This is a set of slides from a presentation given at

RISING WATERS
Maryland Prepares for Floods & Sea Level Rise
2011 Water Resources Symposium

hosted by the Maryland Water Resources Research Center
at the University of Maryland, College Park
on Tuesday, Nov. 15, 2011

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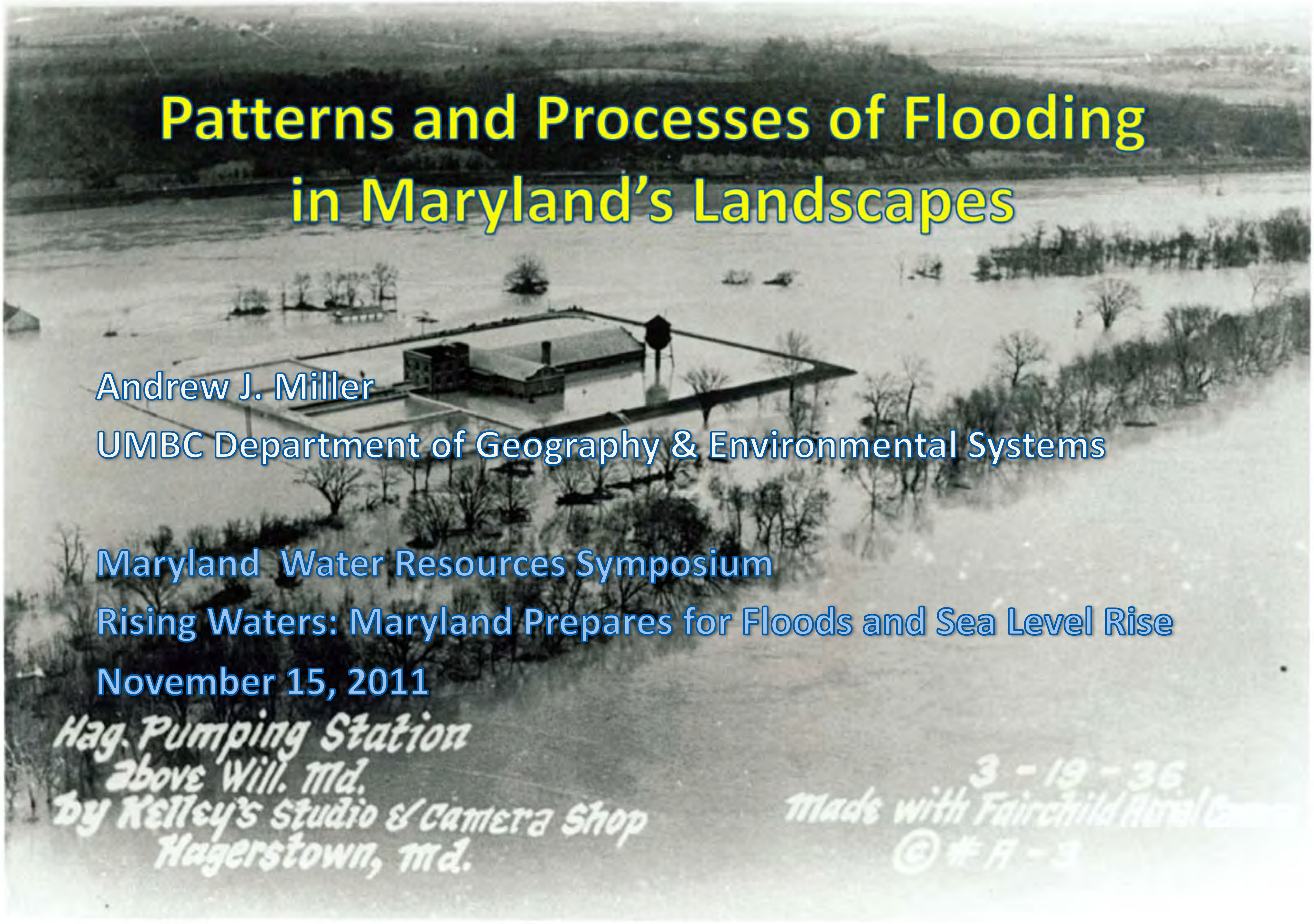
