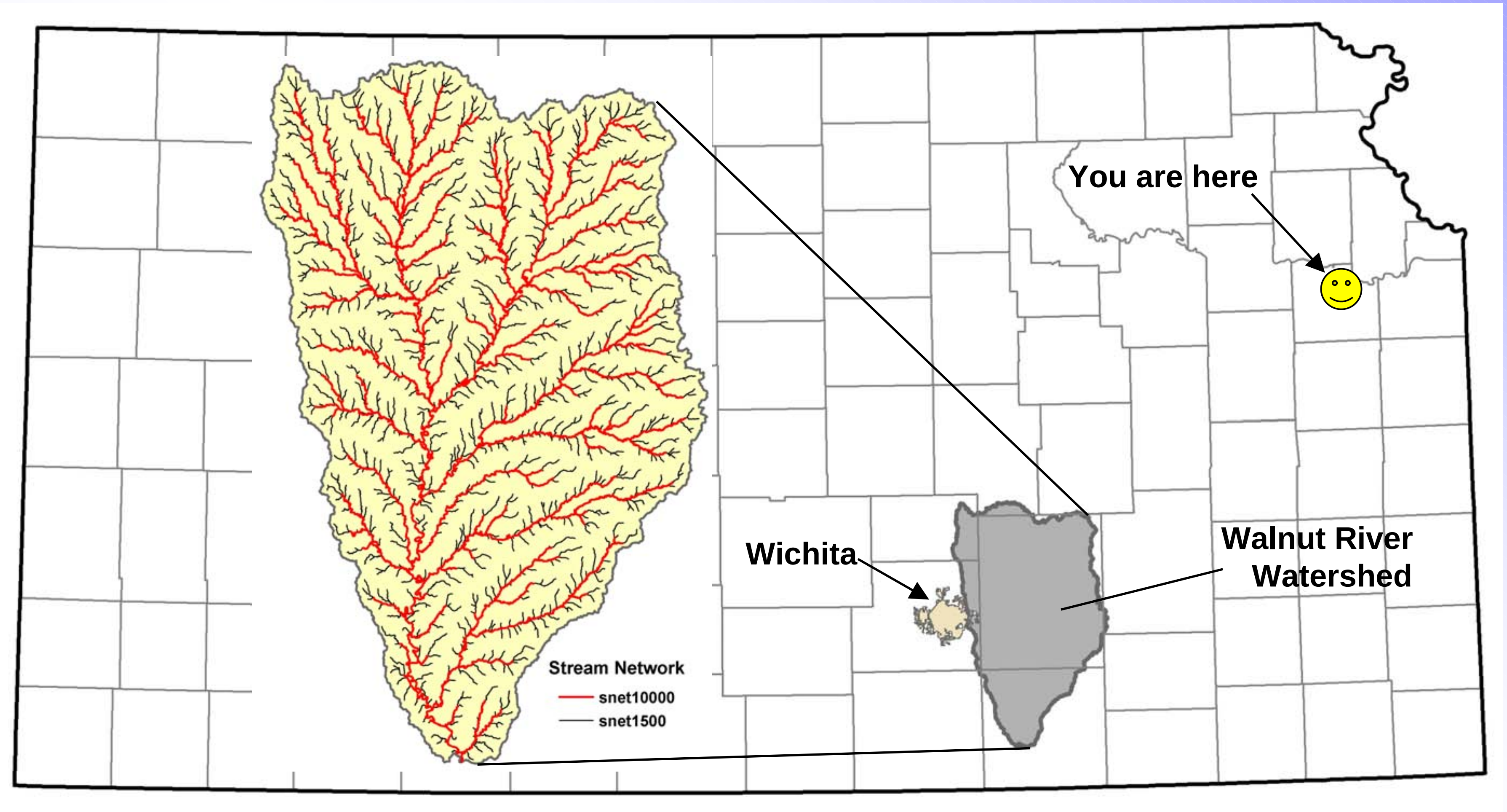
Background Examples: Really Big River



Subset 3: Filled DEM and 25-m Floodplain

Floodplain terracing: Nature's Flood Zones

Background Examples: Drainage Network



Drainage network density depends on catchment size (flow accumulation) threshold.

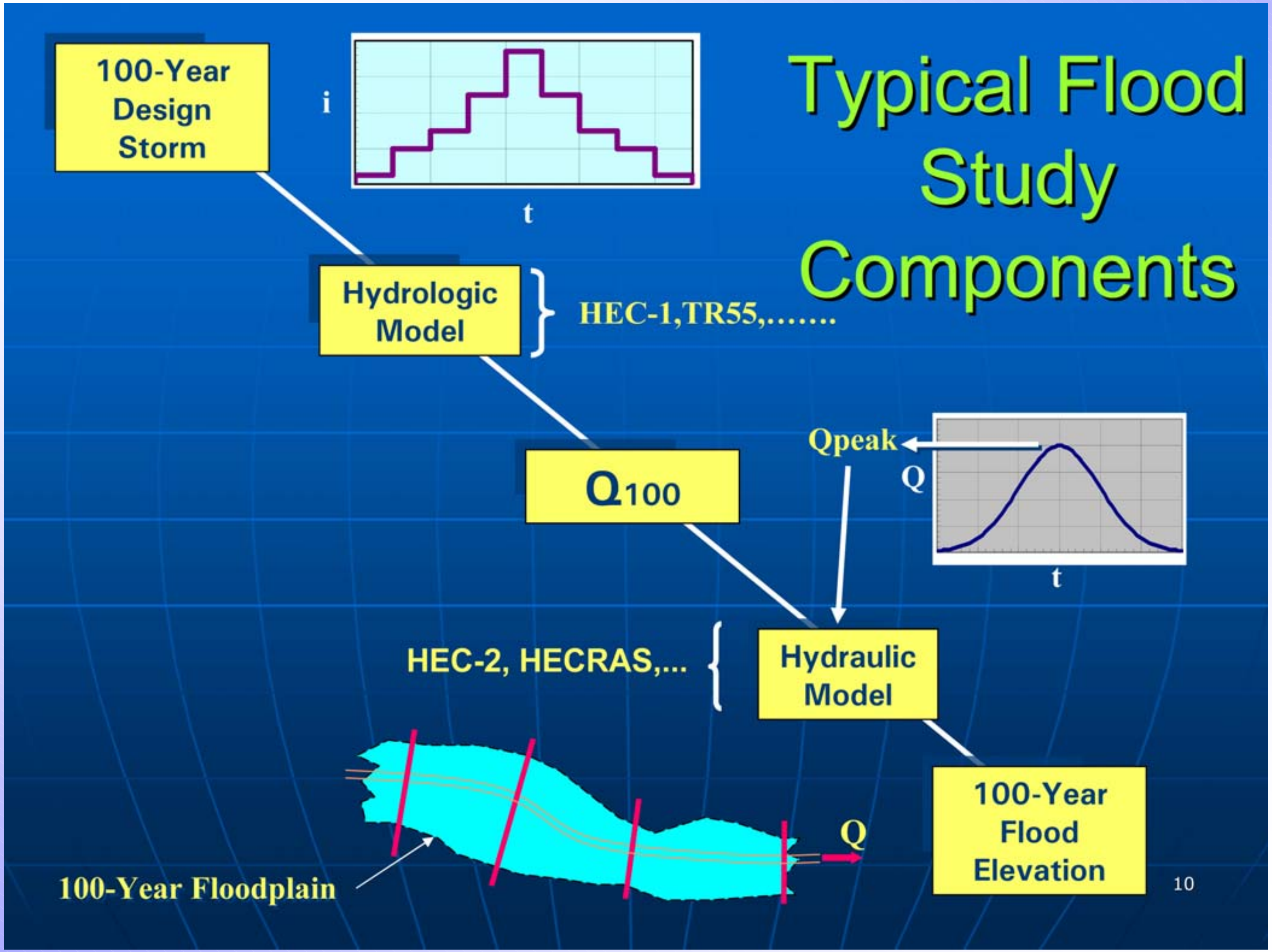
Traditional Flood Event Modeling

Traditional flood modeling methods are dynamic, based on **Navier-Stokes equations** applied in a **free surface flow** setting.

Specifically, the **Saint-Venant “shallow water equations”** are employed.

Examples are the Hydrologic Engineering Center’s River Analysis System (**HEC-RAS**) and the National Weather Service’s **FLDWAV** model.

Flood Event Modeling



Typical Flood Study Components

100-Year Design Storm

Hydrologic Model } HEC-1,TR55,…….

Q100

HEC-2, HECRAS,… { Hydraulic Model

100-Year Flood Elevation

100-Year Floodplain

10

From Dr. A. David Parr's CE855 "Free Surface Flow II" course materials.

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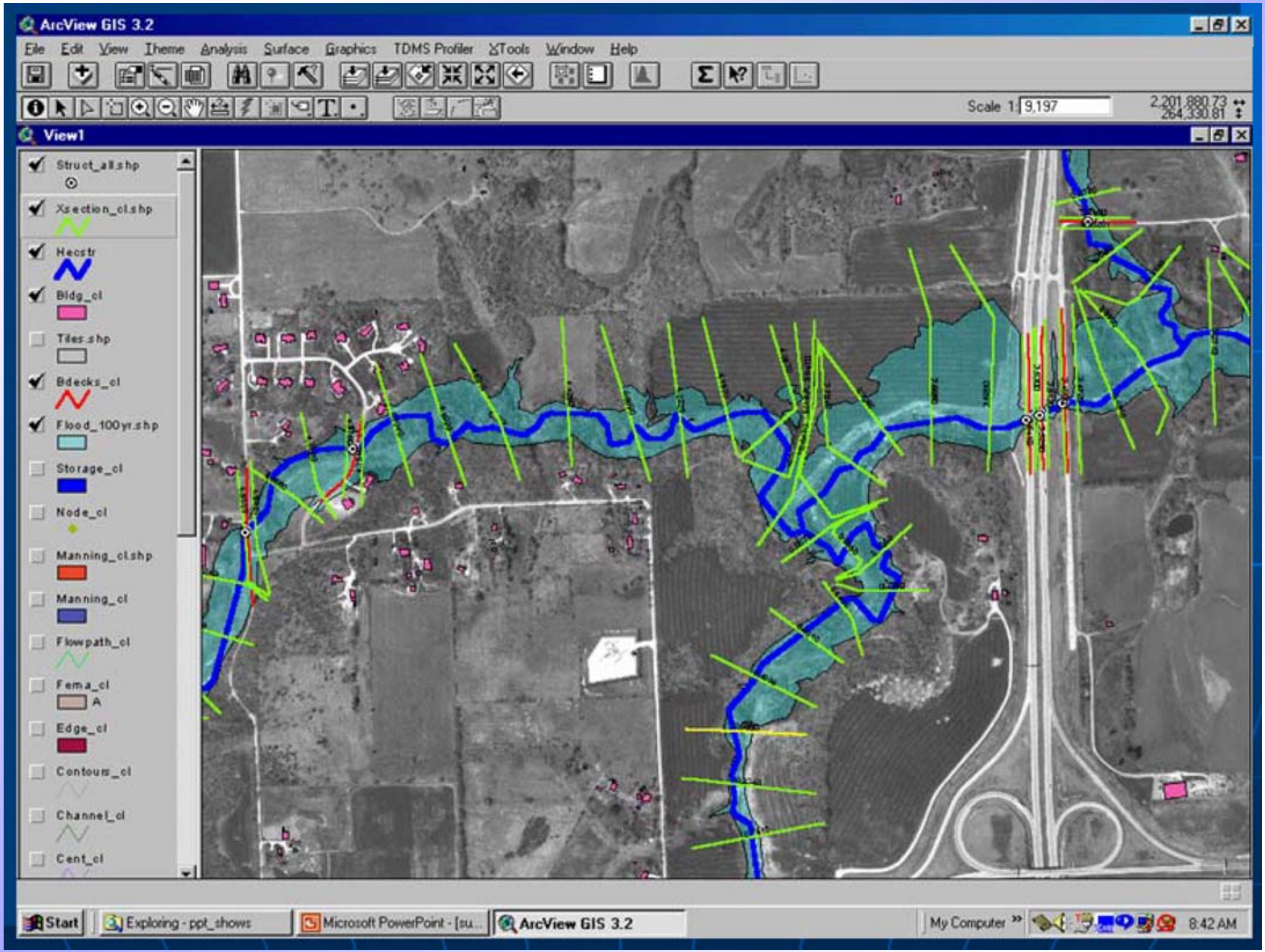
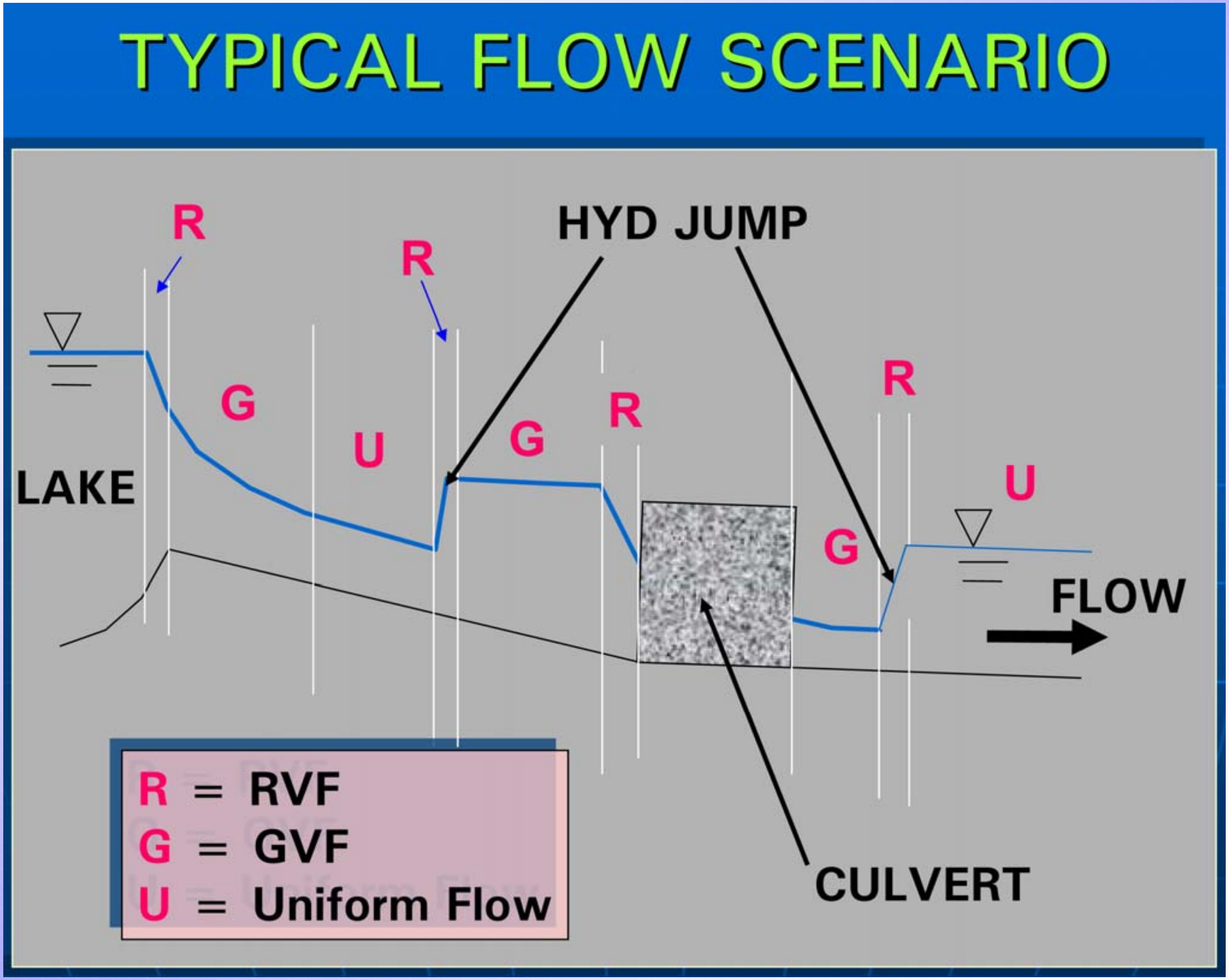
Flood Event Modeling



From Dr. A. David Parr’s CE855 “Free Surface Flow II” course materials.

Flood Event Modeling

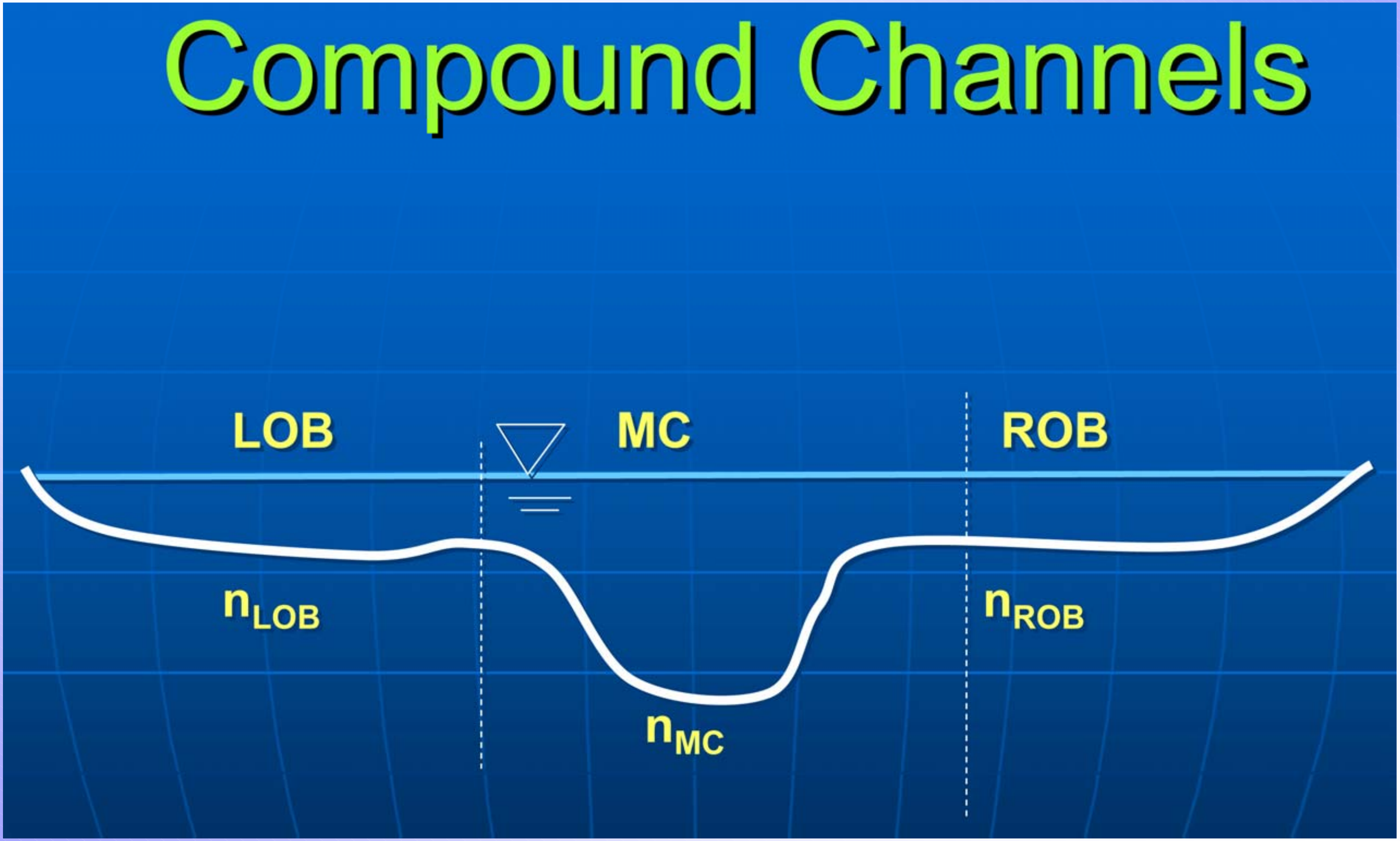


TYPICAL FLOW SCENARIO

R = RVF
G = GVF
U = Uniform Flow

From Dr. A. David Parr’s CE855 “Free Surface Flow II” course materials.

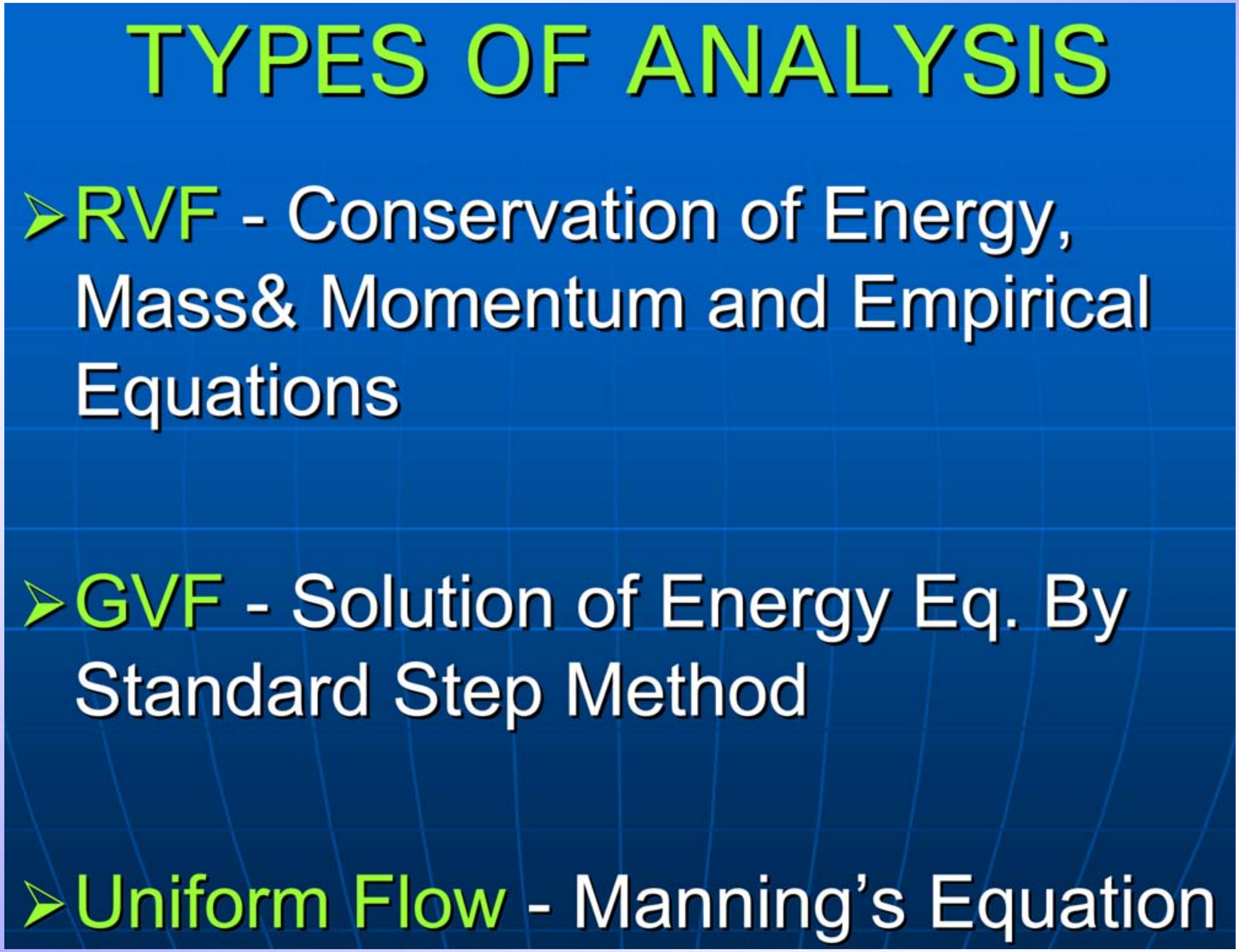
Flood Event Modeling



Compound Channels

From Dr. A. David Parr’s CE855 “Free Surface Flow II” course materials.

