Using Digital Elevation Data for Applications in Floodplain Mapping

Jude H. Kastens (jkastens@ku.edu)
Background Examples: Sink Filling

Digital Elevation Model (DEM)
Background Examples: Sink Filling

DEM with sinks filled (depressionless DEM)
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!
8-digit hydrologic unit code (HUC8) boundaries are shown in red.

These quasi-watersheds depict local catchments.
The 16-m floodplain is shown in light blue.

This particular example was used to identify wetlands for research.
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
Background Examples: Really Big River

Amazon subset: Flow Accumulation
Background Examples: Really Big River

DEM-based Amazon River arc
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

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

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Flood Event Modeling

TYPICAL FLOW SCENARIO

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.
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)
The Flood Zone Map

Define the “pitched channel” to aid concept development.

\[ P = \frac{1}{2} \]

\[ L = \text{landscape plane} \]
\[ C = \text{horizontal channel} \]
\[ S = L + C = \text{pitched channel} \]

channel pitch:
\[ P = \left| \frac{\partial z}{\partial y} \right| / \left| \frac{\partial z}{\partial x} \right| \]
The Flood Zone Map

Must approximate the theoretical flood zone
The Flood Zone Map

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

channel pitch: $P = |\frac{\partial z}{\partial y}| / |\frac{\partial z}{\partial x}| = 1/2$
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
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 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. *Constrained forward flooding* is used to remedy this problem, as well as the under-estimation problem.
Concept development: constrained forward flooding
The Flood Zone Map

channel pitch:
$P = \frac{|\partial z/\partial y|}{|\partial z/\partial x|}$

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
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.
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 $P$. 
This DEM was created by DASC using LIDAR data.

Shown is a portion of the river valley for Mud Creek, Kansas.
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
The Flood Zone Map

Filled DEM with Mud Creek stream segment, identified using the flow direction and flow accumulation maps.
Ridge lines in the flow direction map

Flood zone map BEFORE forward flood correction.
Note the undesirable discontinuities.
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 $BF(h_0)$ 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).
Some Examples Using 30-m DEM Data from the National Elevation Database (NED)
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.
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 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 ($R^2 = 0.47$).
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.
Comparison of modeled flood extents from three different methods
Floodplain Delineation

Comparison between USGS Hydrologic Model and KARS Floodplain Model
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.
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

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

Estimated >85% accuracy

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

Areas of interest

Big Channel
Pinch Point
Bates County
Harry S. Truman Reservoir
St. Clair County
Vernon County
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
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
The Traveling Wave Model

Draw the wave downstream, preserving the contained volume at each step.
The Traveling Wave Model

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
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

Lake Dabinawa

dam
The Breach Inundation Map

DEM subset
The Breach Inundation Map

Flood zone map
**Time 0:** 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 **maximum flood depth** (e.g., a function of the dam height or breach depth) and the **released volume**.
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.
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.)
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 "the most dangerous dam in the world" 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
The 5-m flood zone map is shown at right, developed using 90-m NED data.

Much of Baghdad is included.
Smaller streams require higher resolution DEMs.

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

Any Questions?