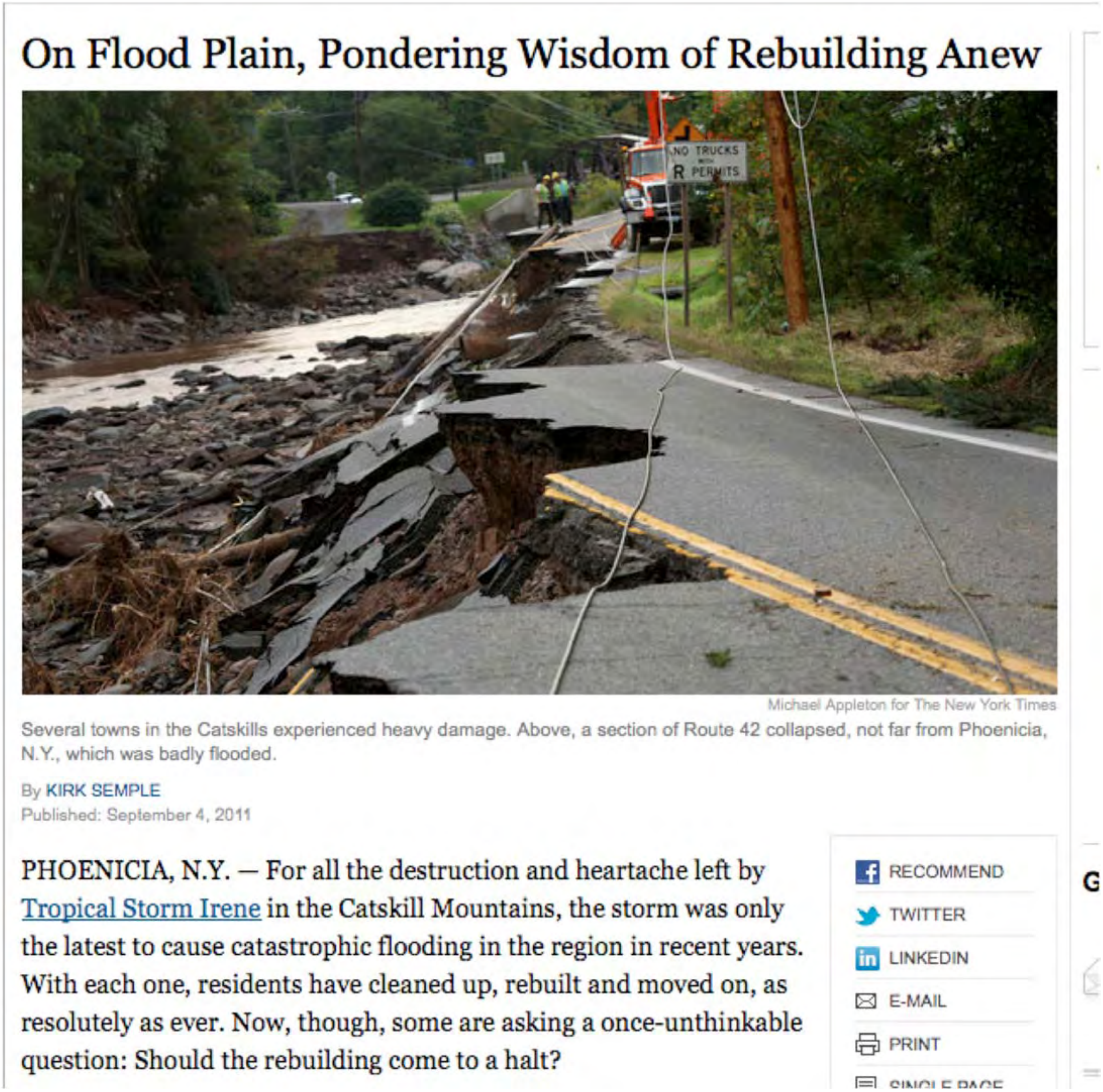


# Patterns and Processes of Flooding in Maryland's Landscapes

Andrew J. Miller
UMBC Department of Geography & Environmental Systems

Maryland Water Resources Symposium
Rising Waters: Maryland Prepares for Floods and Sea Level Rise
November 15, 2011