Flood Event Modeling

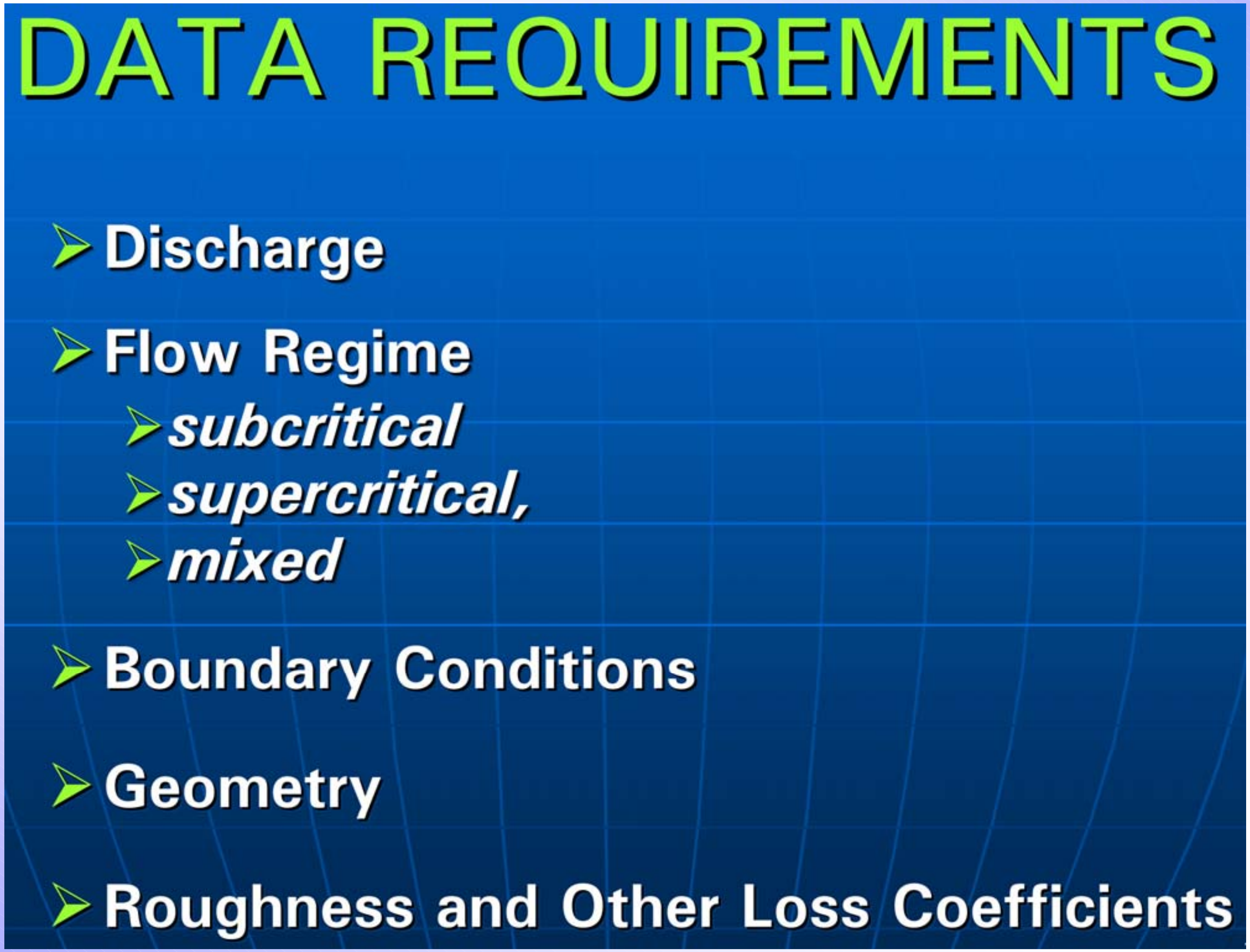


TYPES OF ANALYSIS

- RVF - Conservation of Energy, Mass& Momentum and Empirical Equations
- GVF - Solution of Energy Eq. By Standard Step Method
- Uniform Flow - Manning's Equation

From Dr. A. David Parr's CE855 "Free Surface Flow II" course materials.

Flood Event Modeling

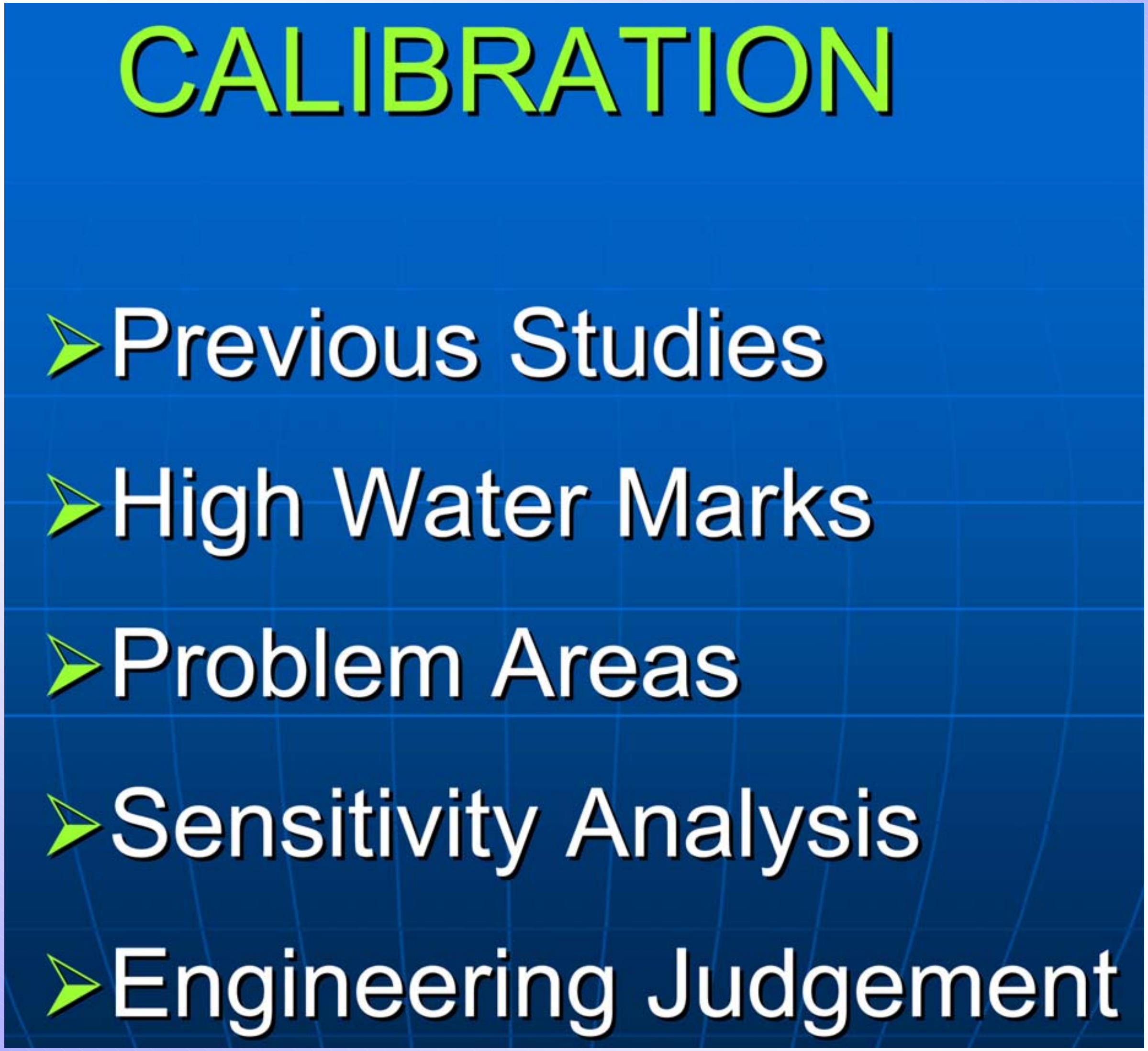


DATA REQUIREMENTS

- **Discharge**
- **Flow Regime**
  - ***subcritical***
  - ***supercritical,***
  - ***mixed***
- **Boundary Conditions**
- **Geometry**
- **Roughness and Other Loss Coefficients**

From Dr. A. David Parr’s CE855 “Free Surface Flow II” course materials.

Flood Event Modeling



CALIBRATION

- Previous Studies
- High Water Marks
- Problem Areas
- Sensitivity Analysis
- Engineering Judgement

From Dr. A. David Parr’s CE855 “Free Surface Flow II” course materials.

Traditional Flood Event Modeling

The bottom line: Traditional flood modeling methods are useful for simulating a wide variety of scenarios. However, implementing such models is a highly involved task.

The models require many inputs AND substantial professional training/experience for implementation.

Model outputs must be examined and the model re-calibrated until an acceptable, physically reasonable solution is obtained.

Recent developments have incorporated 2-D diffusion wave models (e.g., JFLOW, LISFLOOD). These approaches better utilize the detailed topographic information found in DEMs, and can help improve the 1-D models.

Floodplain Delineation

The ***Floodplain Algorithm*** was developed at the Kansas Biological Survey (KBS) to permit parametrically simple, automated floodplain delineation.

The algorithm requires:

- DEM data
- DEM-derived flow direction data
- DEM-derived set of starting points, typically identifying a stream segment or network
- Two user inputs: one or more water surface elevation **or** maximum flood depth values, **and** a flood depth step size (for iteration)

The Flood Zone Map*

**A replica of floodplain topography, but with the stream slope removed*

The Flood Zone Map:

- *Specifies “depth to flood” required for inundation (the map)*
- *Links each floodplain pixel to its most immediate “flood source pixel” in the stream channel (in a separate database)*

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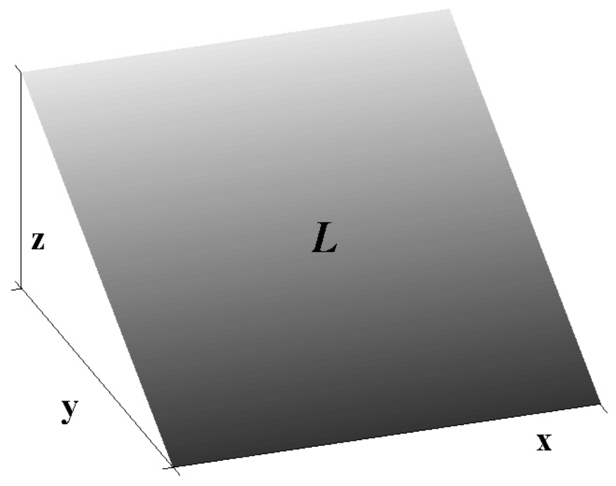
The Flood Zone Map



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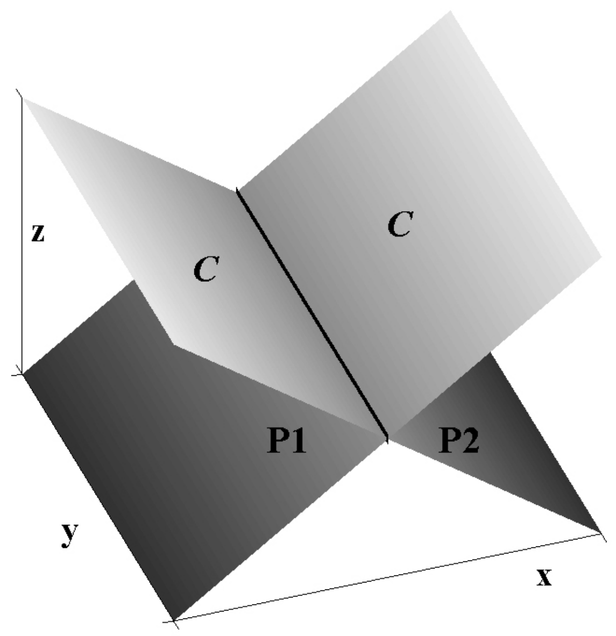

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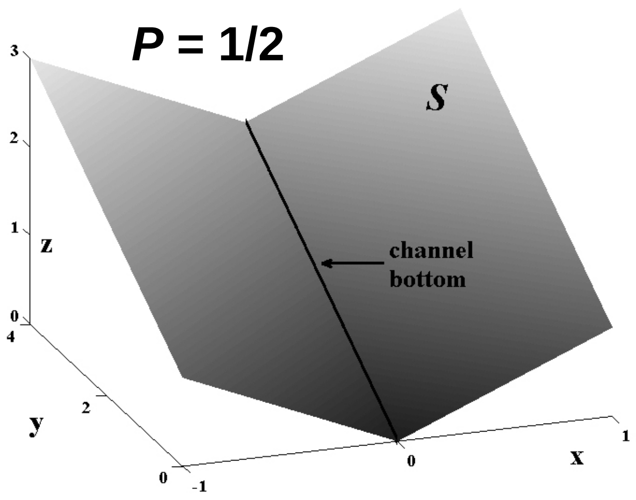


L **= landscape plane**

C **= horizontal channel**

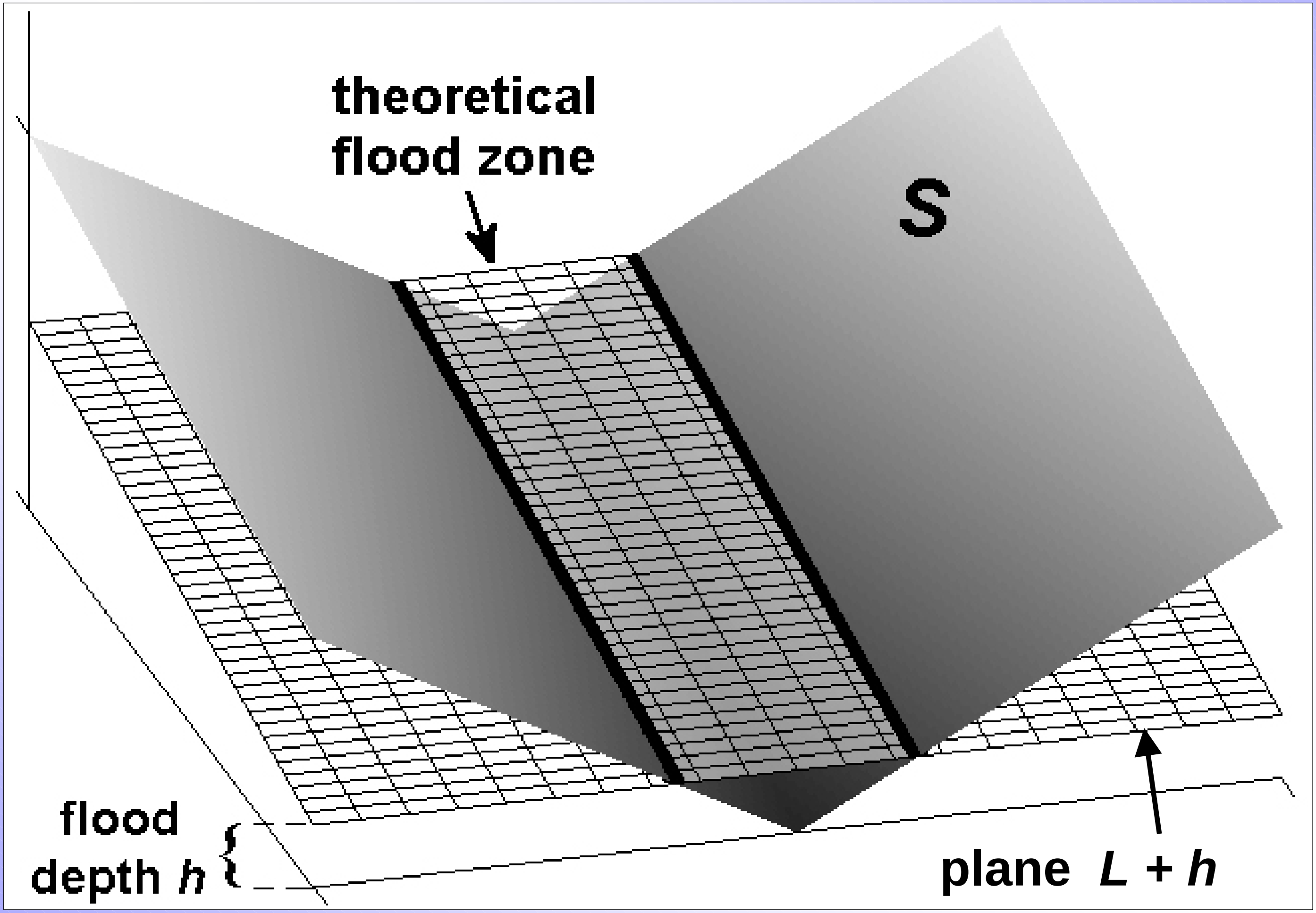
S **=** ***L*** **+** ***C*** **= pitched channel**

channel pitch:

$$P = |\partial z/\partial y| / |\partial z/\partial x|$$

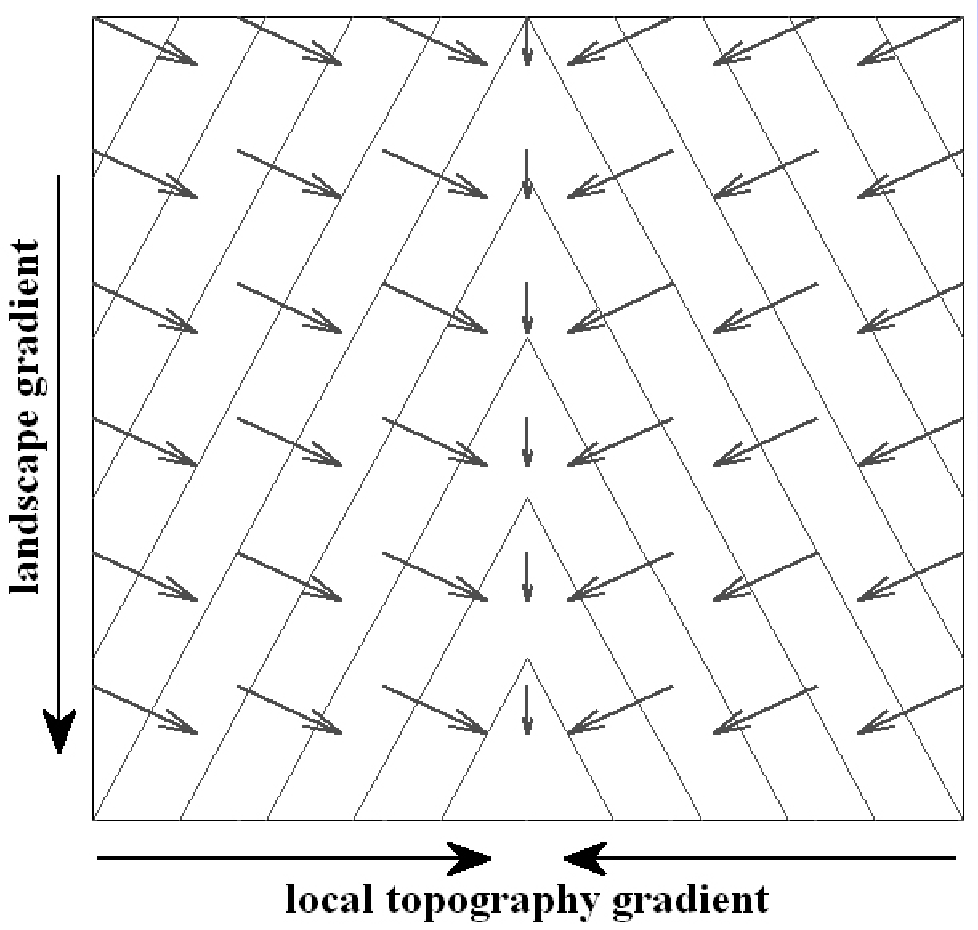
Define the “pitched channel” to aid concept development.

The Flood Zone Map



Must approximate the theoretical flood zone

The Flood Zone Map



channel pitch:

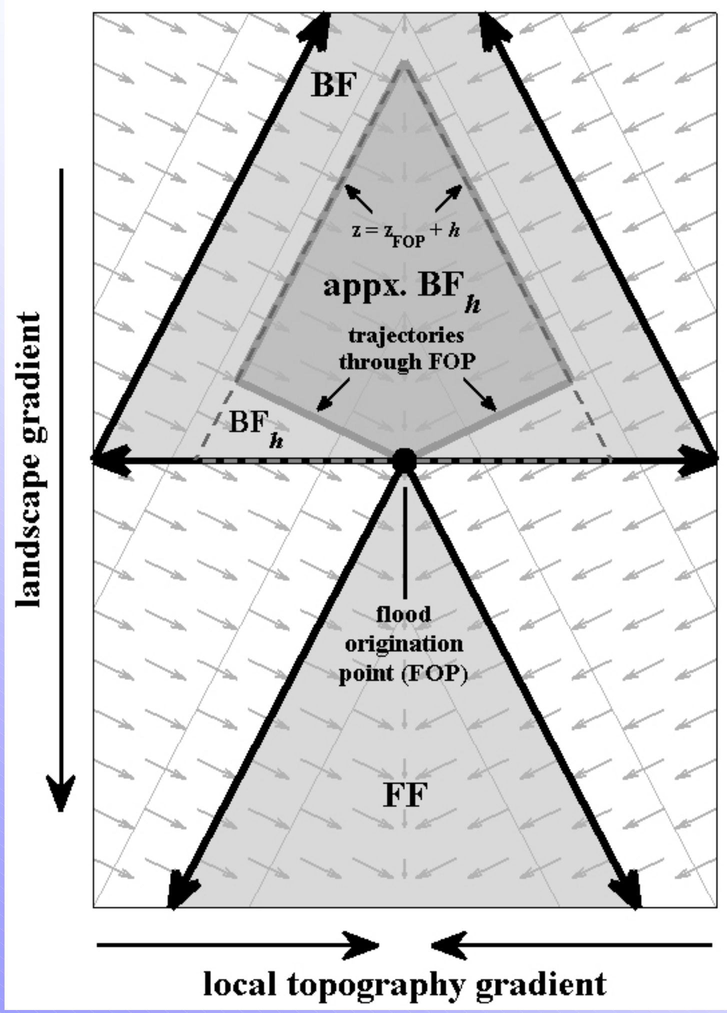
***P* = |∂*z*/∂*y*|/ |∂*z*/∂*x*|**

= 1/2

The gradient and contour map around the channel bottom of surface ***S***

The Flood Zone Map

Conceptualize the flood zones for a single ***flood origination point* (FOP)** at the bottom of the channel:



FF = forward flood zone

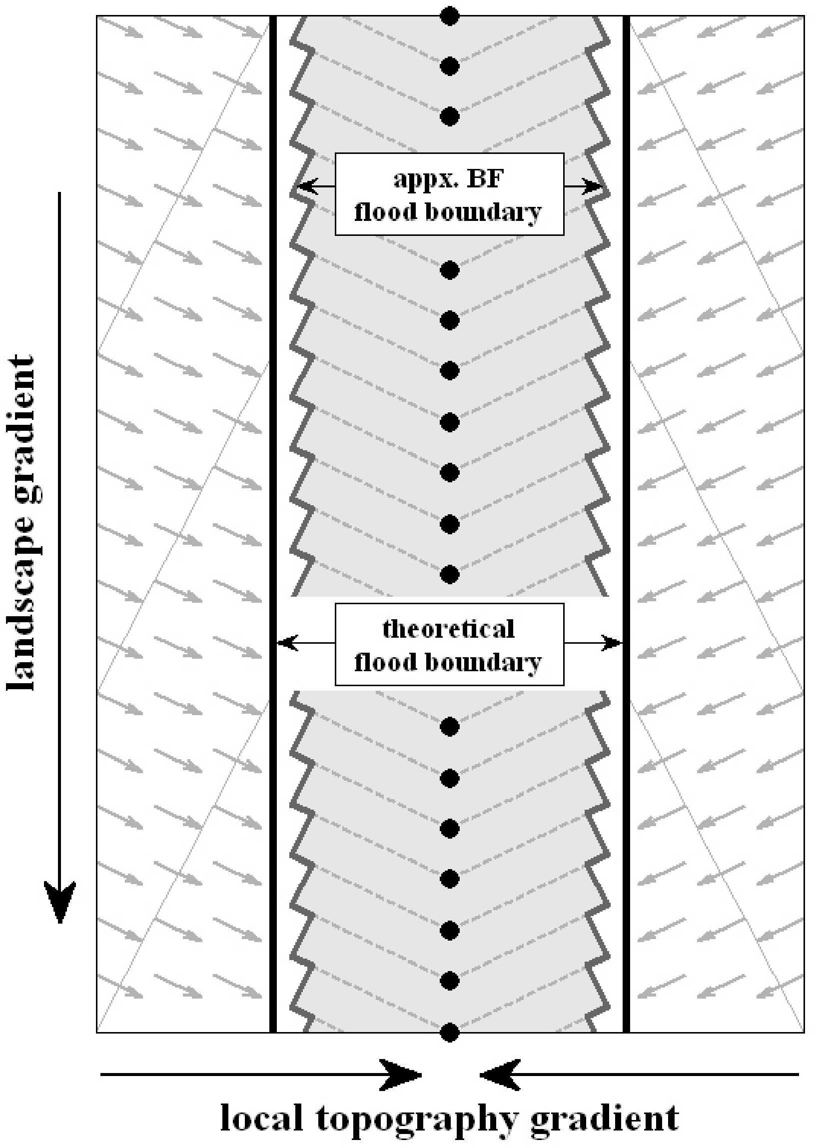
BF = backfill flood zone

appx. BF = approximate backfill flood zone

The boundary of the 'appx. BF' is determined by

1. ***contours*** from the DEM and
2. ***trajectories*** through the FOP

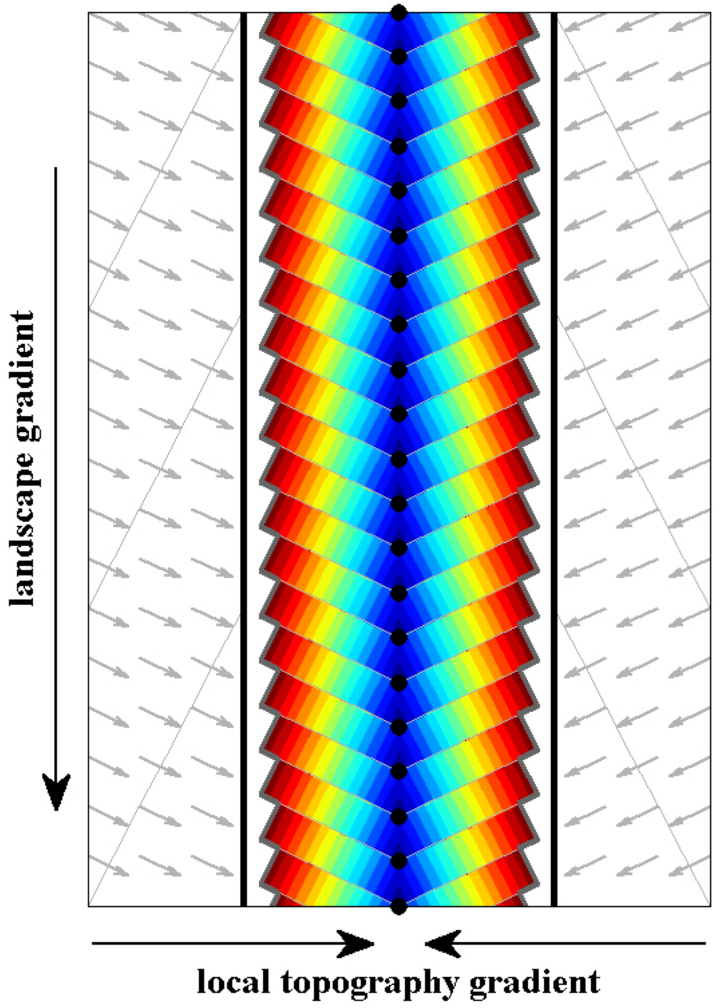
The Flood Zone Map



Evaluate the appx. BF for a series of flood origination points and ***merge the results*** to obtain the BF flood zone

The Flood Zone Map

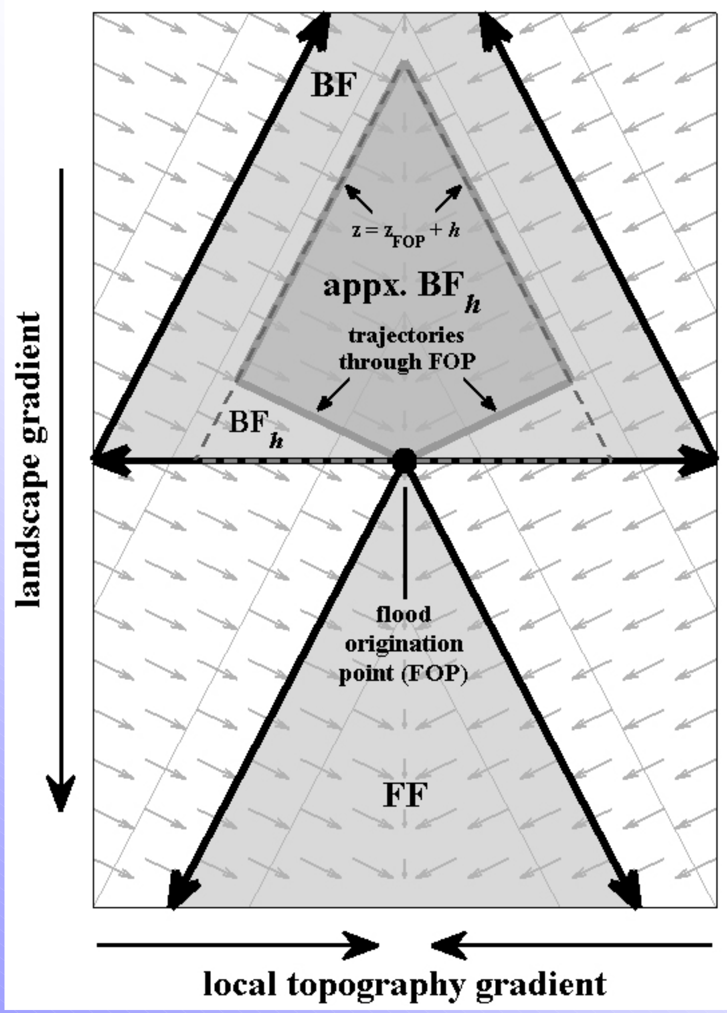
The ***flood zone map*** is created using different flood depths, ranging from $h = 0$ to $h = h_0$.

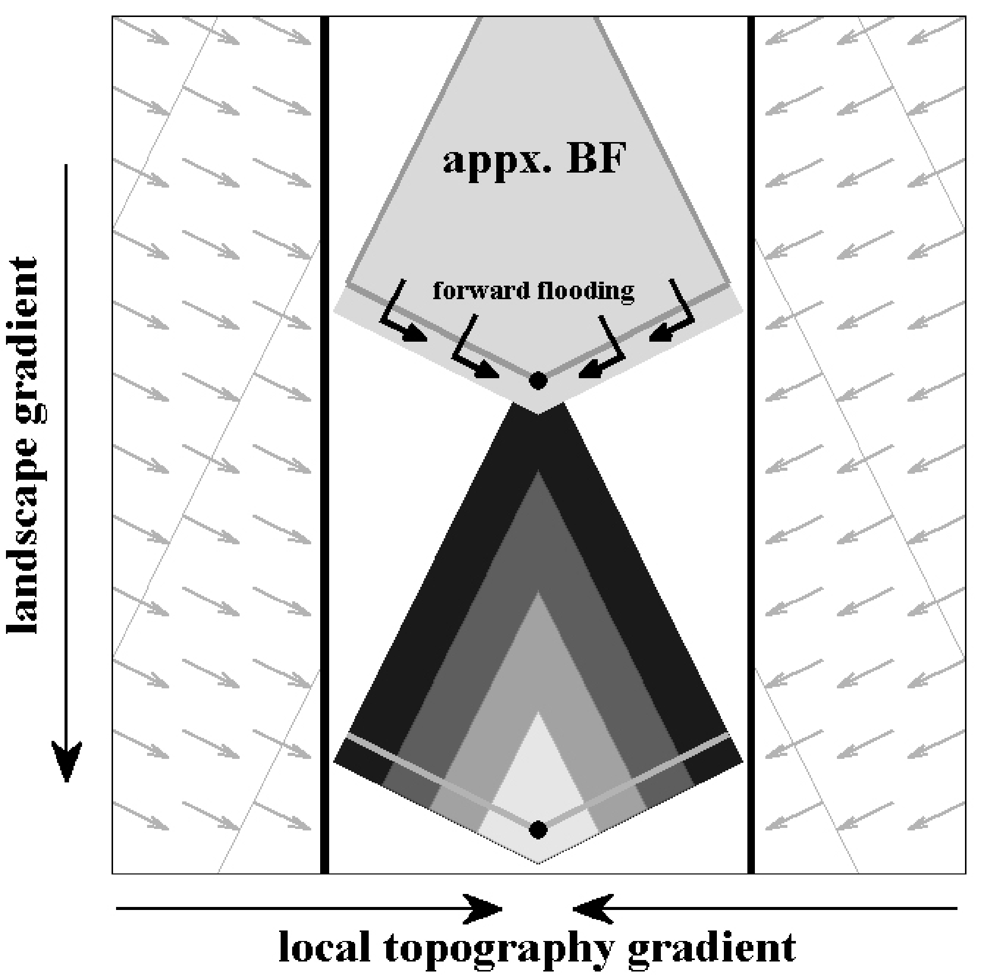


Colors indicate minimum h values required for appx. BF inundation, increasing from blue ($h = 0$) to red ($h = h_0$, for some h_0).

Ideally, the colors should be continuous across the FOP-specific, appx. BF boundaries. *<u>Constrained forward flooding</u> is used to remedy this problem, as well as the under-estimation problem.*

The Flood Zone Map





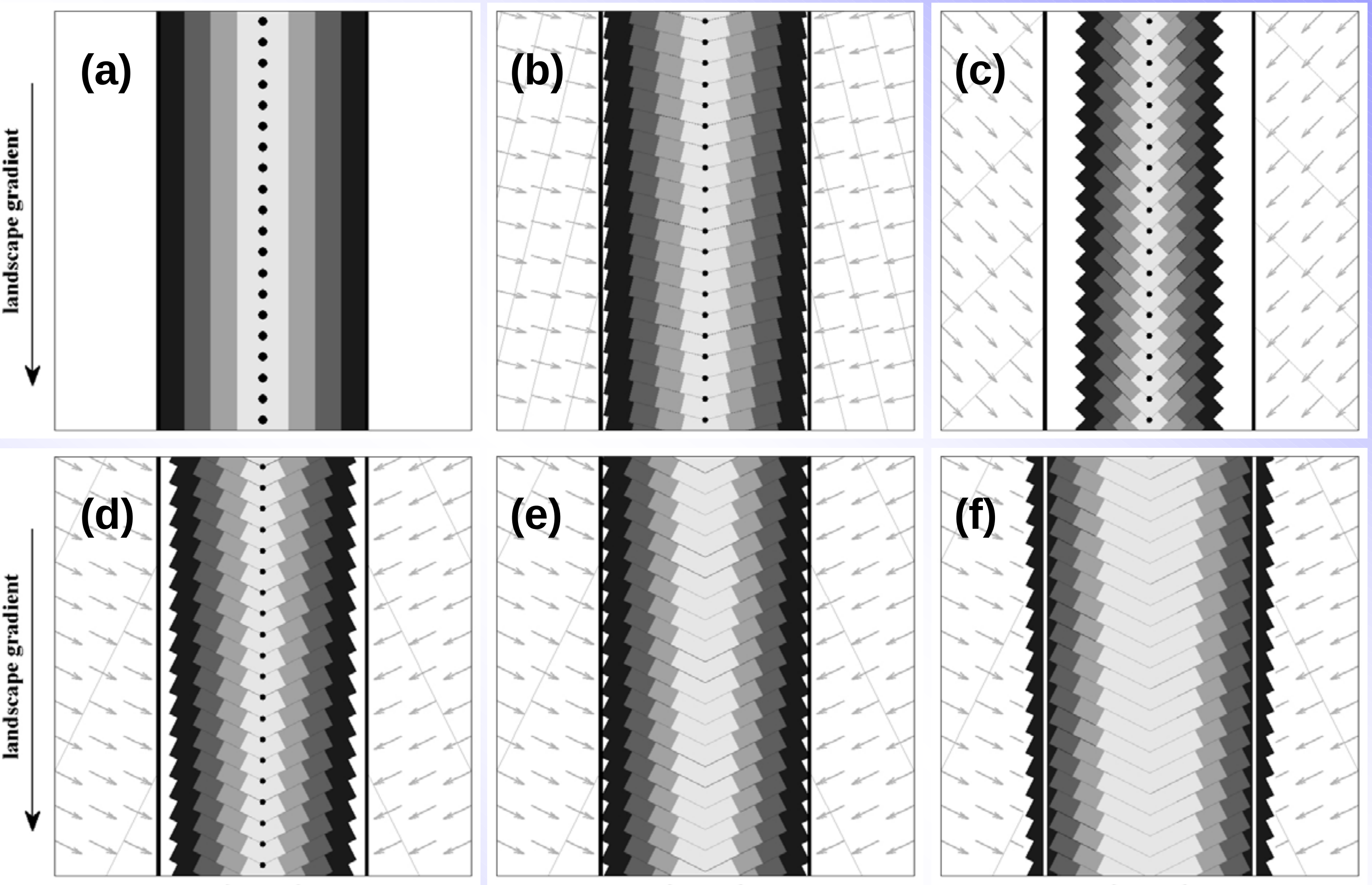
Concept development: *constrained forward flooding*

The Flood Zone Map

channel pitch:

$P = |\partial z/\partial y| / |\partial z/\partial x|$

The dots denote FOPs



(a) theoretical (*P*-independent); (b) *P* = 1/4; (c) *P* = 1; (d)-(f) *P* = 1/2; (e) near-optimal forward flooding; (f) too much forward flooding

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The Flood Zone Map

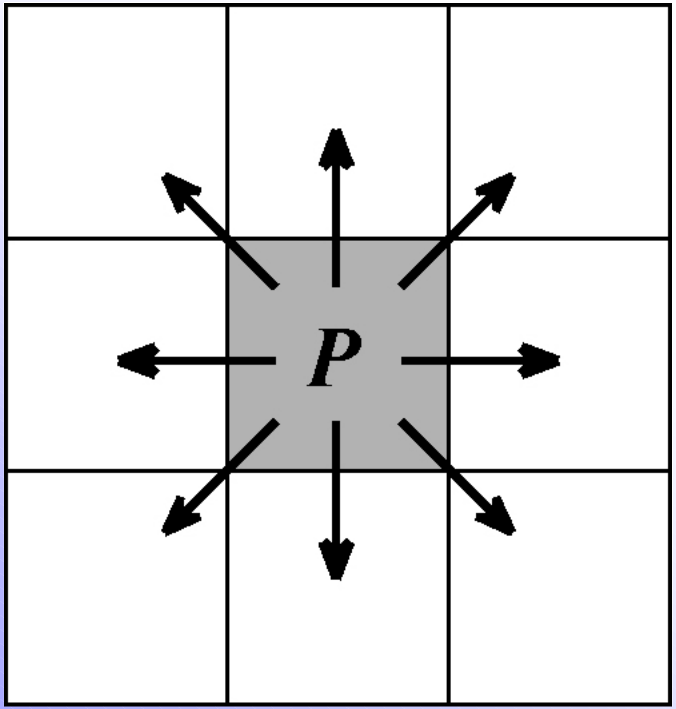
1. Every pixel in the floodplain is assigned a "**depth to flood**" estimate
2. Every pixel in the floodplain is assigned a "**flood source pixel**" in the stream channel

Typically, these linkages are made using backfill flooding. However, **reassignments are made when corrections for forward flooding are indicated.**

Need to estimate the gradient with the ***flow direction map***, a required input for estimating the flood zone map.

The Flood Zone Map

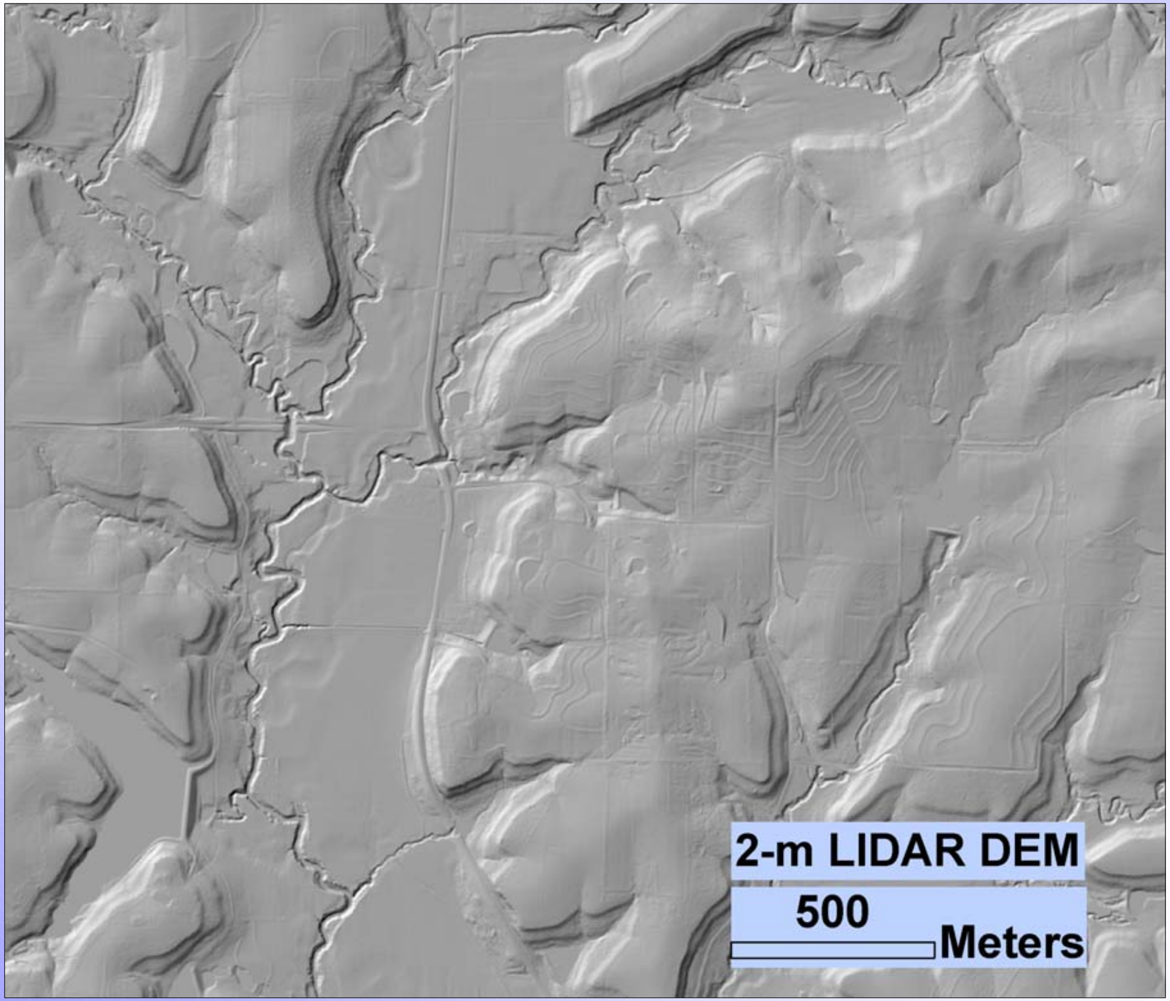
Approximate the local gradient for each pixel in the study area:



Using the depressionless DEM, difference quotients are calculated between each pixel ***P*** and its 8 neighbors.

The neighbor exhibiting the largest distance-weighted elevation drop from ***P*** determines the flow direction at ***P***.

The Flood Zone Map

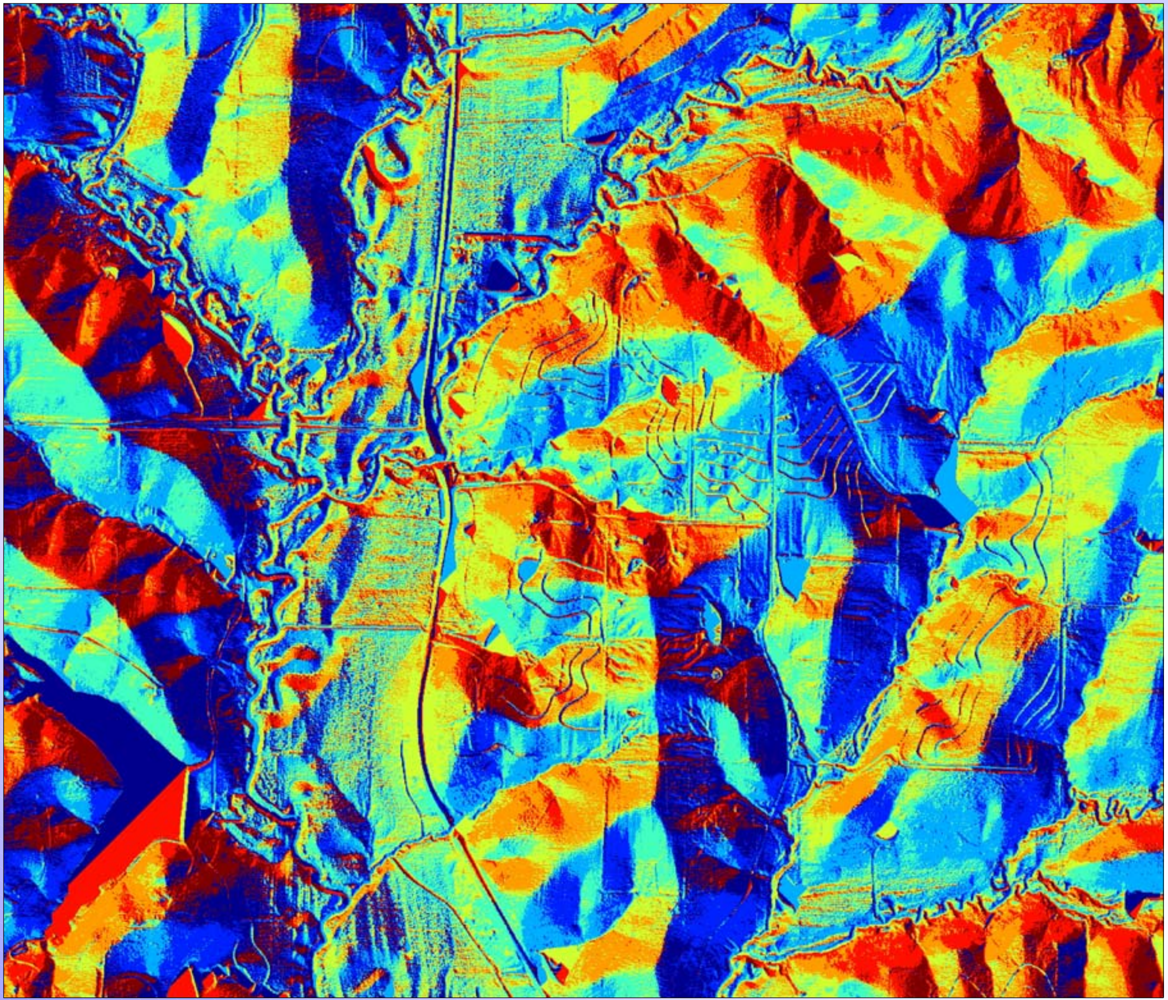


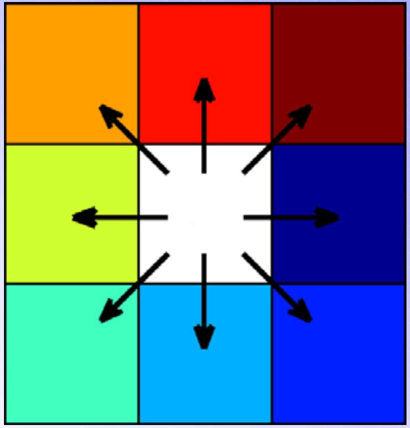
This DEM was created by DASC using LIDAR data.

Shown is a portion of the river valley for Mud Creek, Kansas.

Sample Filled DEM

The Flood Zone Map



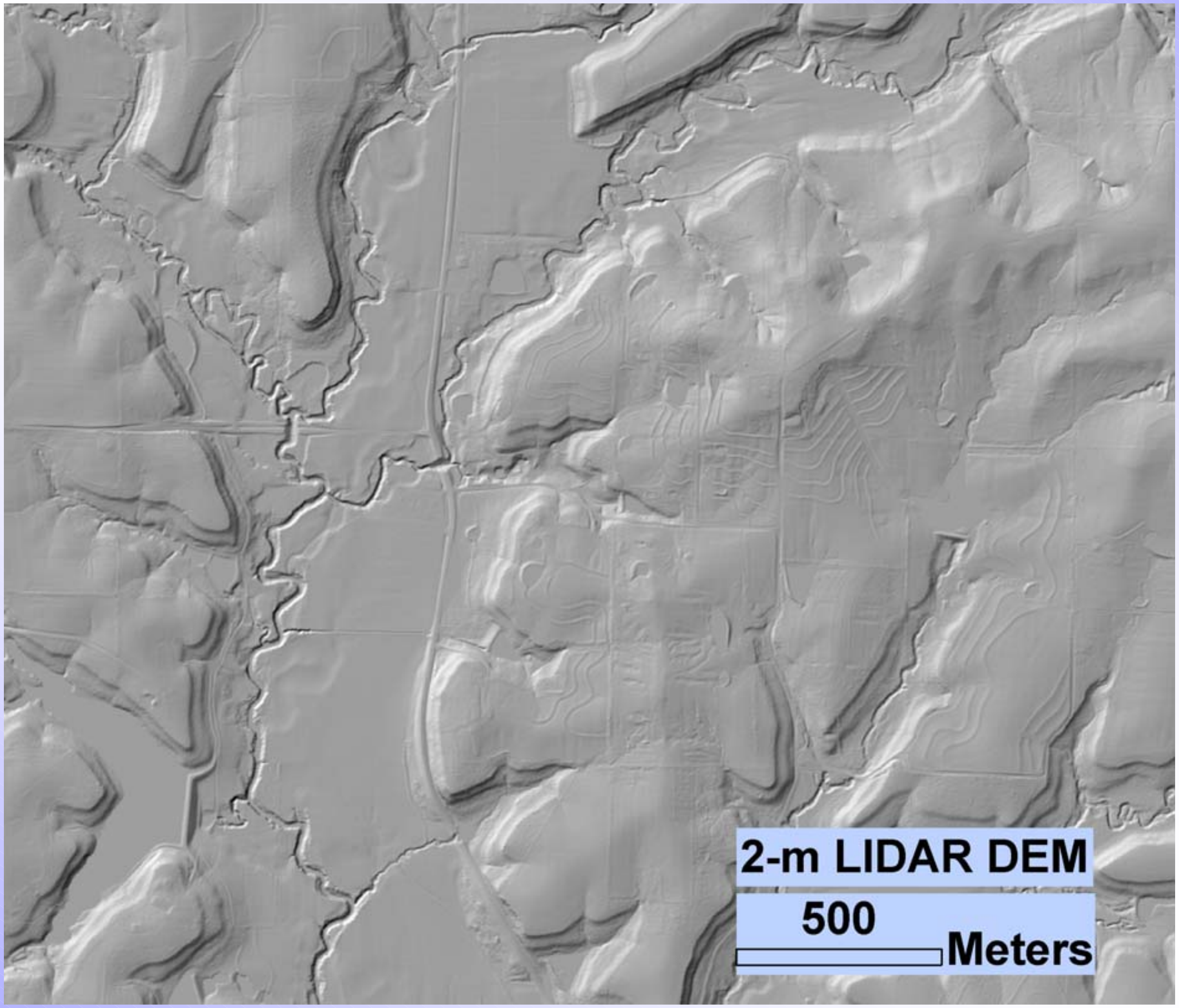


Each pixel is colored based on its flow direction.