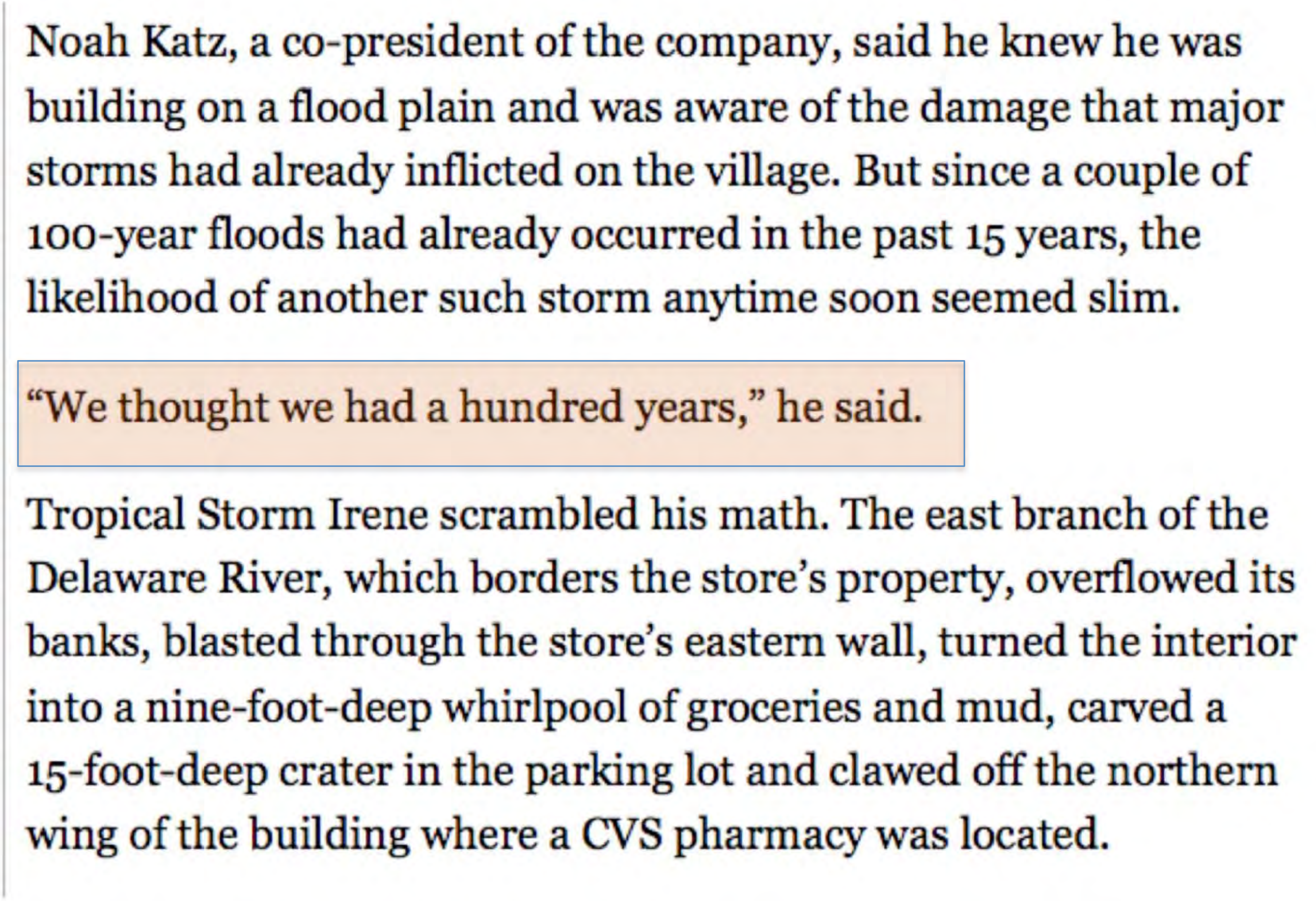
# On Flood Plain, Pondering Wisdom of Rebuilding Anew

Michael Appleton for The New York Times

Several towns in the Catskills experienced heavy damage. Above, a section of Route 42 collapsed, not far from Phoenicia, N.Y., which was badly flooded.