Navigating by flow direction, every pixel has a single path (trajectory) out of the image.

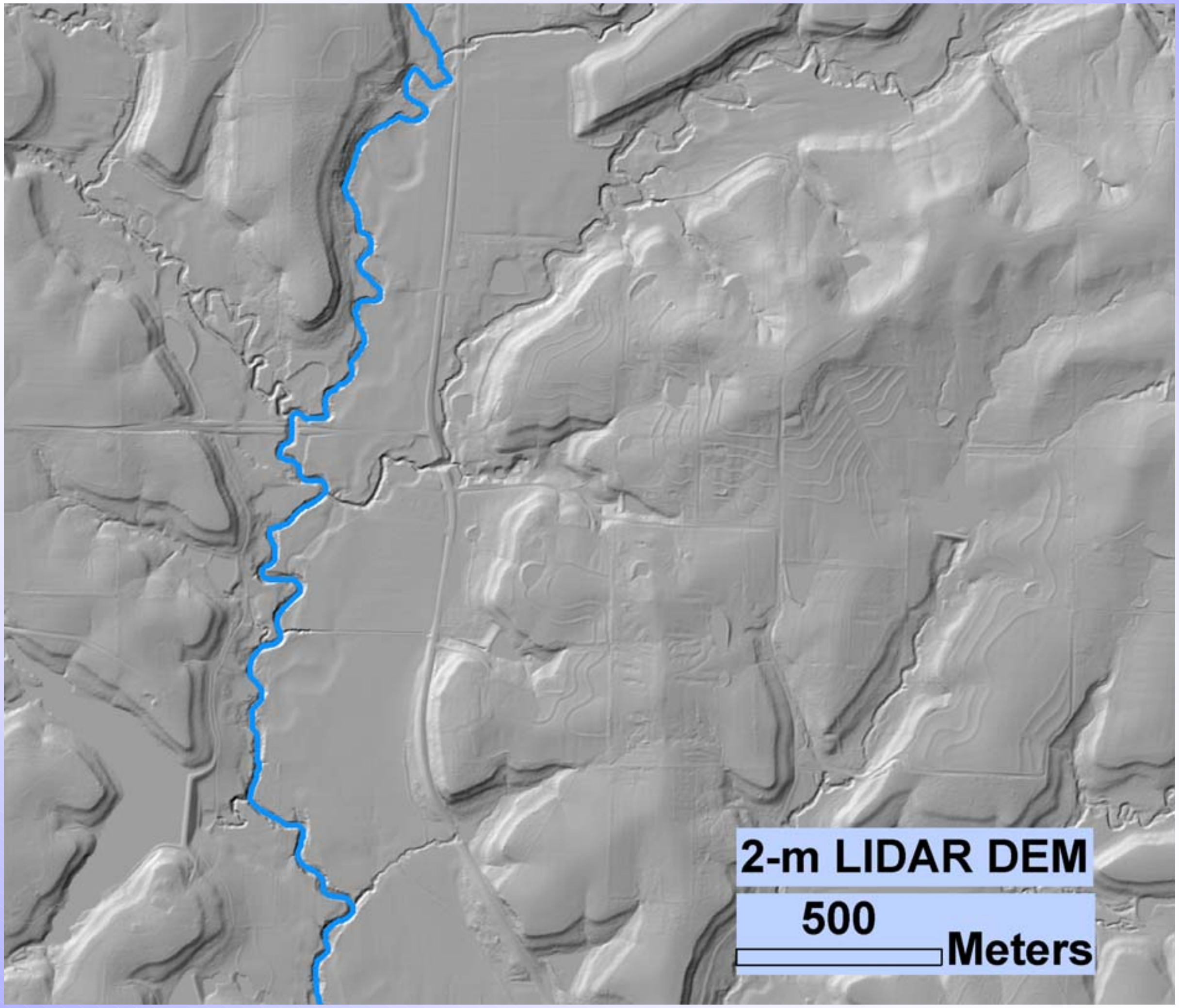
Flow direction map (gradient approximation)

The Flood Zone Map



Filled DEM

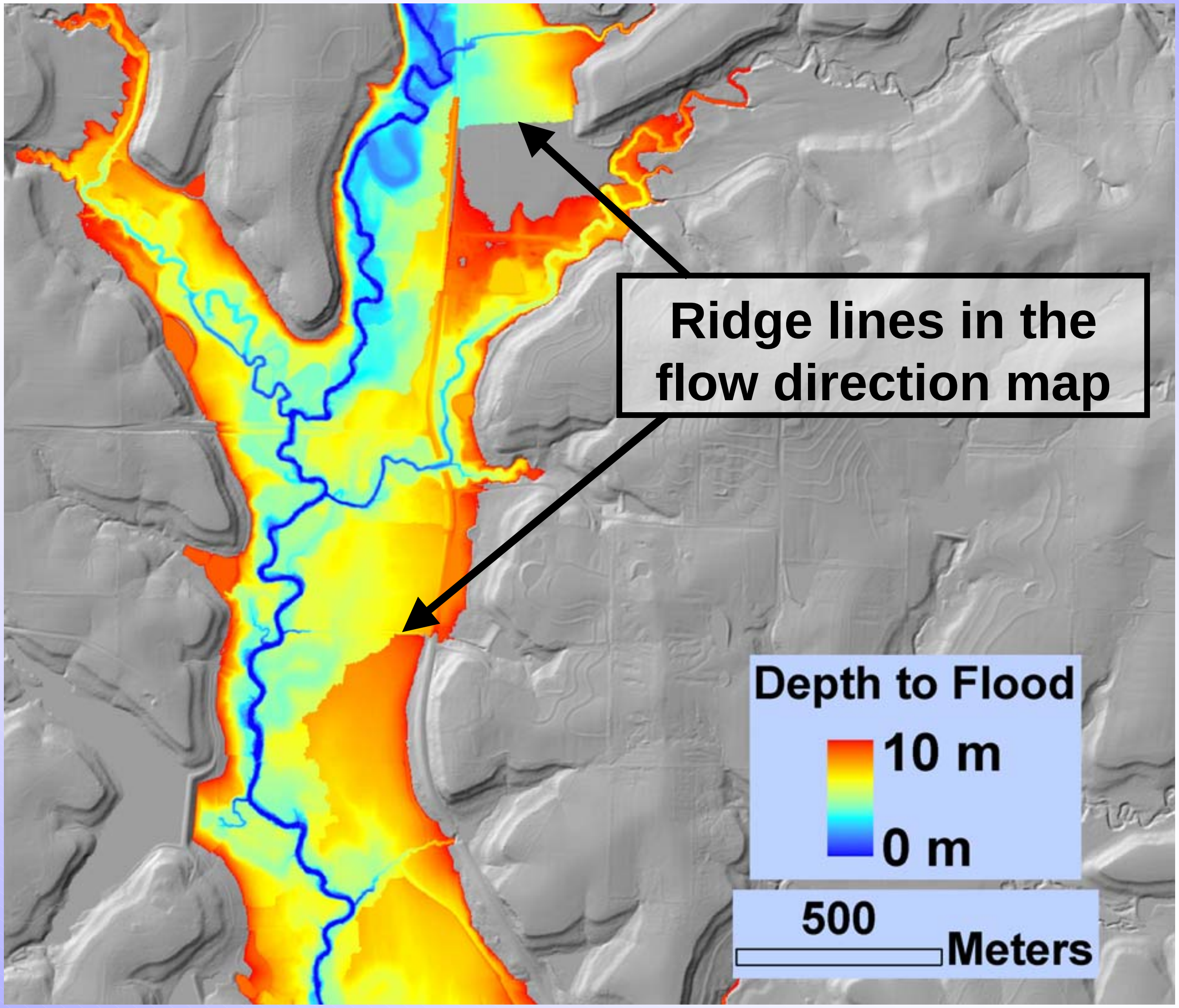
The Flood Zone Map



Filled DEM with Mud Creek stream segment, identified using the flow direction and flow accumulation maps

The Flood Zone Map

10-m BF flood zone map

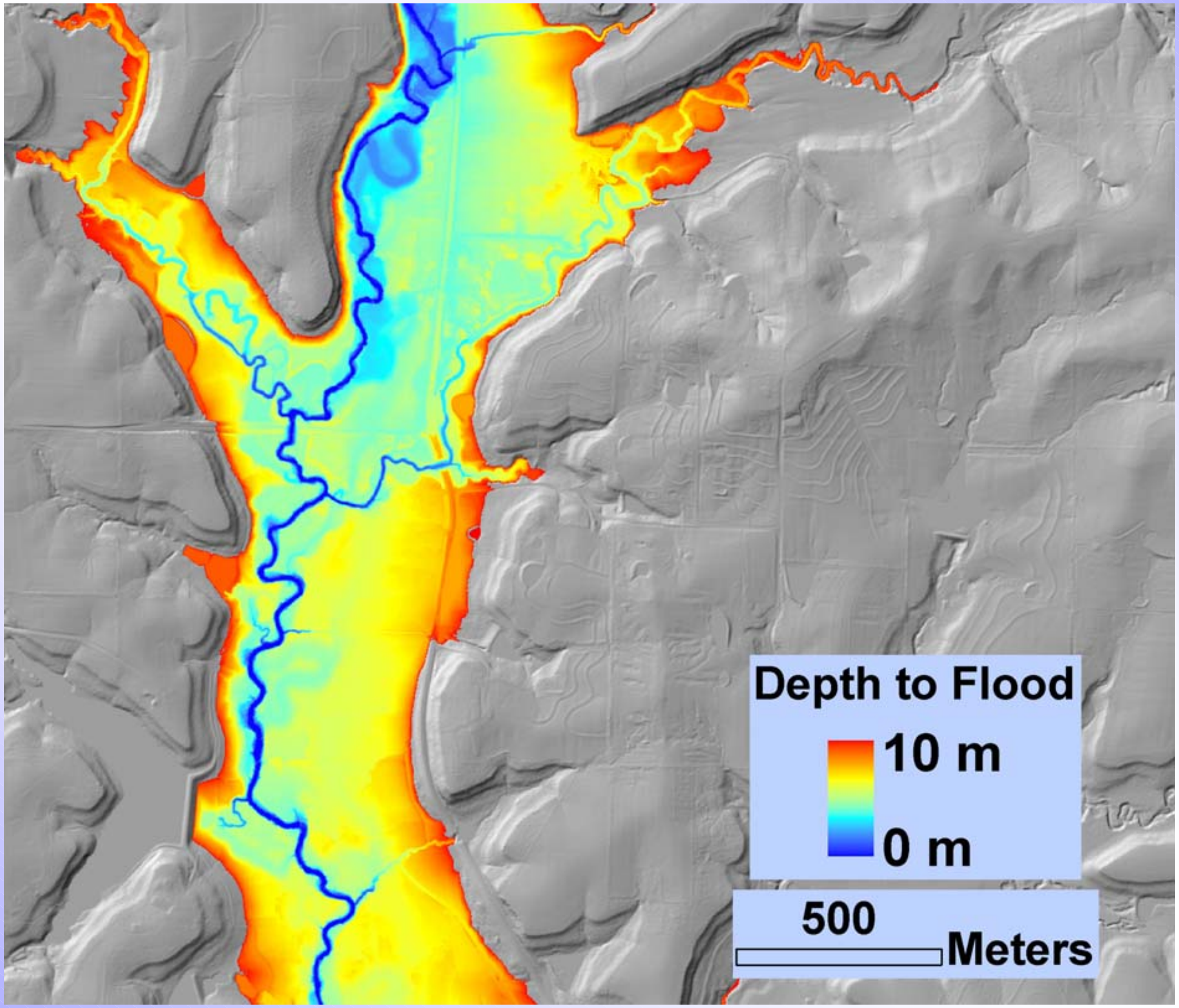


Ridge lines in the flow direction map

Flood zone map BEFORE forward flood correction.
Note the undesirable discontinuities.

The Flood Zone Map

h = 10 m
dh = 1 m
(10 iterations)



Flood zone map AFTER forward flood correction.
Most of the discontinuities have been fixed.

The Floodplain Algorithm--Initialization

Data requirements: Filled DEM, flow direction map, and a set S of FOPs (typically a stream segment or network)

Let Z denote the current flood zone, initialized to $Z = S$.

Two parameters $\{h, dh\}$ are required. h is the maximum flood depth, and dh is the depth step size. Initialize $h_0 = dh$.

Let $\mathrm{BF}(h_0)$ denote the backfill flood zone with maximum depth h_0.
Let $\partial_i(Z)$ denote the set of interior boundary pixels for Z.
Let $\partial_e(Z)$ denote the set of exterior boundary pixels for Z.

The Floodplain Algorithm

(**required ~700 lines of non-comment MATLAB code**)

1. Determine BF(h_0) for $\partial_i(Z)$
2. Update Z by assimilating BF(h_0) into Z
3. Identify $\partial_i(Z)$ and $\partial_e(Z)$
4. Determine “spillover” points $\{Y_k\}$ in $\partial_e(Z)$
5. Determine the maximum available flood depth and corresponding flood source pixel in $\partial_i(Z)$ for each Y_k
6. For each “spillover” point Y_k:
    a) Determine flow path $T(Y_k)$, halting growth appropriately
    b) Determine appropriate BF flood zone for $T(Y_k)$
    c) Assimilate new flood zone pixels into Z, overwriting existing flood zone pixels in Z as necessary
7. Update $h_0 \rightarrow h_0 + dh$
8. If $h_0 < h$, identify $\partial_i(Z)$ and go back to step (1).

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Some Examples Using 30-m DEM Data from the National Elevation Database (NED)

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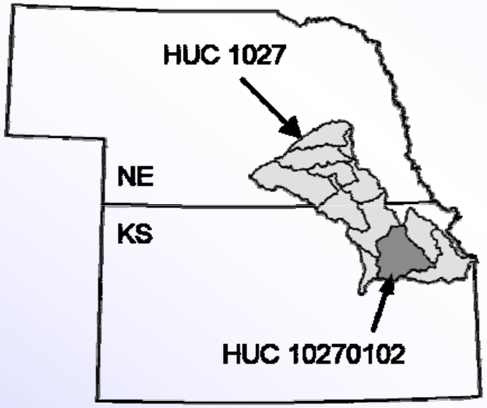
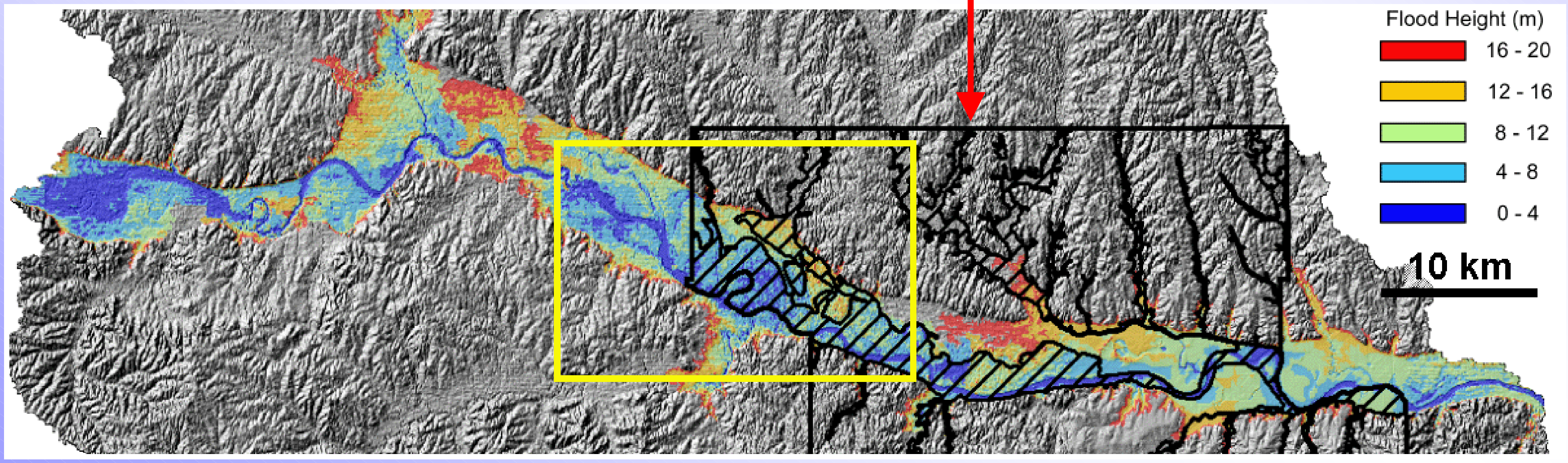
Floodplain Delineation



Example:

Backfill flood zones (max height = 20 m) for the Kansas River segment located in HUC 10270102 (Middle Kansas River), roughly spanning the stream reach between Manhattan and Lawrence, Kansas.

Black line work depicts FEMA Q3 100-year floodplain boundary for Shawnee County, Kansas.



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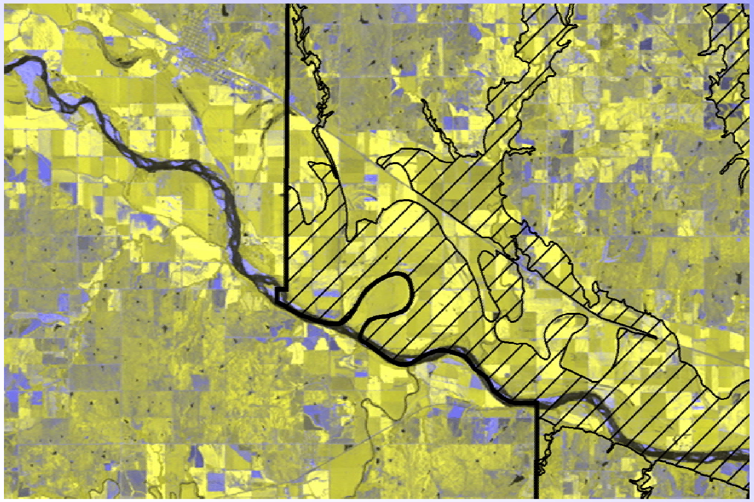
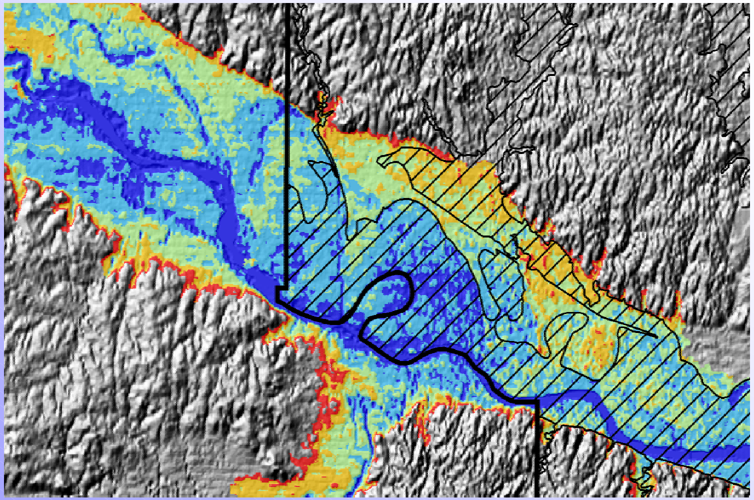
Floodplain Delineation

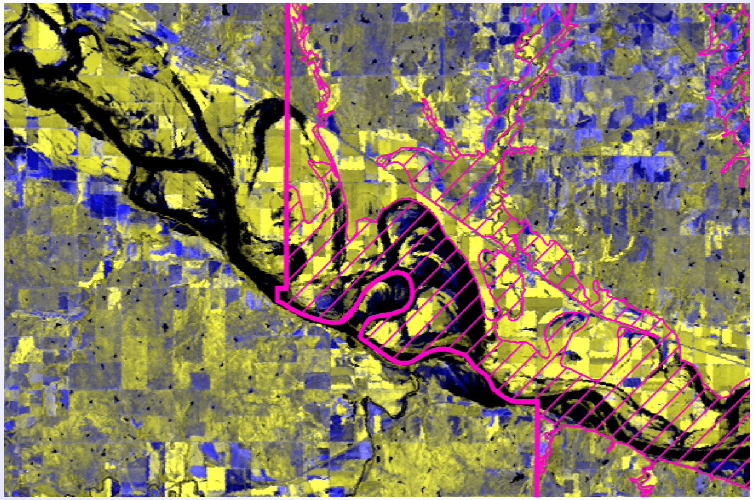
Cross-hatched area indicates FEMA Q3 100-year floodplain extent for Shawnee County, Kansas.



Near-normal conditions (July 2000)

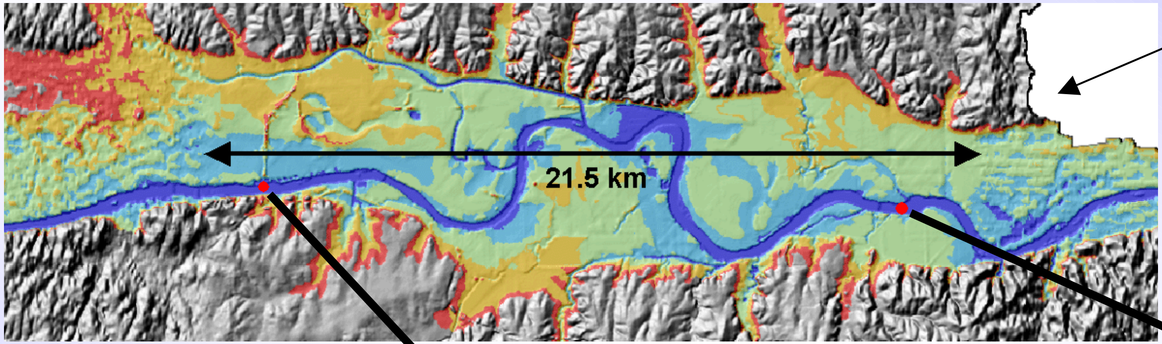


20-m Backfill Flood Zone map

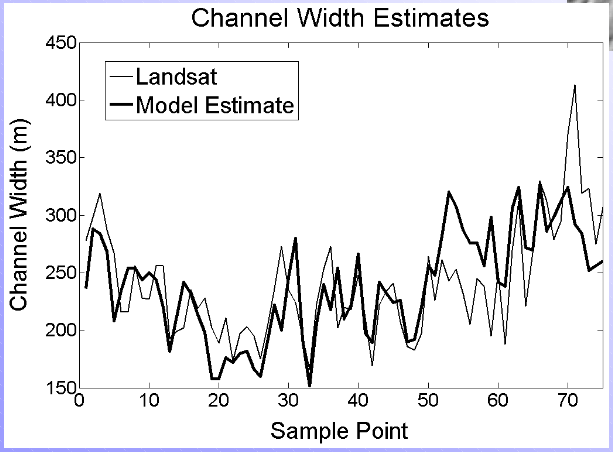


Flooded conditions (July 1993)

Channel Width Estimation



The two-headed arrow shows the extent of an NED data tile derived using higher quality DEM source data than was used in the surrounding area.



Channel width was estimated from a Landsat scene depicting normal stream conditions. Width was estimated at 75 regularly spaced points along a nearly 20-km Kansas River segment surrounding Topeka, Kansas.

These width values were compared to model values estimated using the 1-m floodplain (shown immediately above), with results depicted in the graph to the left ($R^2 = 0.47$).

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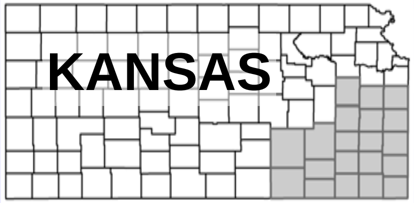
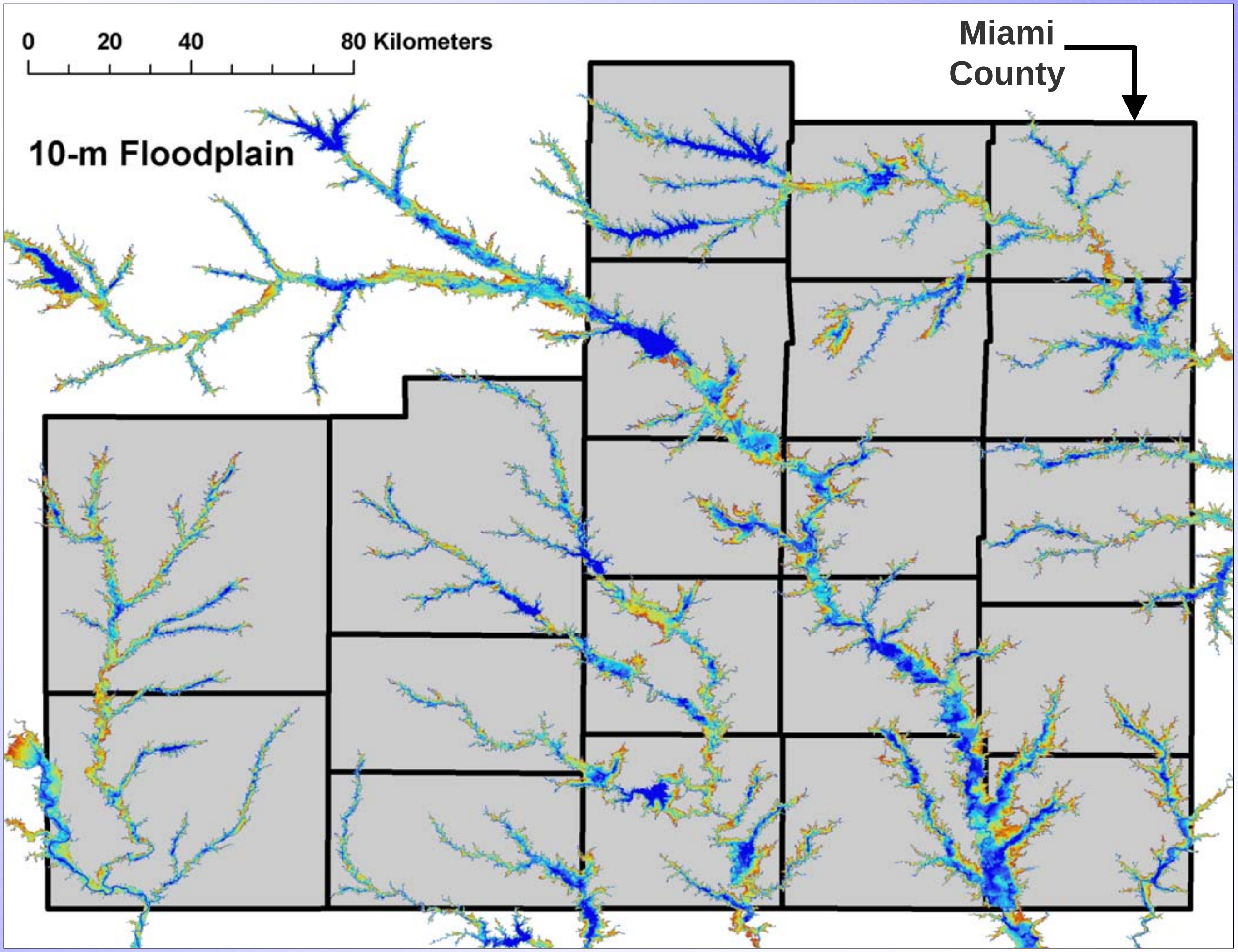
Floodplain Delineation





Between June 26th and 30th, 2007, southeast Kansas counties received nearly 20 inches of rain, causing extensive flooding.