By KIRK SEMPLE
Published: September 4, 2011

PHOENICIA, N.Y. — For all the destruction and heartache left by Tropical Storm Irene in the Catskill Mountains, the storm was only the latest to cause catastrophic flooding in the region in recent years. With each one, residents have cleaned up, rebuilt and moved on, as resolutely as ever. Now, though, some are asking a once-unthinkable question: Should the rebuilding come to a halt?



Noah Katz, a co-president of the company, said he knew he was building on a flood plain and was aware of the damage that major storms had already inflicted on the village. But since a couple of 100-year floods had already occurred in the past 15 years, the likelihood of another such storm anytime soon seemed slim.

"We thought we had a hundred years," he said.

Tropical Storm Irene scrambled his math. The east branch of the Delaware River, which borders the store's property, overflowed its banks, blasted through the store's eastern wall, turned the interior into a nine-foot-deep whirlpool of groceries and mud, carved a 15-foot-deep crater in the parking lot and clawed off the northern wing of the building where a CVS pharmacy was located.

# Key points

- Floods are predictable events, i.e. we know they will occur
- Floods are unpredictable events, i.e. we don’t know when they will occur
- We think we know about how often they are likely to occur, at least in watersheds with historic records
- Except that we don’t know whether we can trust those records, especially in the face of anticipated climate change
- But we have to plan for them anyway; and at minimum we should continually update our estimates of risk

# Key points

- Significant floods in Maryland include inland rainfall-runoff events and coastal floods caused by wind-driven storm surge superimposed on tidal cycles
- The same hydrometeorological event (e.g. a tropical cyclone or a nor’easter) may cause either coastal flooding or inland flooding or both, but for different reasons (e.g. Agnes vs. Isabel)
- We will focus mostly on inland floods, with brief discussion of coastal floods
- Flood-generating storms vary in intensity, duration, and spatial scale
- Flood impacts vary with these factors and with the characteristics of the landscapes in which they occur

- Nonstationarity in flood frequency can result from land-cover change, river regulation, climate change
  - Occurs at all time scales with cycles or perturbations of varying length
  - Affects ability to make predictions based on historic records