Advance floodplain delineation can help focus emergency response, damage assessment, and recovery efforts.

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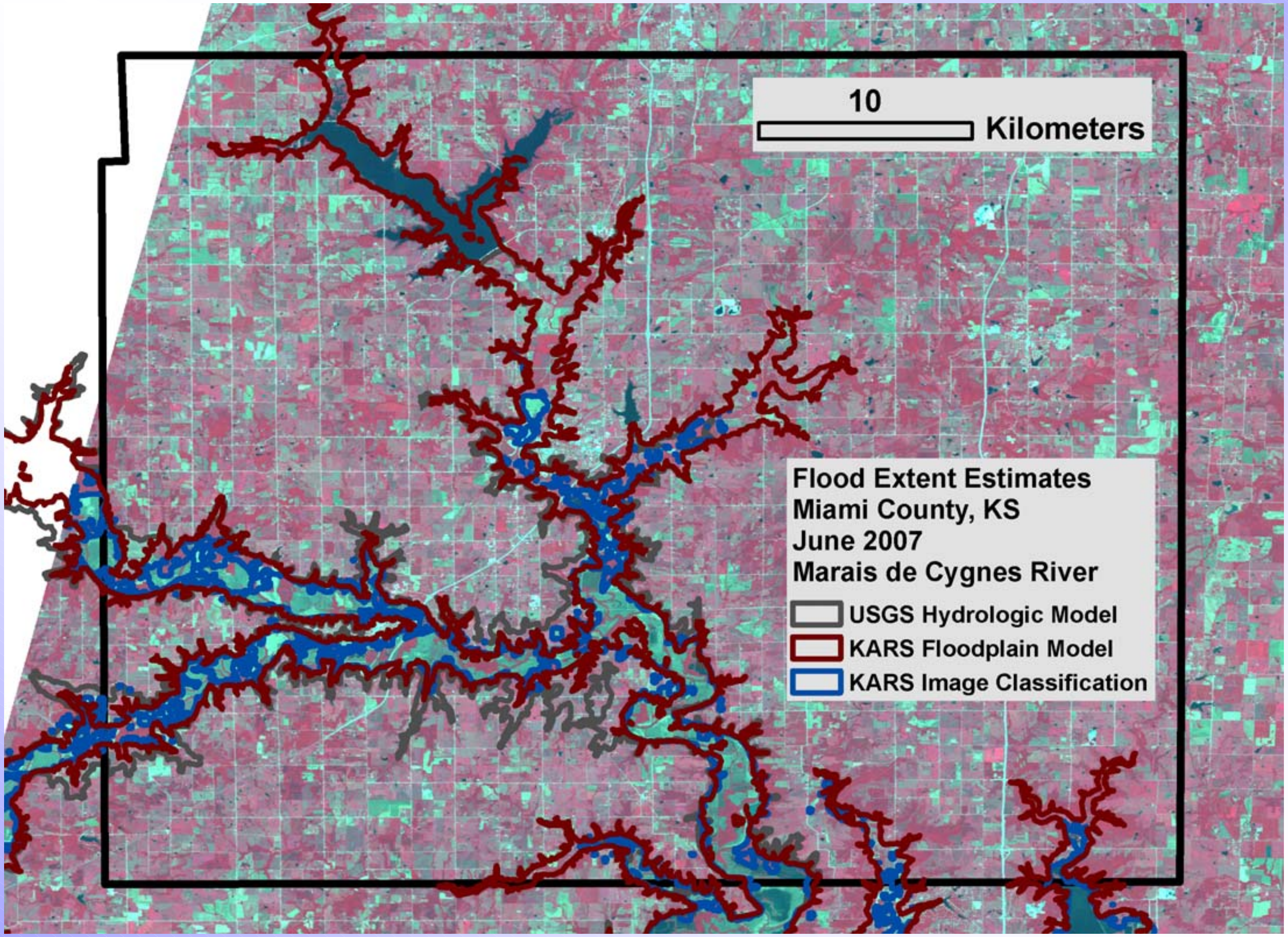
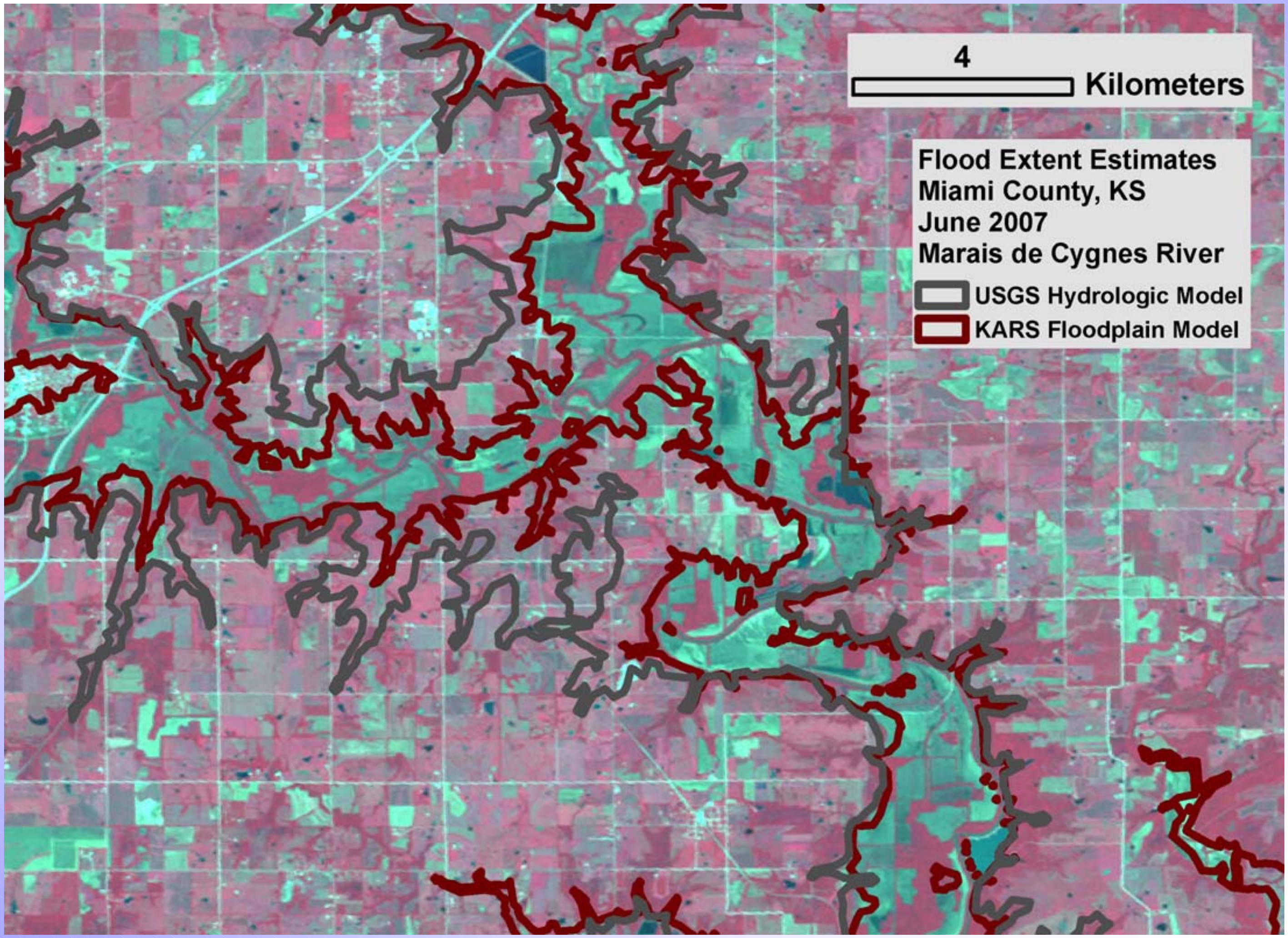
Floodplain Delineation



Comparison of modeled flood extents from three different methods

Floodplain Delineation



Comparison between USGS Hydrologic Model and KARS Floodplain

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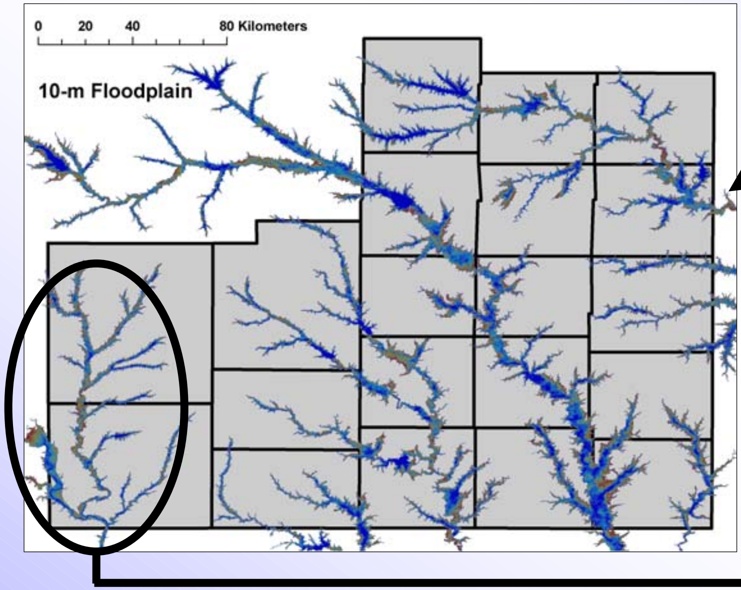
Floodplain Delineation

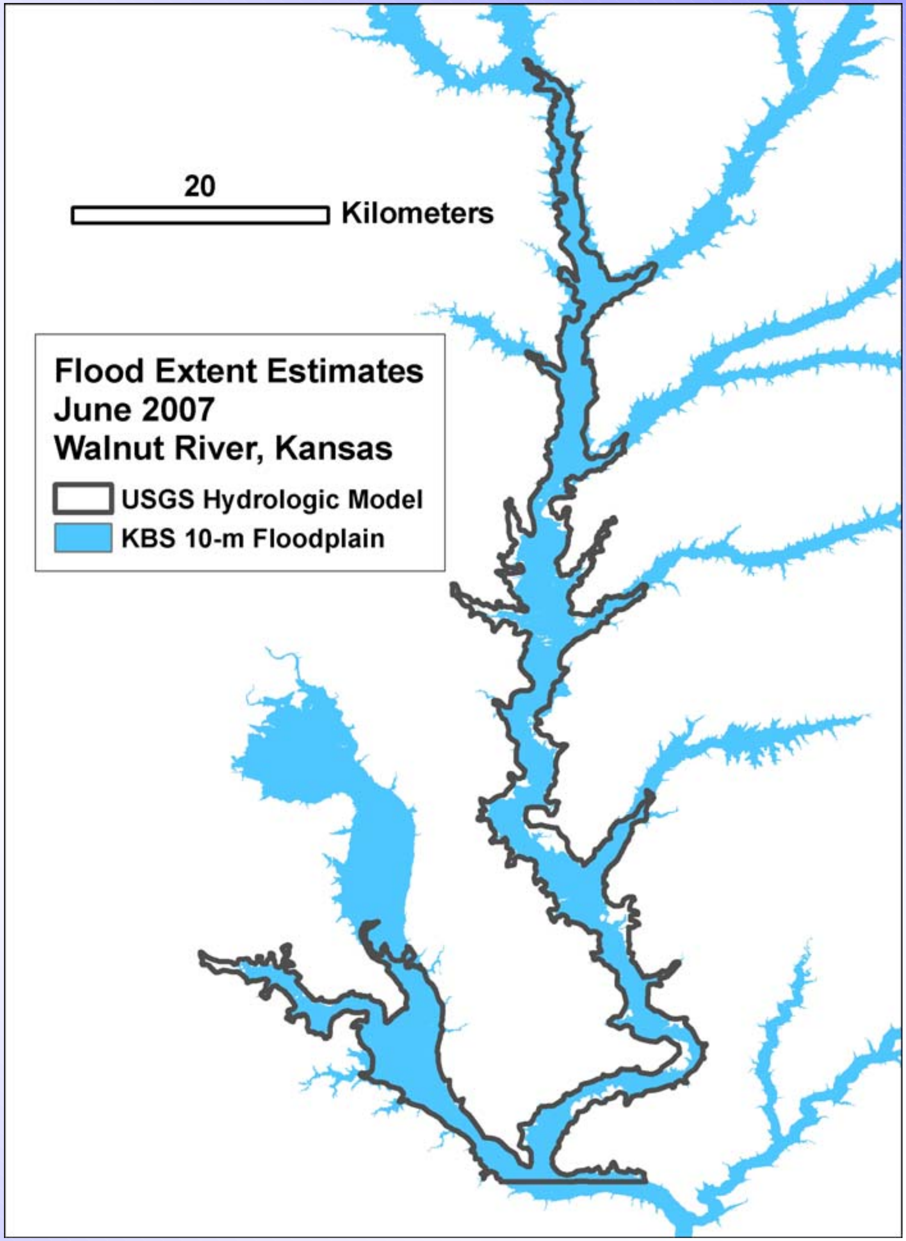


next slide

The U.S. Army Corps of Engineers HEC-RAS model is a widely used in floodplain modeling applications.

The KBS method is static, based purely on DEM data, yet its output exhibits a high level of correspondence with the USGS model.

Accuracy of actual flood extent capture is comparable between the two methods.



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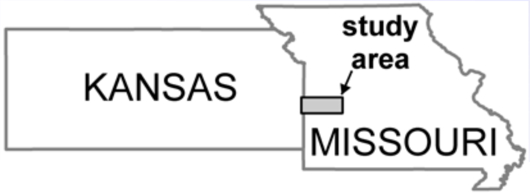
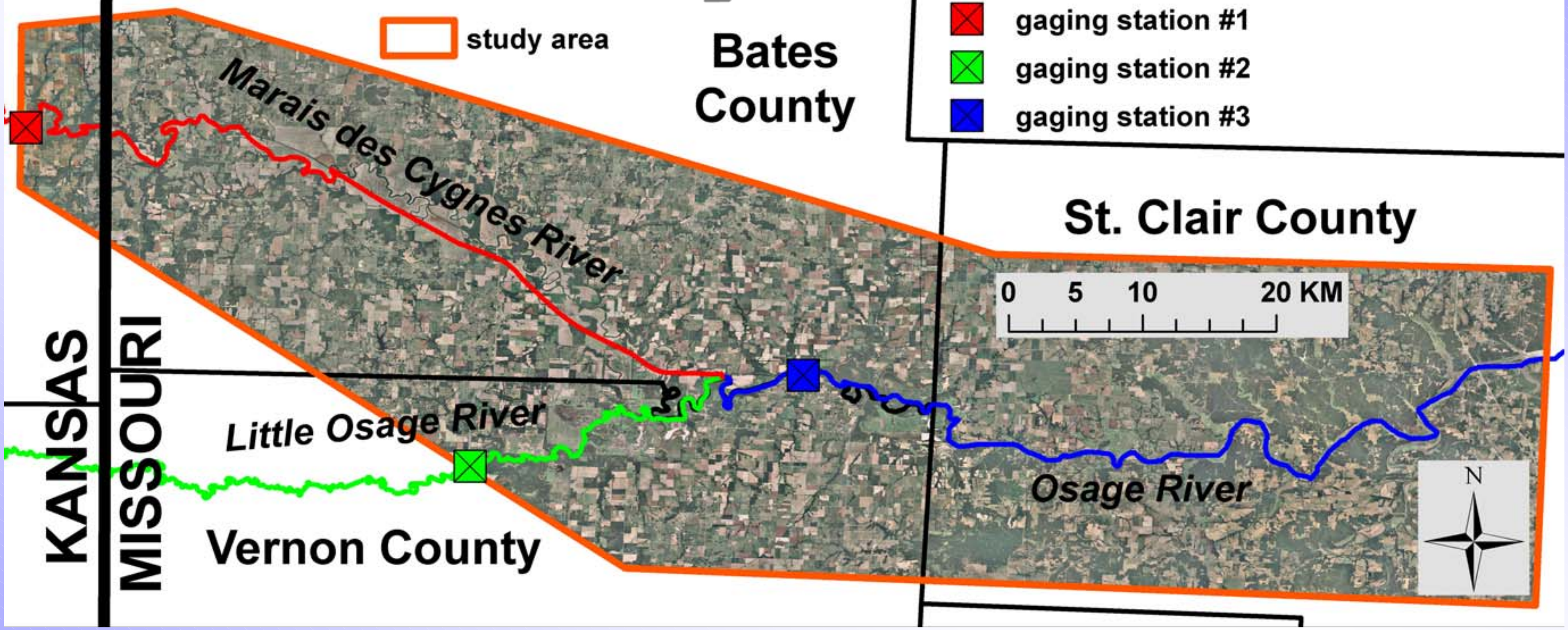
Floodplain Delineation

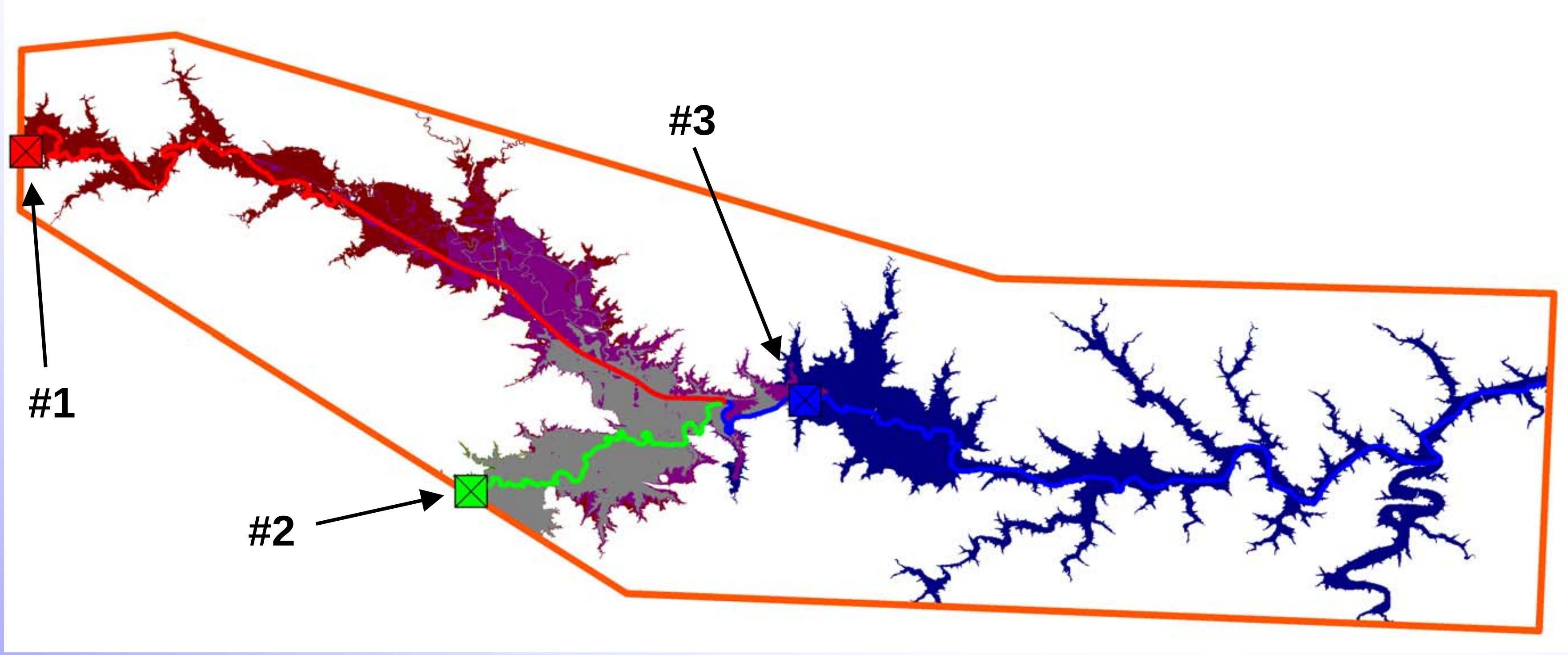
validation study





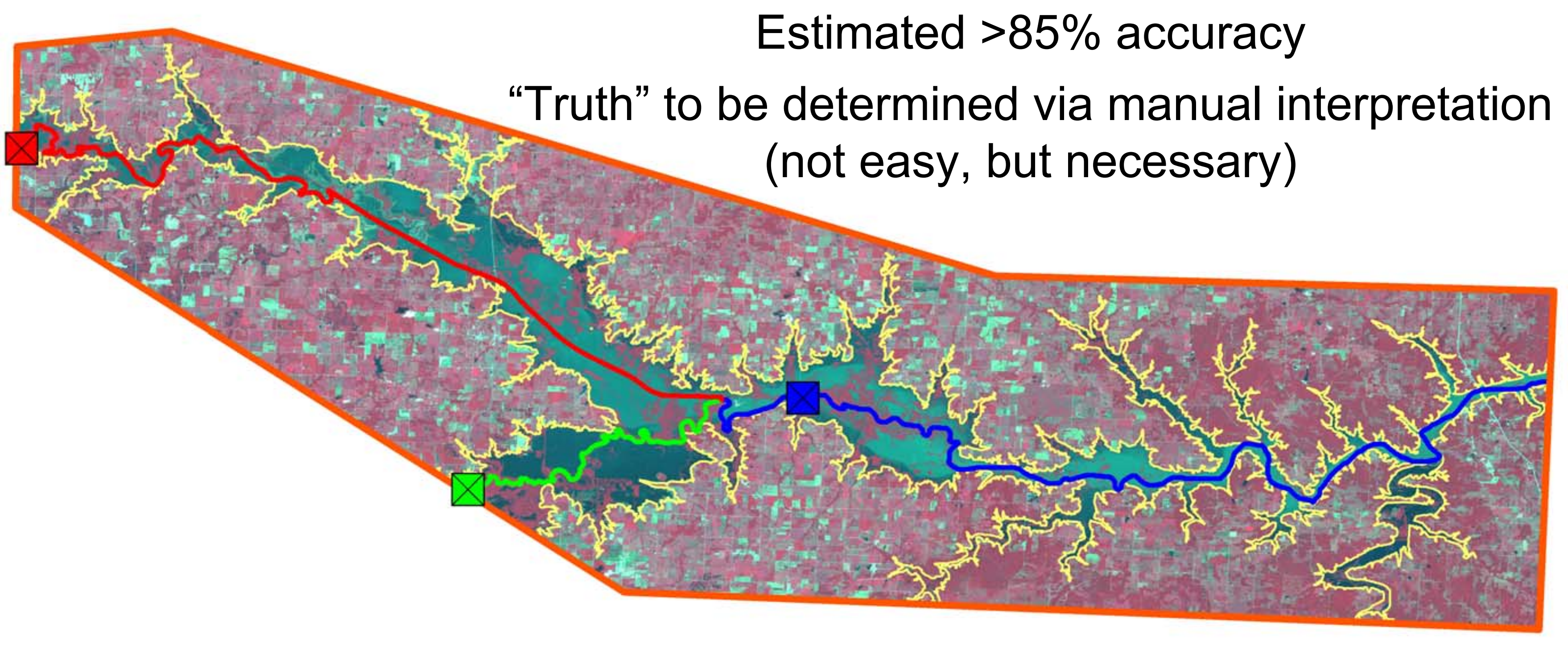
Flooding crested along the Marais des Cygnes, Little Osage, and Osage Rivers in early July 2007.
(2006 NAIP 1-m image)

Floodplain Delineation



False-color composite of the three, segment-specific flood zone extents (bands coincide with RGB stream segment colors). Each extent was generated using the crest mean daily gage height measured at its respective gaging station (9.58 m (#1), 5.05 m (#2), 9.02 m (#3)).