CLIMATE CHANGE

SCIENCE VOL 319 1 FEBRUARY 2008

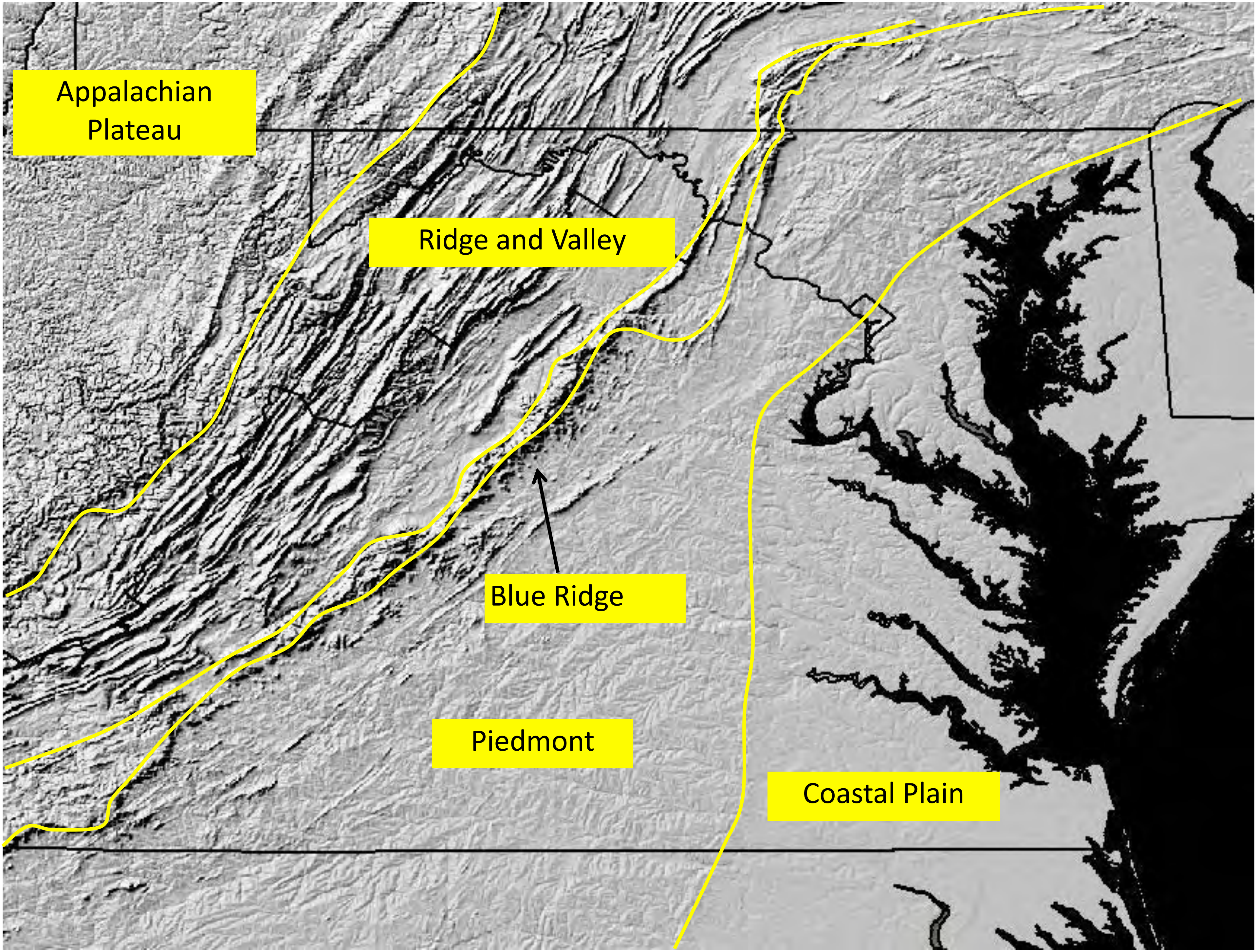
**Stationarity Is Dead: Whither Water Management?**

**P. C. D. Milly,[1*] Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]**

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

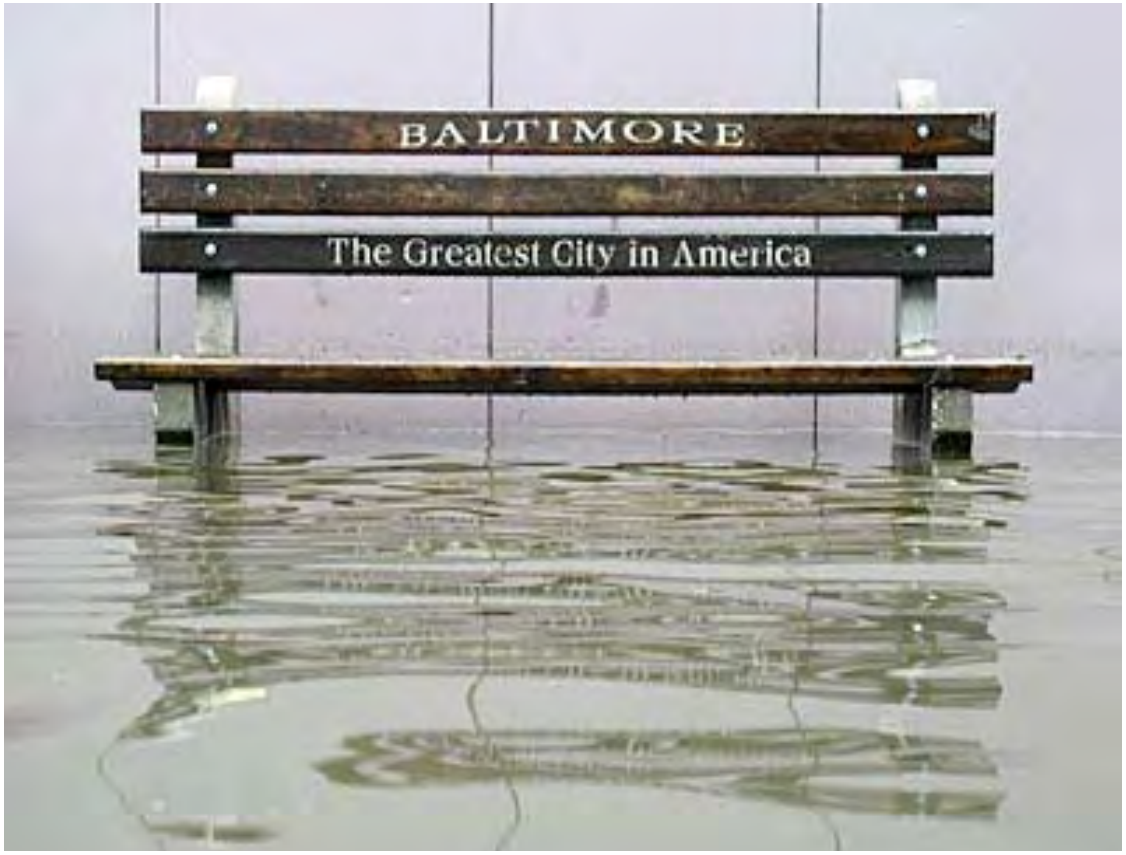
# What are the major flood-generating weather systems across different landscape types?