Floodplain Delineation



Estimated >85% accuracy

“Truth” to be determined via manual interpretation (not easy, but necessary)

Landsat-5, color infrared post-flood image (30-m). The exterior perimeter of the merged flood zone extent is shown in yellow.

By USGS calculations, this could be a 4000-year flood event

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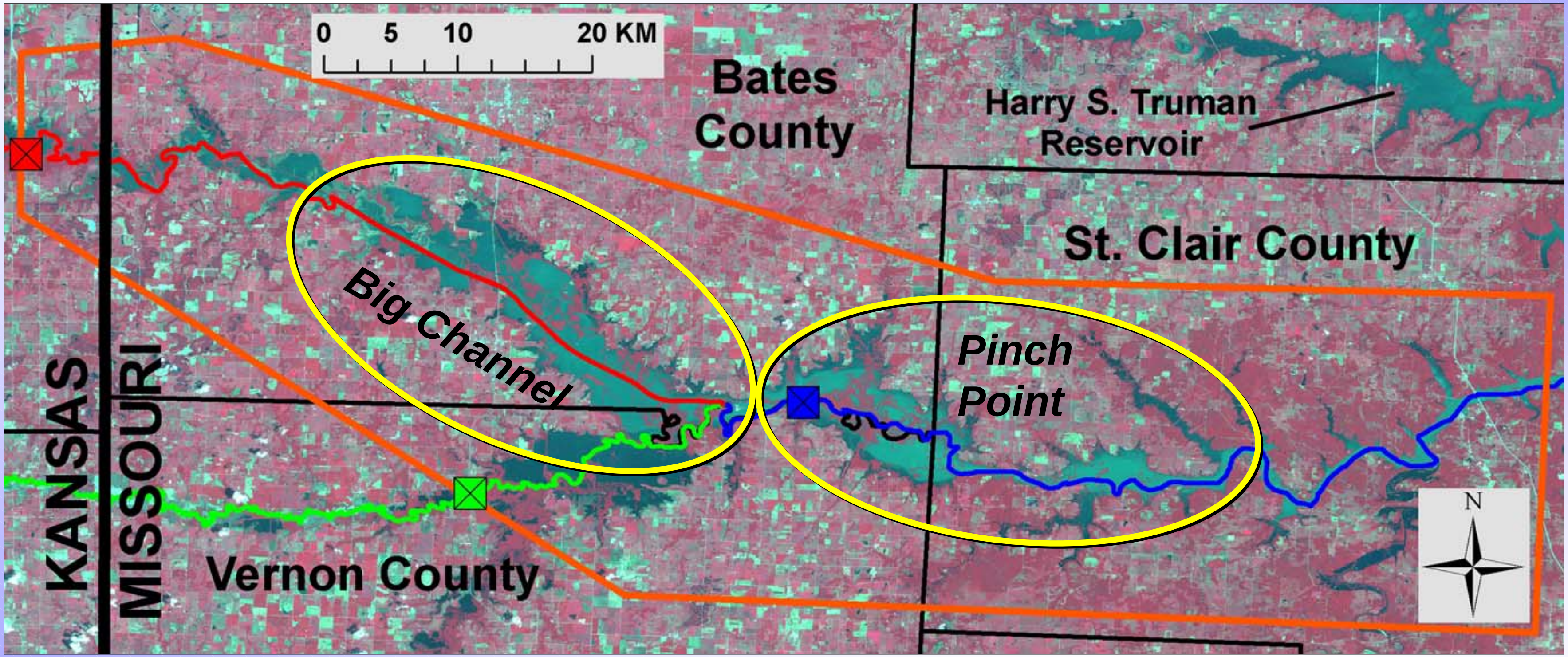
Floodplain Delineation



Areas of interest

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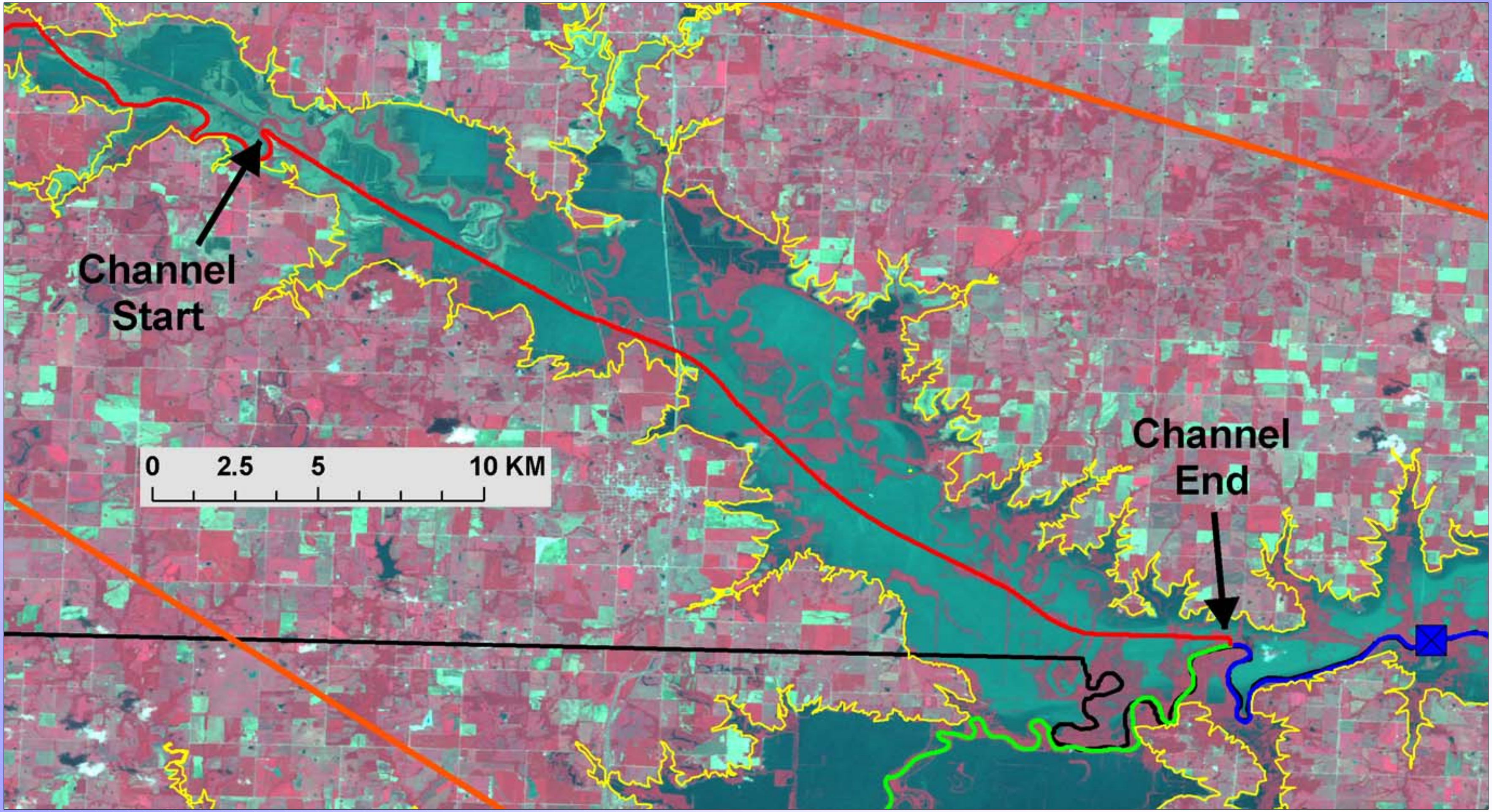
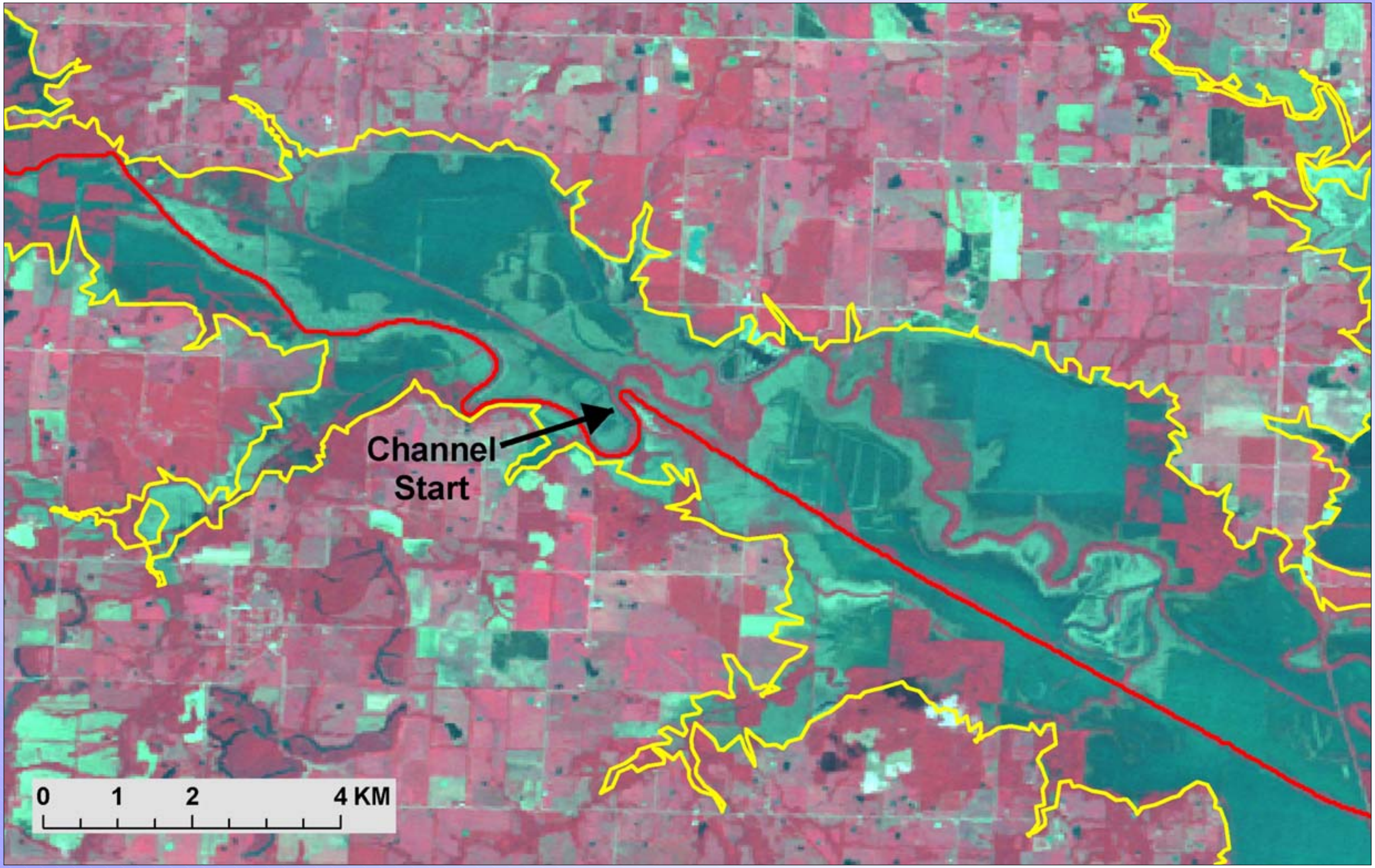
Floodplain Delineation



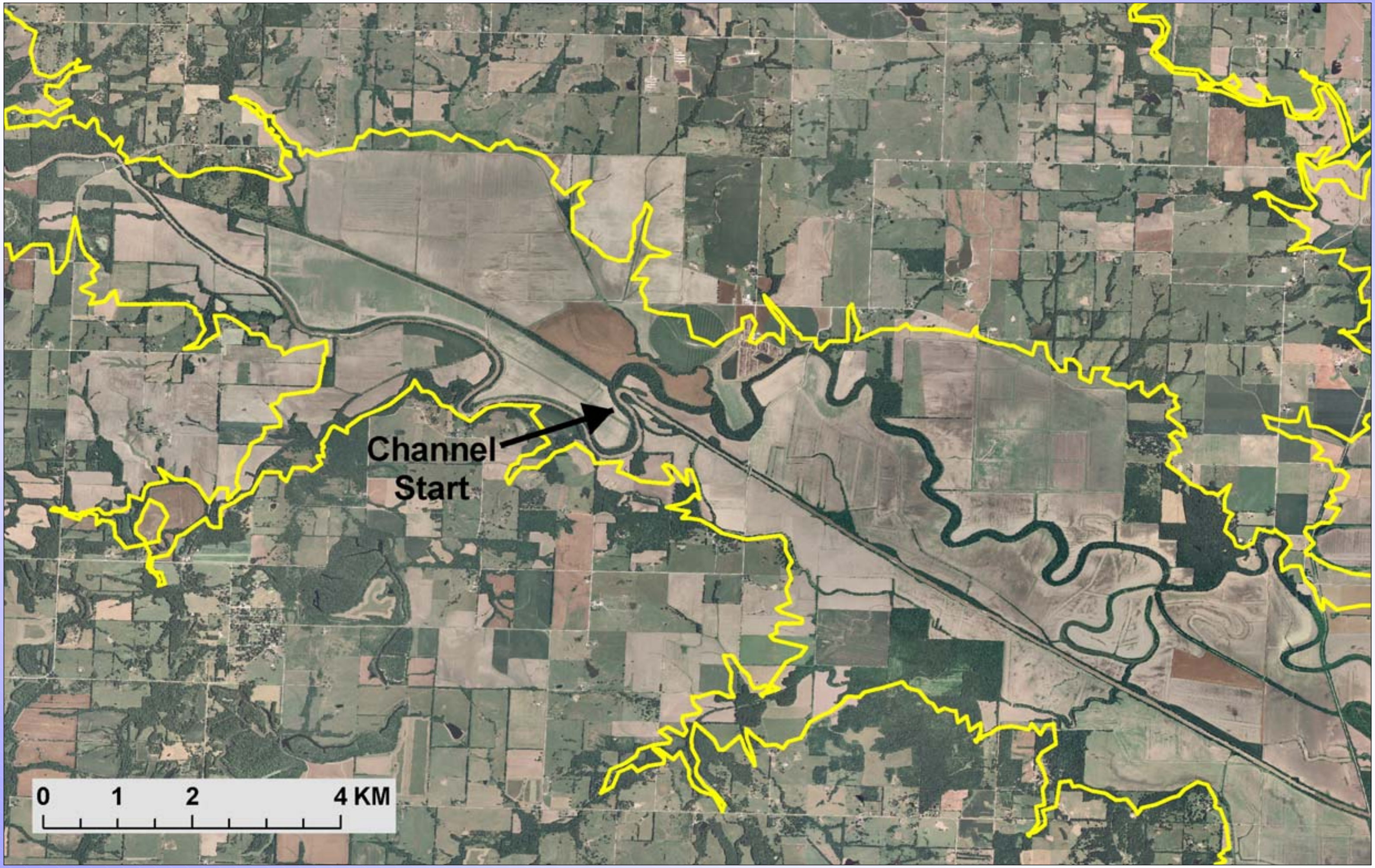
Human Modification: Big Channel (~30 km)

Floodplain Delineation



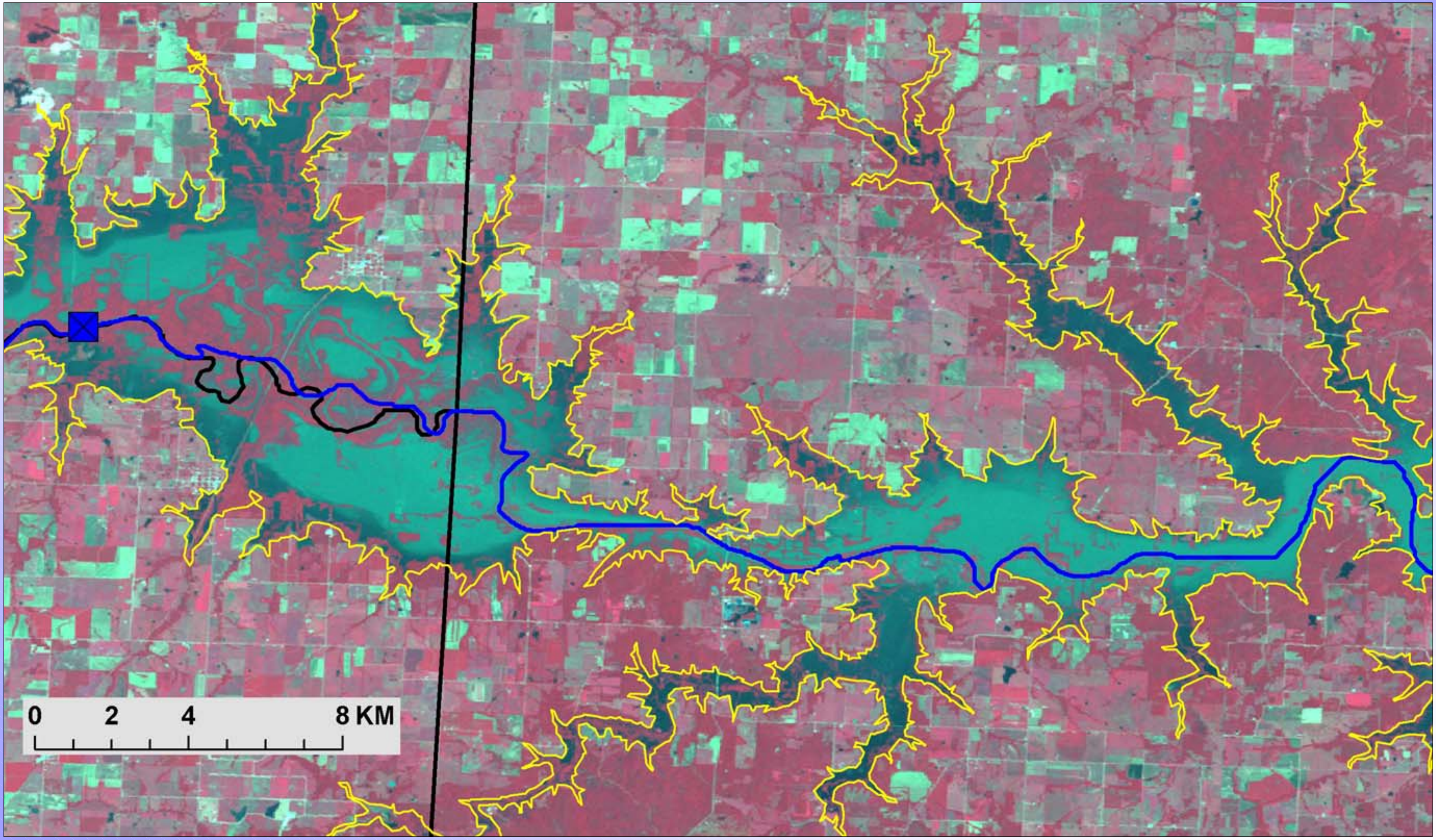
Big Channel Start
Landsat 5 image from July 7, 2007

Floodplain Delineation



Big Channel Start
1-m NAIP imagery from 2006

Floodplain Delineation



Pinch Point: An abrupt change in the floodplain

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A New Technique for Dam Breach Inundation Estimation Using Digital Elevation Models

Two constructs are required:

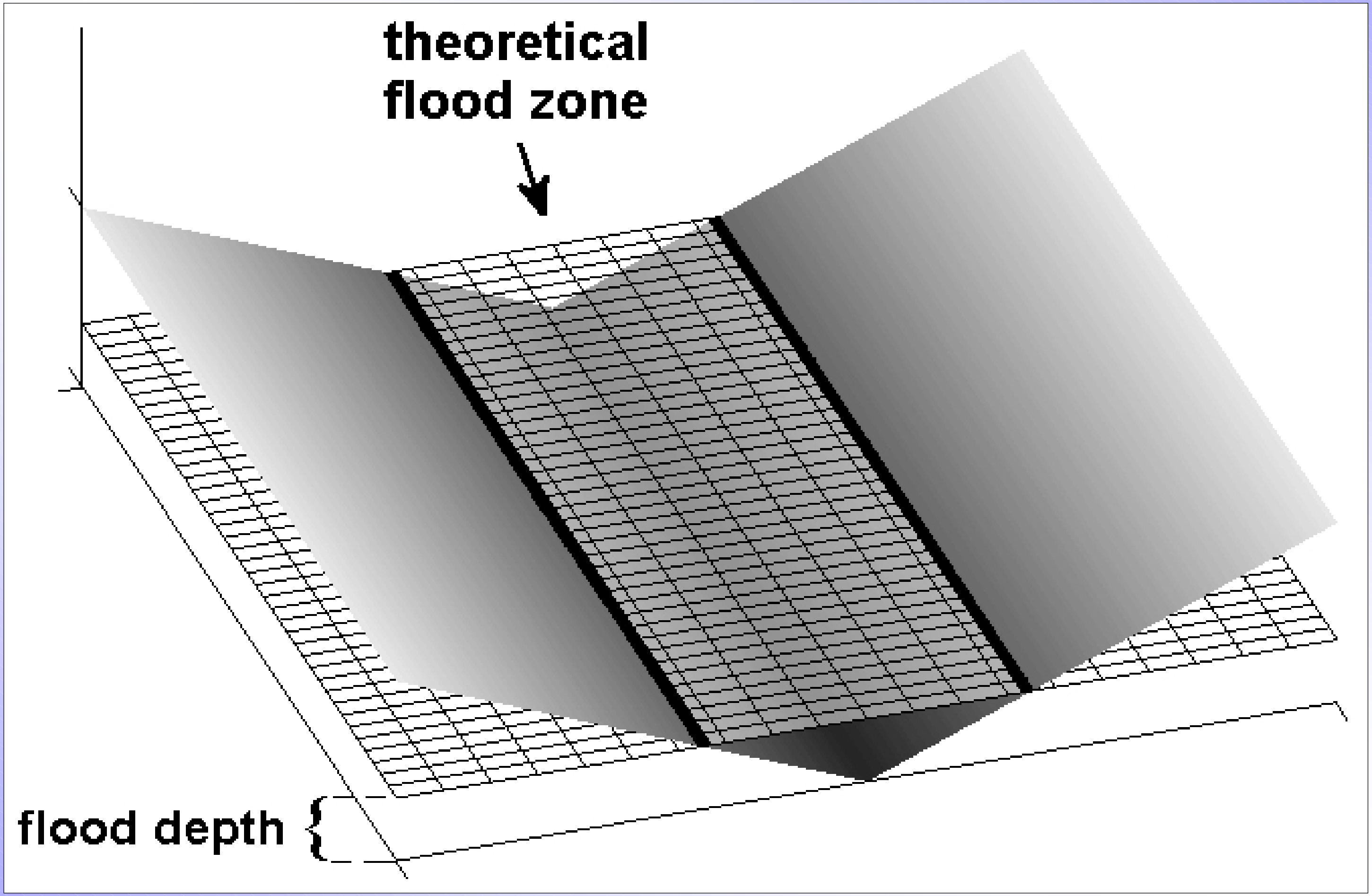
1) The Flood Zone Map
   - DTF and FSP values

2) A traveling wave model

The Traveling Wave Model

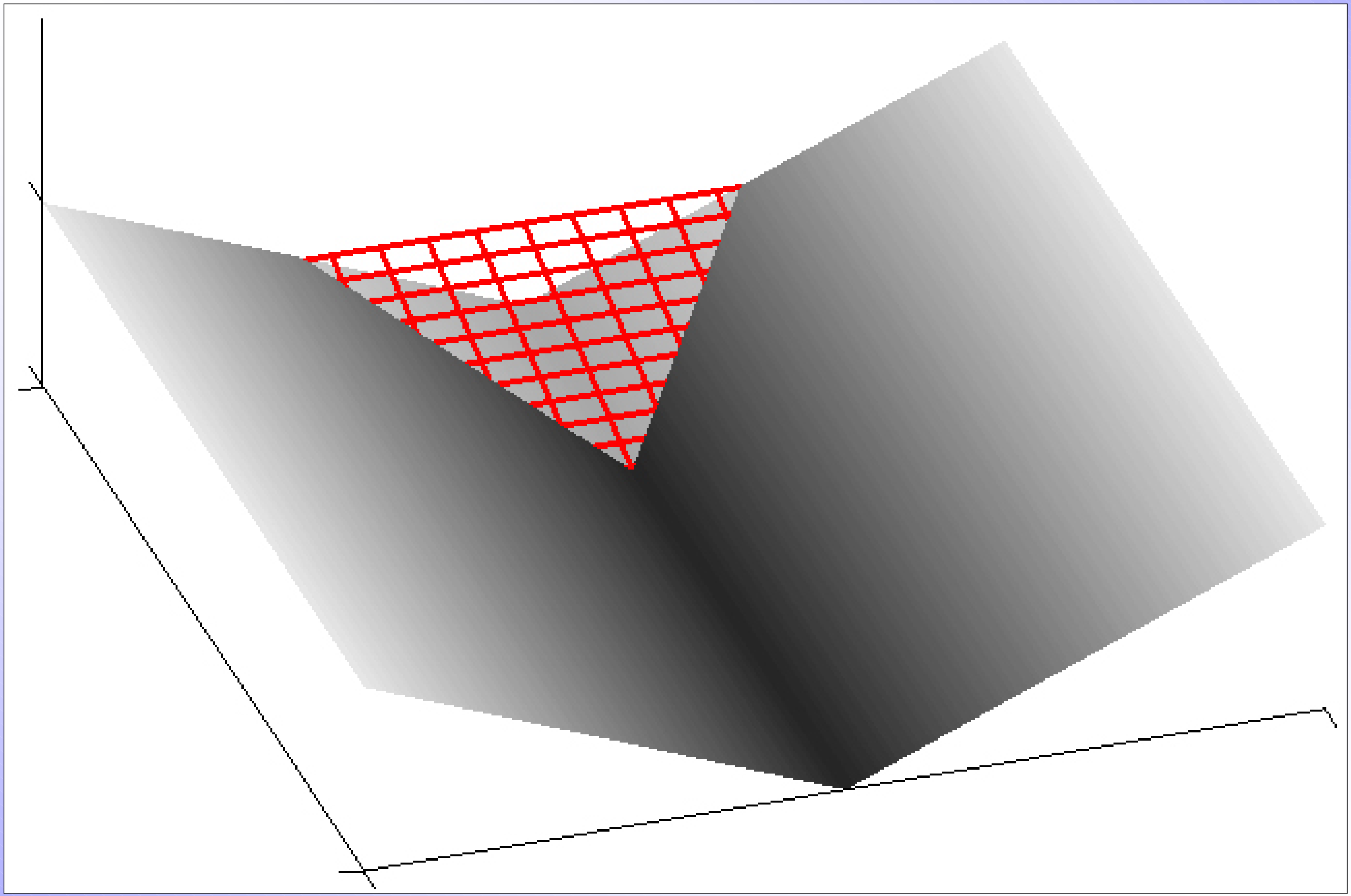
- *Must be a function of time*
- *Must be physically constrained*

The Traveling Wave Model



Start with a ***theoretical flood zone*** for a simple horizontal channel.

The Traveling Wave Model



Pinch it off to form a wave front characterized by (1) a maximum depth, and (2) a fixed volume

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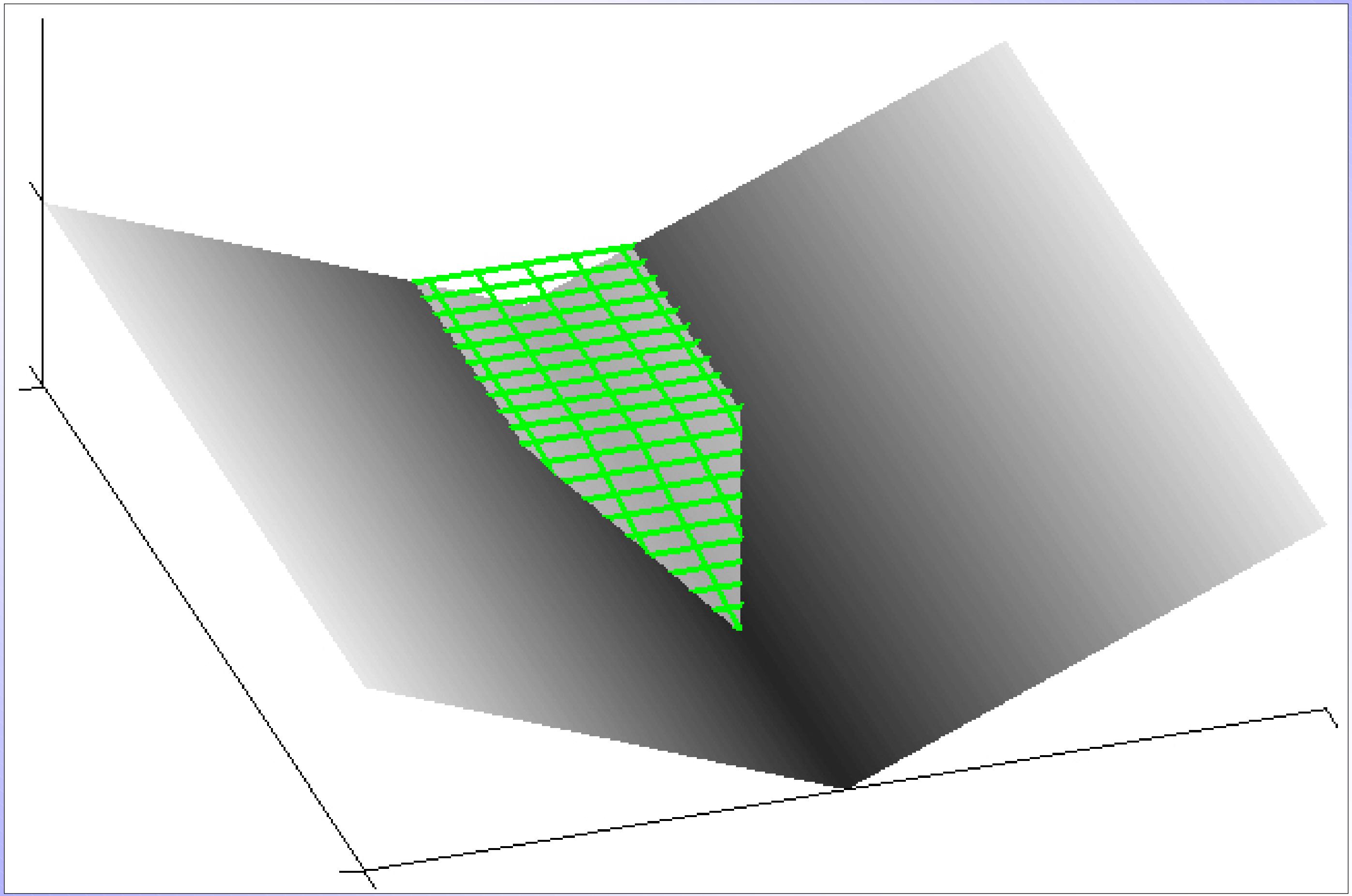
The Traveling Wave Model



Draw the wave downstream, ***preserving the contained volume*** at each step

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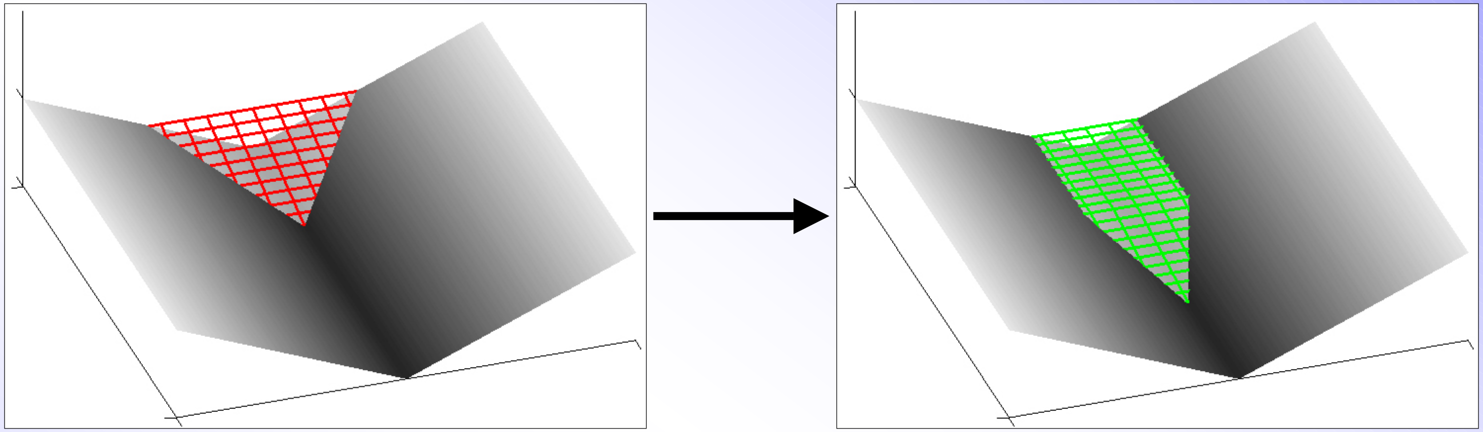
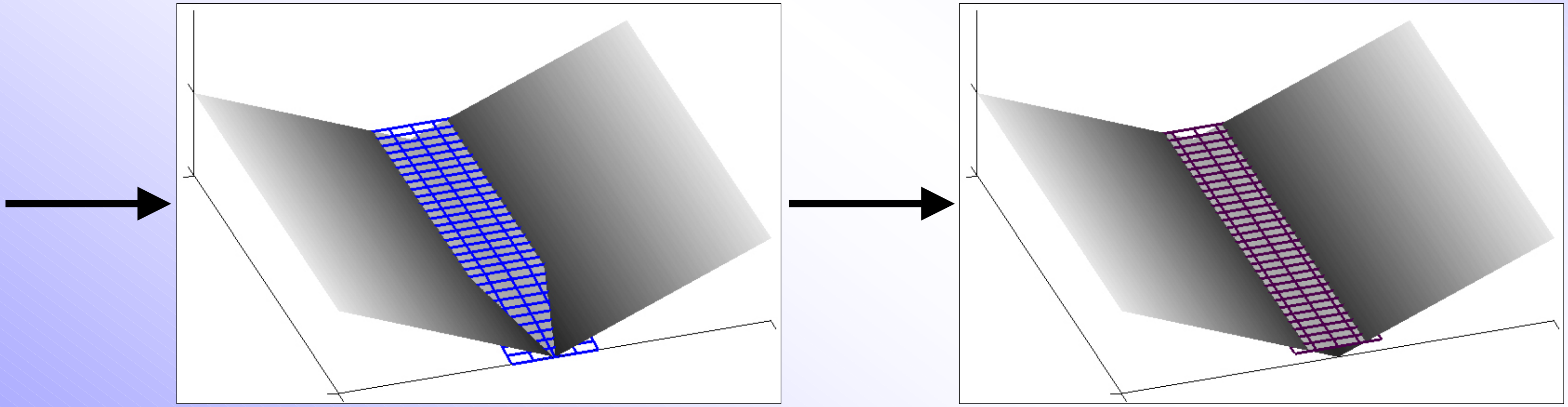
The Traveling Wave Model



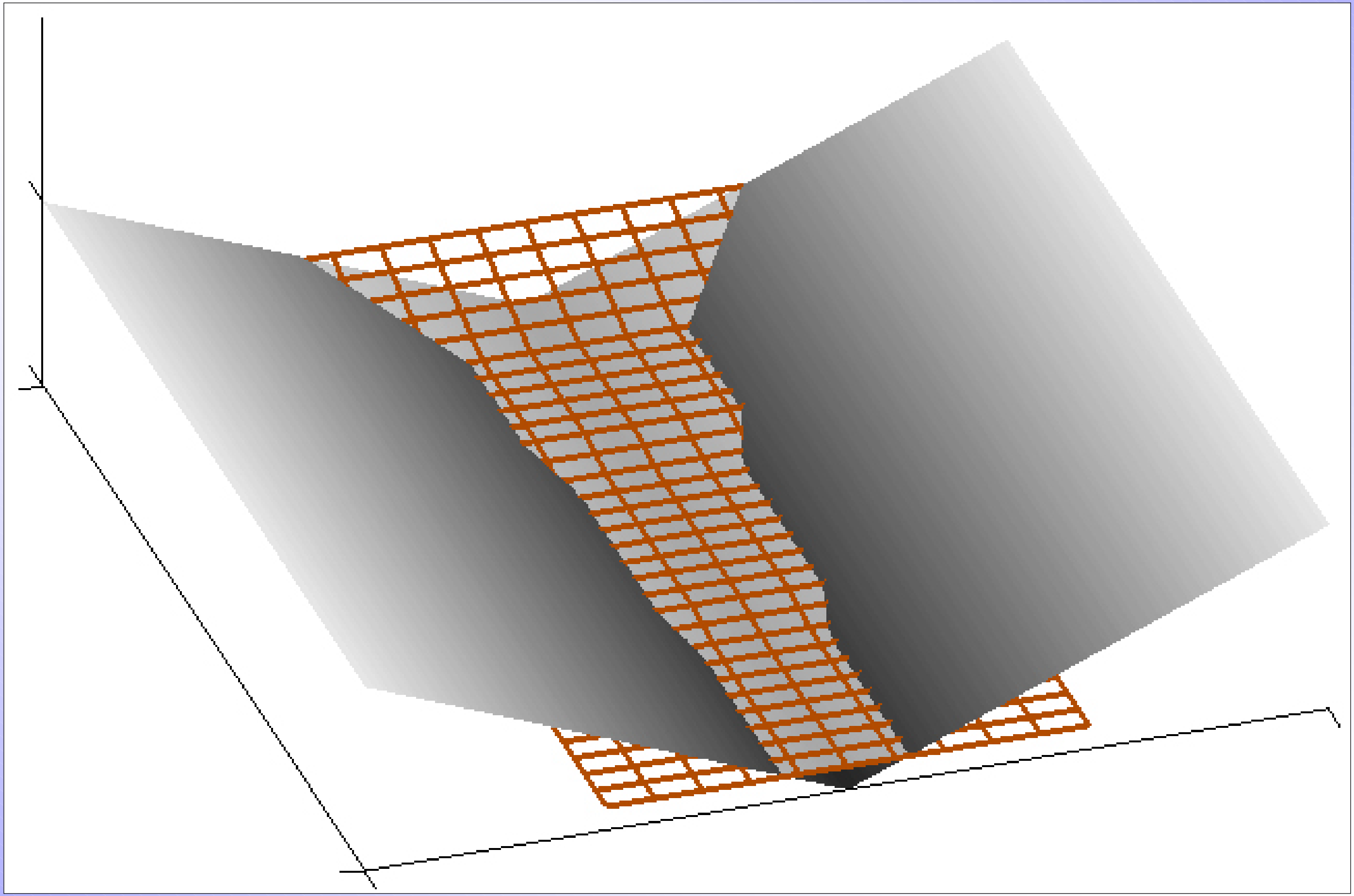
time 0 **time 1**



time 2 **time 3 (final)**

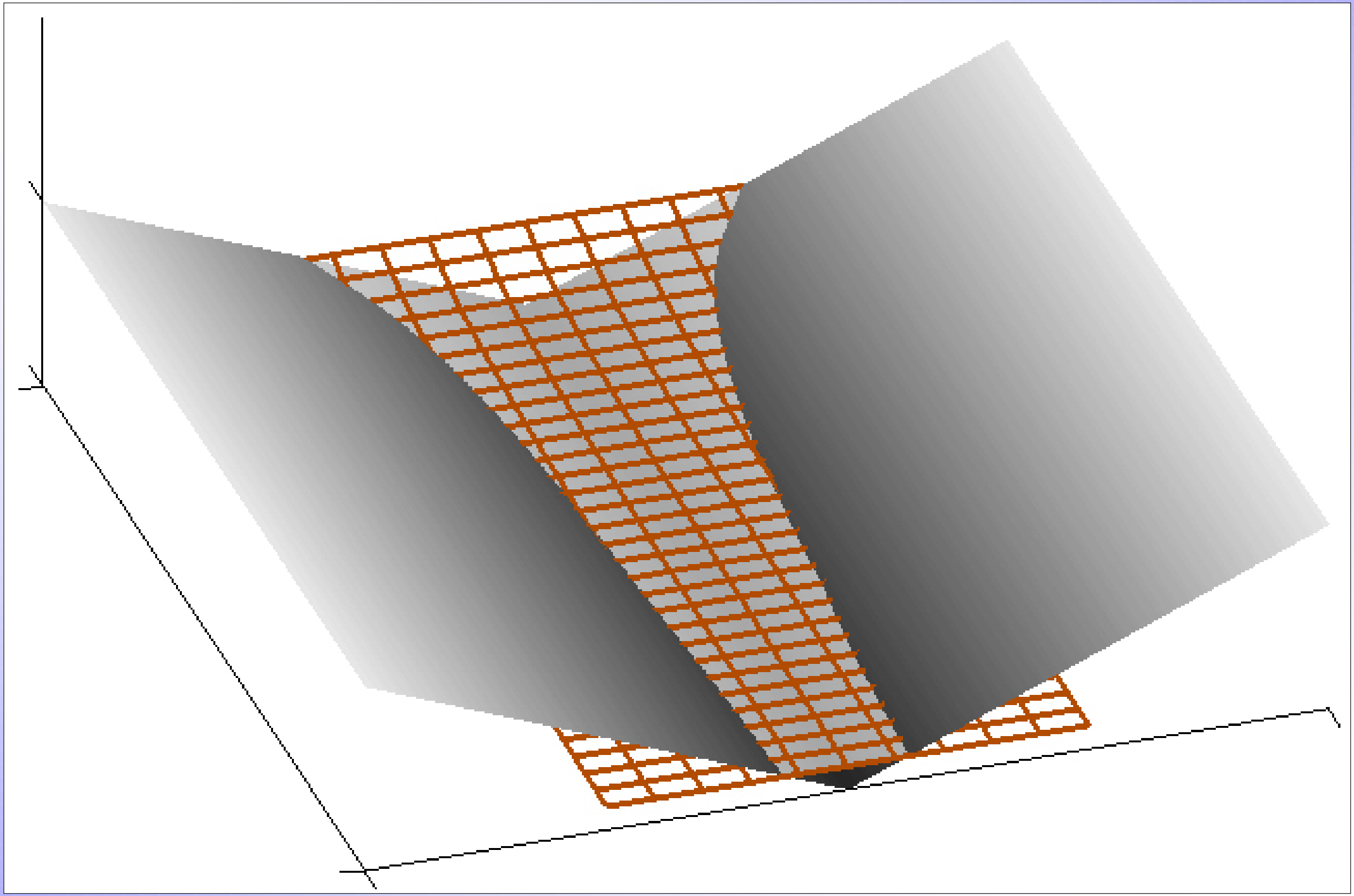
Propagate the wave out of the study area

The Breach Inundation Map



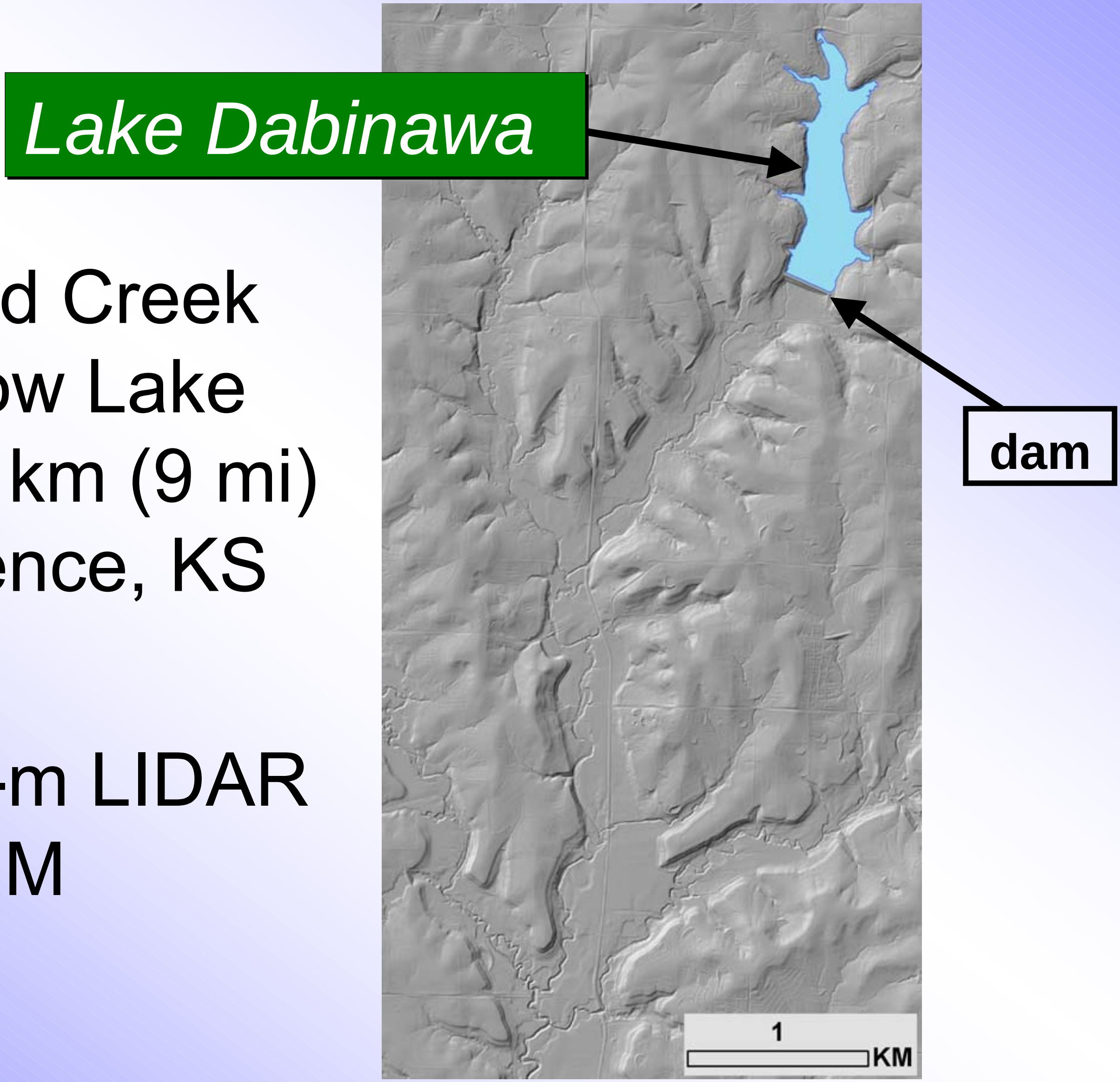
Merge the four time steps (time 0 – 3) to generate the ***breach inundation map***

The Breach Inundation Map



Breach inundation map, with 600 time steps

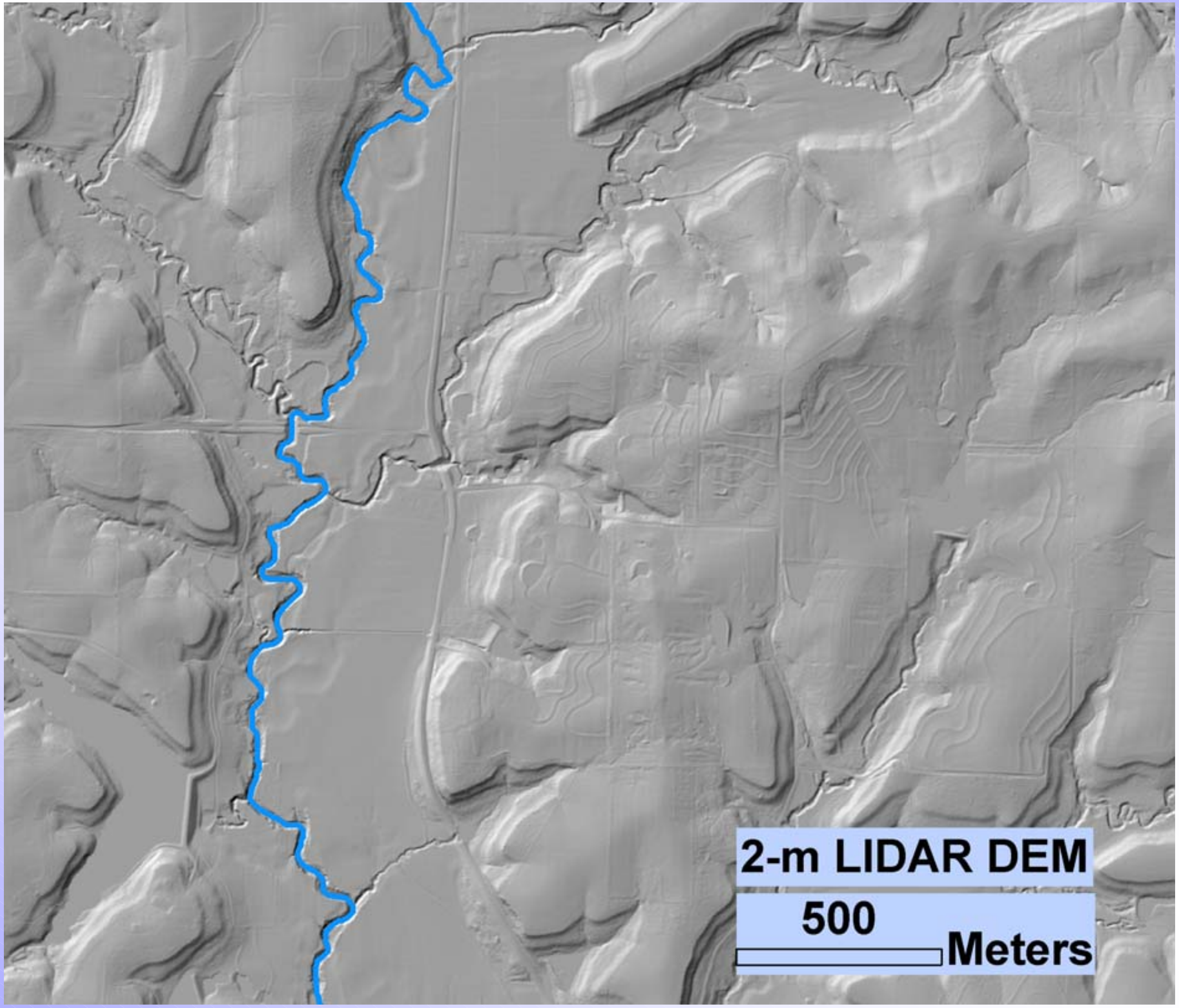
The Breach Inundation Map



Study Area: Mud Creek floodplain below Lake Dabinawa, 15 km (9 mi) north of Lawrence, KS

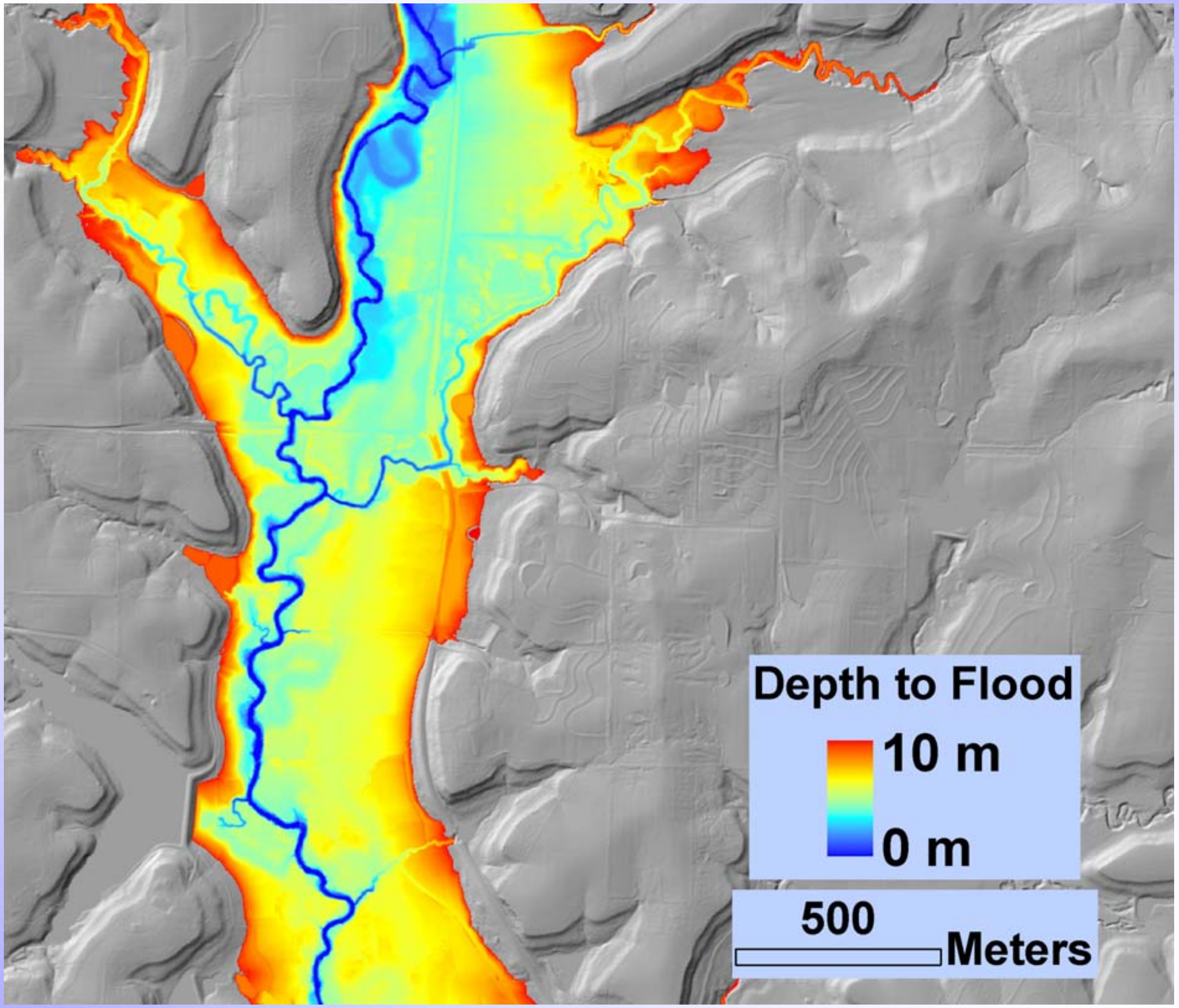
Source Data: 2-m LIDAR bare Earth DEM

The Breach Inundation Map



DEM subset

The Breach Inundation Map

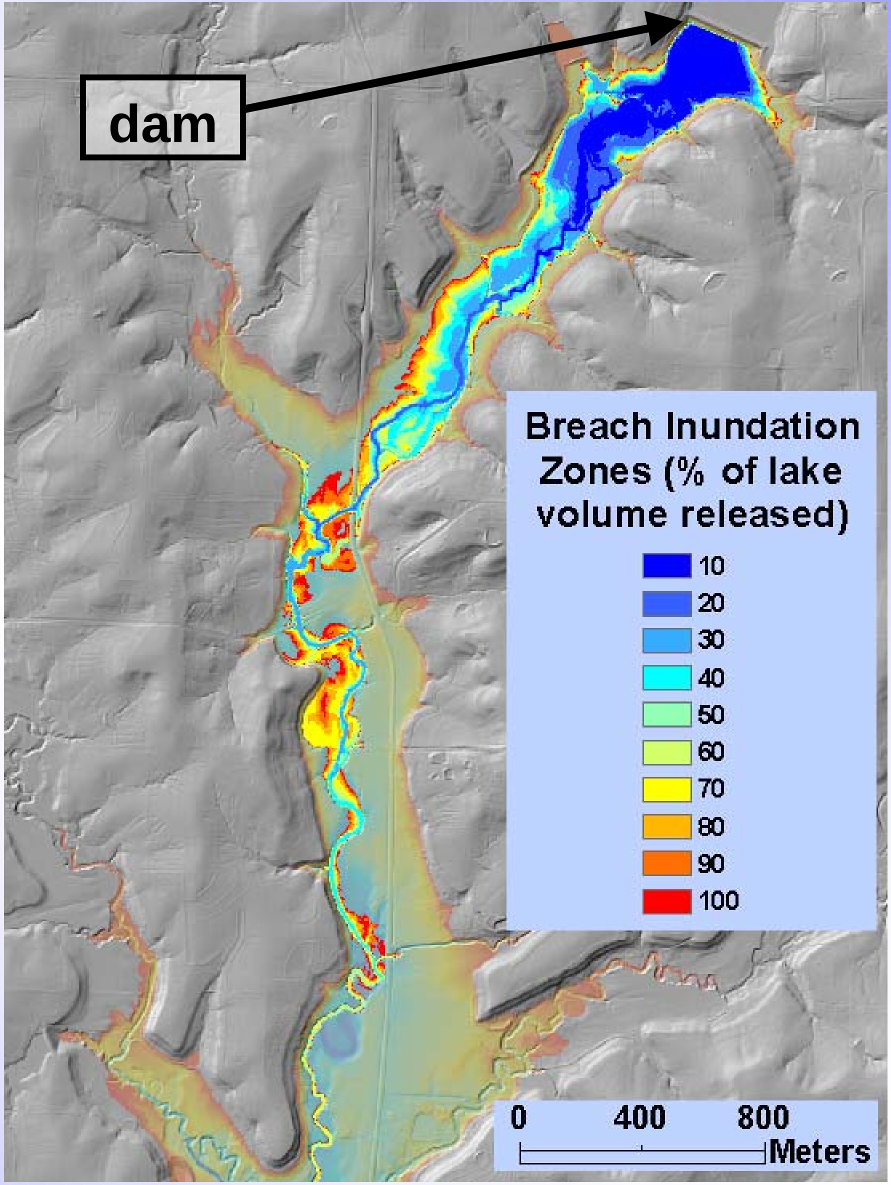


Flood zone map

The Breach Inundation Map (initial)

<u>Time 0:</u> The instant when the released volume has completely exited the reservoir.

Using DTF and FSP values obtained during calculation of the flood zone map (shown in the background), the initial breach inundation map is completely determined by the ***<u>maximum flood depth</u>*** (e.g., a function of the dam height or breach depth) and the ***<u>released volume</u>***.

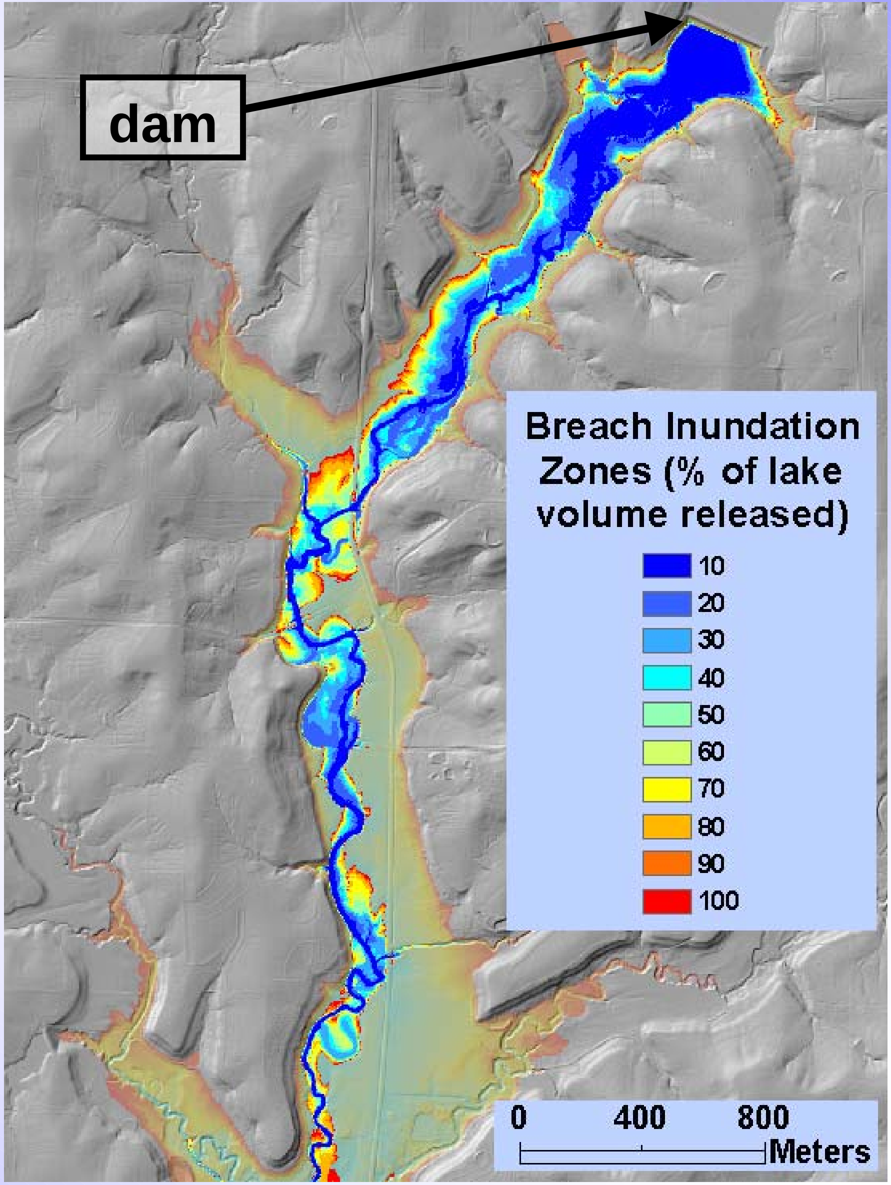


The Breach Inundation Map (final)

Time final: The instant when the flood wave front has exited the study area.

The flood zone map appears in the background.

Shown is the final breach inundation map, generated by merging the inundation zones created by propagating the wave front downstream one stream pixel at a time, ***preserving the volume*** at each step.



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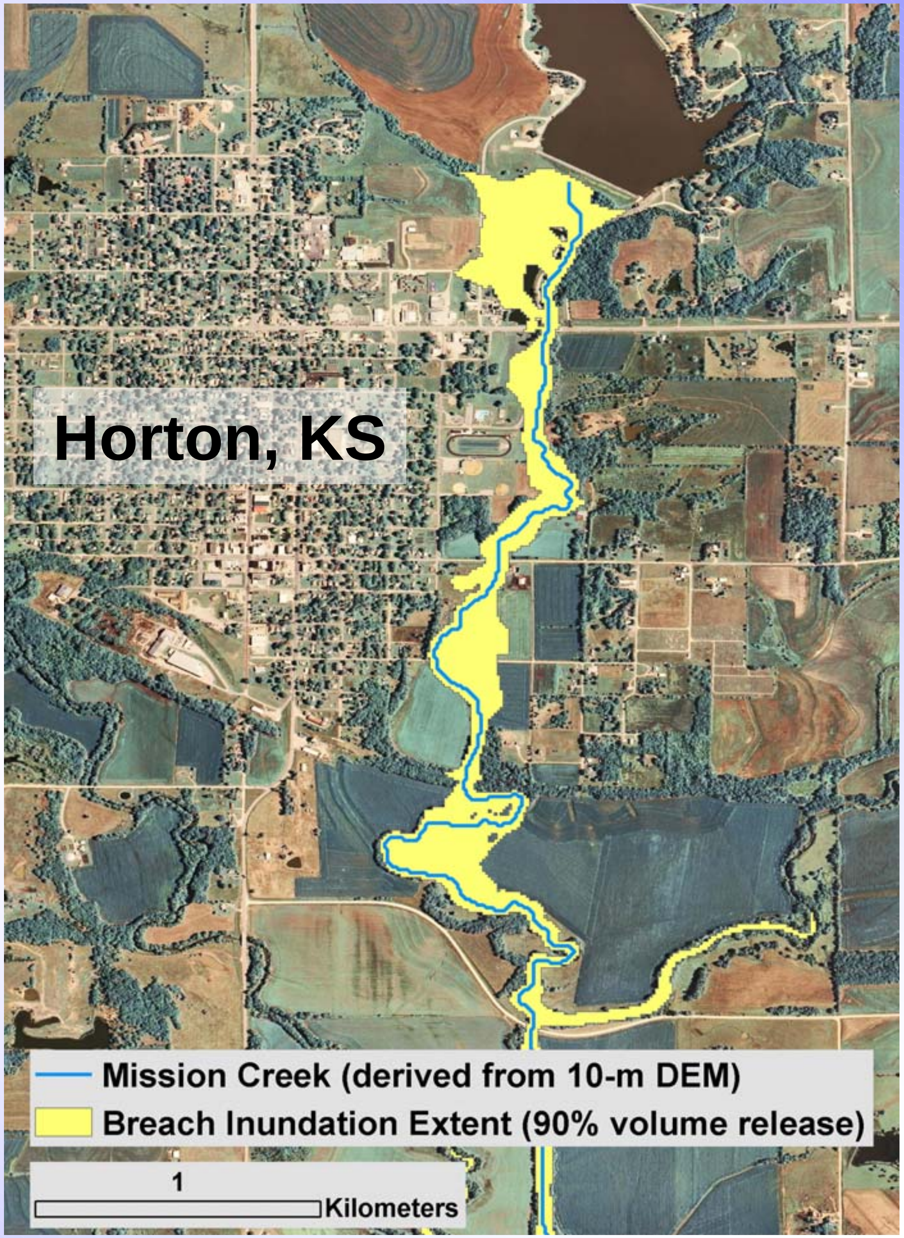
Quantifying Dam Breach Flood Risk

Increasing reservoir volume increases the flood risk in the event of a dam breach.

For Mission Lake, the proposed **60% increase in volume** produces a **20% increase in inundation extent**.

(The breach inundation extent is shown using the post-dredging volume, or 1655 ac.ft.)



On Deck: Mosul Dam in Iraq

MOSUL DAM:

- Impounds the Tigris River ~45 miles north of Mosul
- Key component in Iraq's national power grid (320 Mw/day)
- Normal capacity is >11 billion m^3
- Dubbed "*<u>the most dangerous dam in the world</u>*" by the US Army Corps of Engineers in 2006
- Upon failure, could flood Mosul (pop: 1.7 million) with 20 m, Baghdad with 5 m

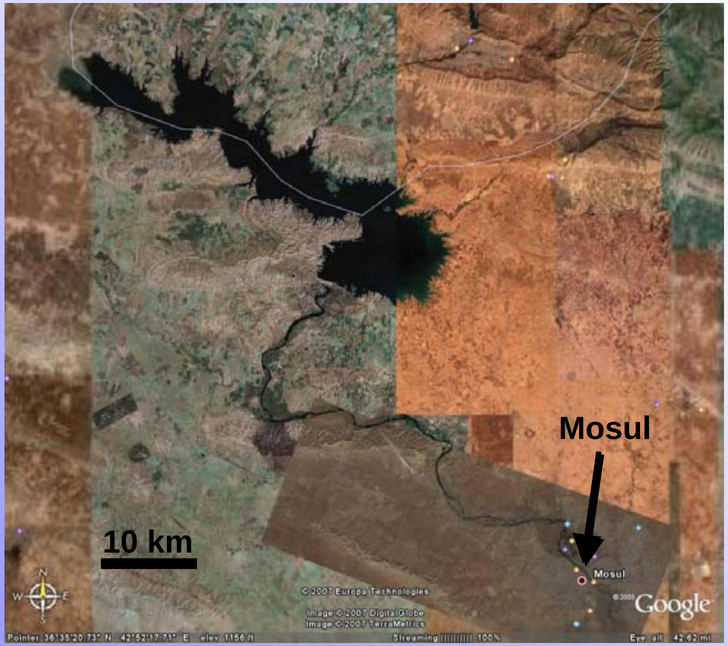
Mosul Dam

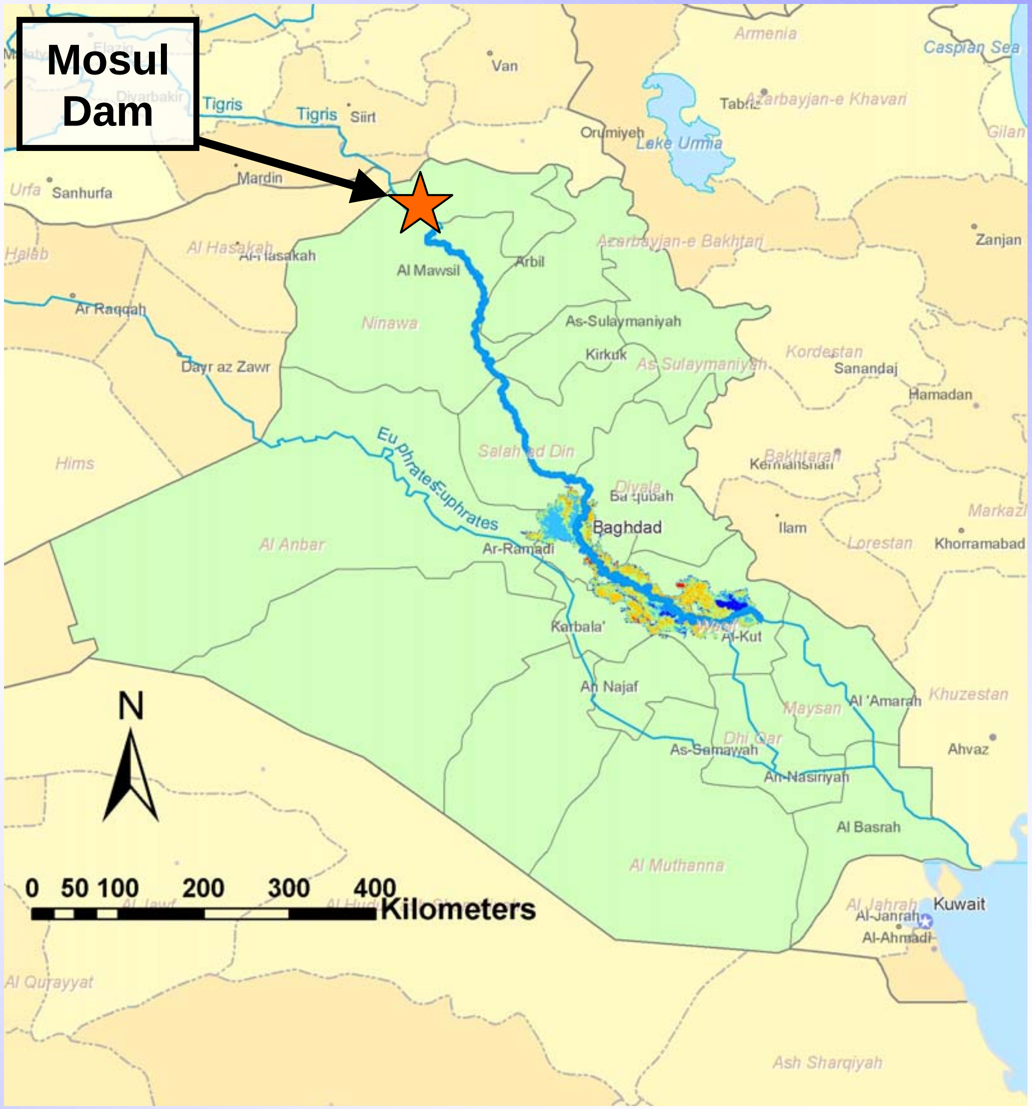
On Deck: Mosul Dam in Iraq

- The 5-m flood zone map is shown at right, developed using 90-m NED data.

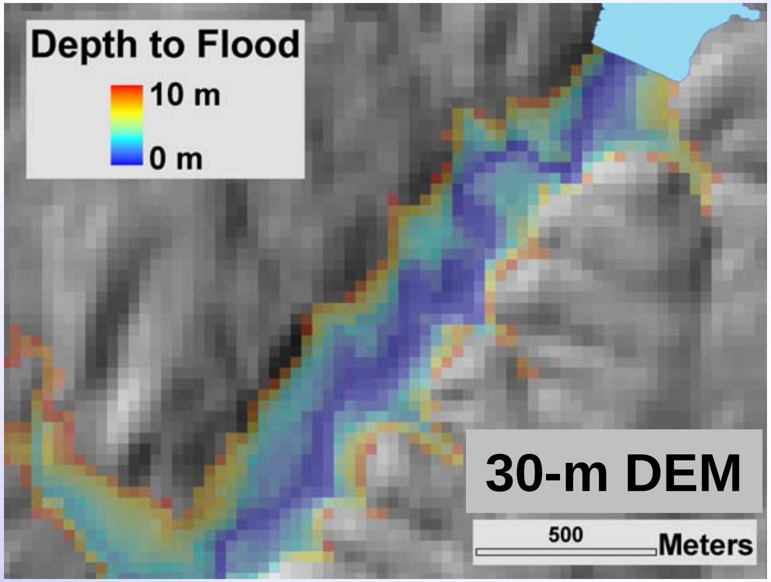
- Much of Baghdad is included.

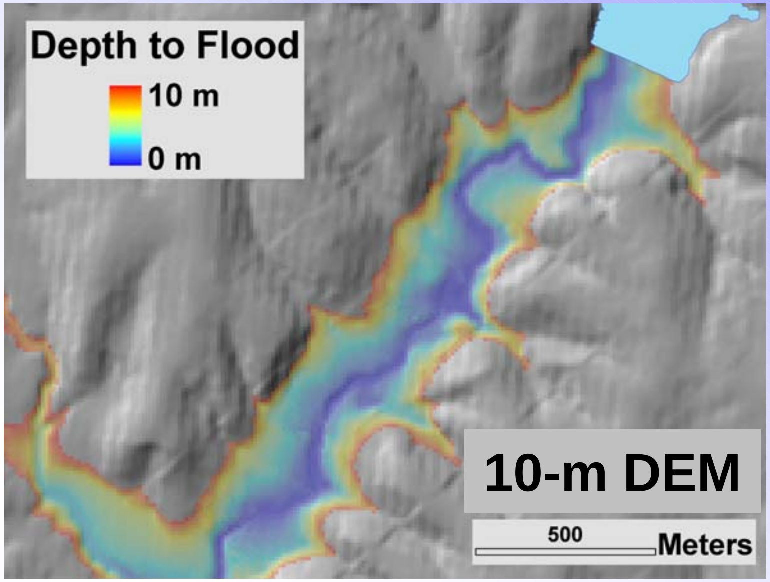
aerial view





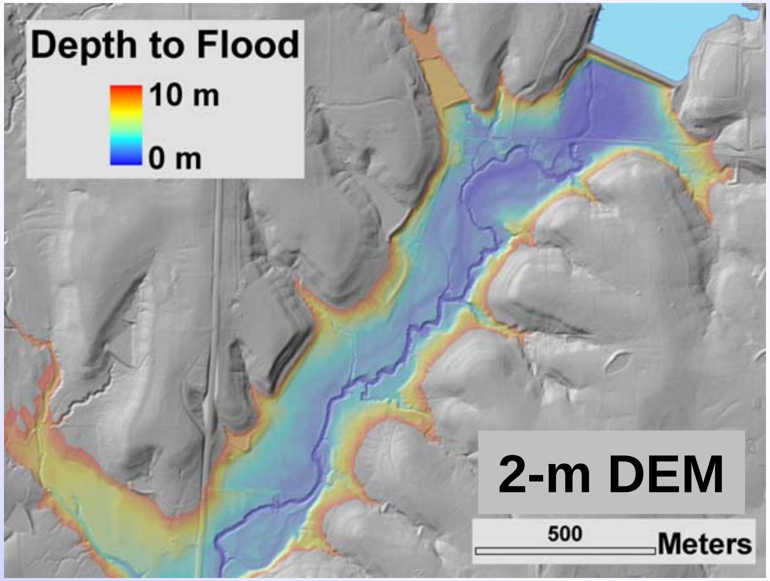
Final Thoughts: Resolution Matters





Smaller streams require higher resolution DEMs.

(The Mud Creek floodplain below Lake Dabinawa, KS, is shown using three different data resolutions.)



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THANKS FOR LISTENING

Any Questions?