- Coastal storm surge/tidal flooding
  - Tropical cyclones
  - Extratropical cyclones/nor’easters
- Inland rainfall-runoff flooding
  - Extratropical cyclones/nor’easters; rain on snow/ frozen ground
  - Tropical cyclones, often with extratropical transition
  - Warm-season convective precipitation


Appalachian Plateau
Ridge and Valley
Blue Ridge
Piedmont
Coastal Plain

# Coastal floods

- Causal factors are related to low pressure, wind direction and intensity, timing in relation to tidal cycles, and location of low relative to the axis of Chesapeake Bay

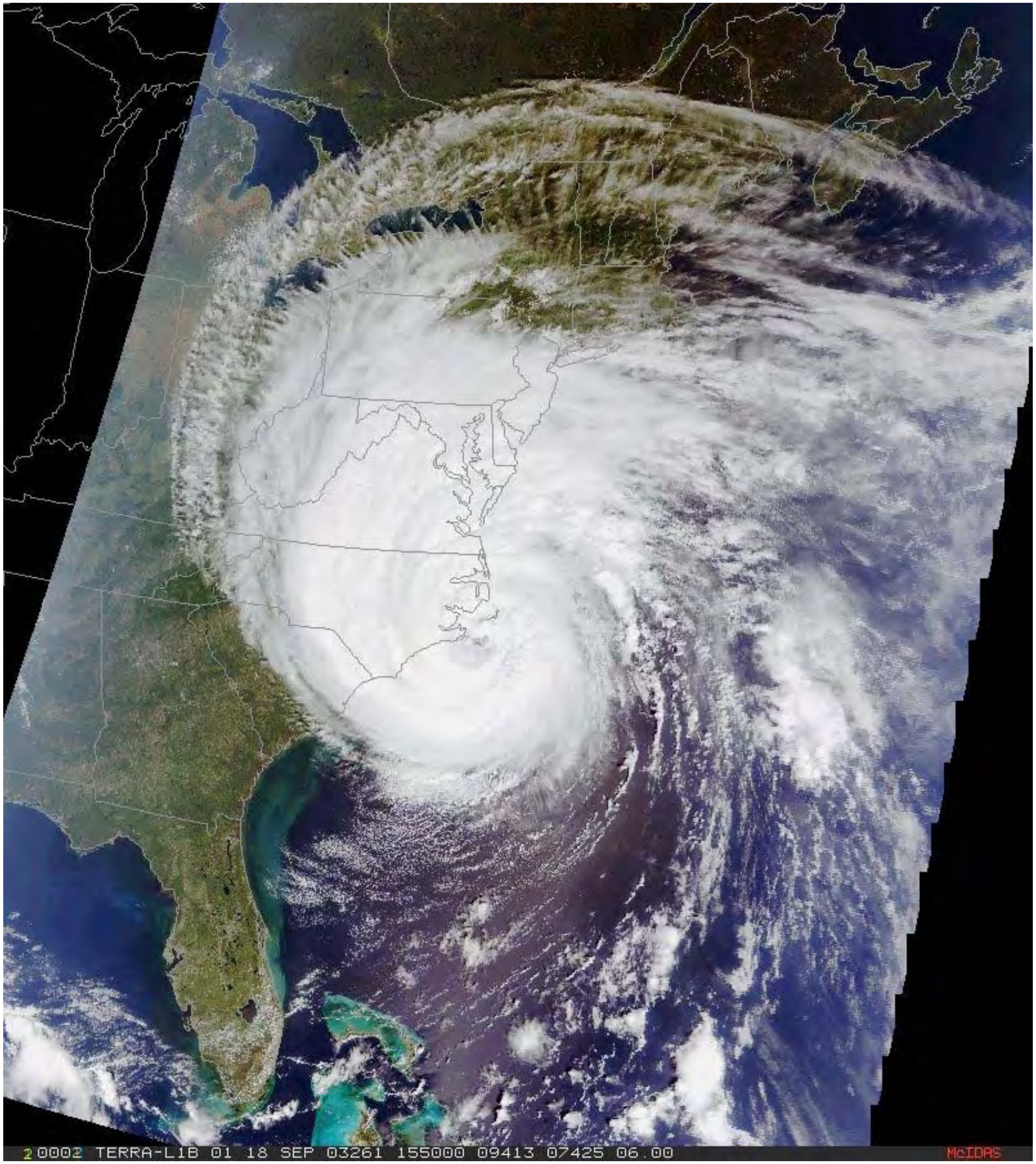


# Hurricane Isabel
September 2003

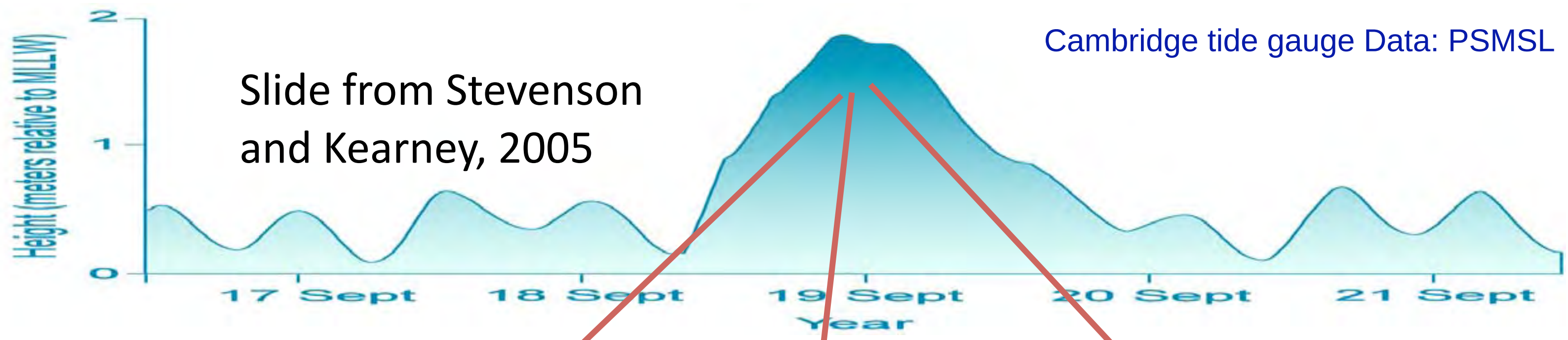
Caused minimal inland flooding in Maryland, but major coastal flooding

(opposite of Agnes in 1972)

See Sellner, 2005, CRC Publication 05-160
http://www.chesapeake.org/pubs/Isabel/isabel.htm



# Isabel: surge height and impact



Slide from Stevenson and Kearney, 2005

Cambridge tide gauge Data: PSMSL


Photo: Monica Salerno

Cambridge


Photo: Don Merritt

Horn Point


Photo: Don Boesch

Annapolis

# The Role of Waves

- Waves ride on top of the storm surge
  - Galveston Hurricane is a classic example
  - *Increased flooding*
- As sea level rises, greater depths of water increase the potential for generation of larger waves from the same wind field
  - *Increases the flood risk*

Slide from Stevenson and Kearney, 2005

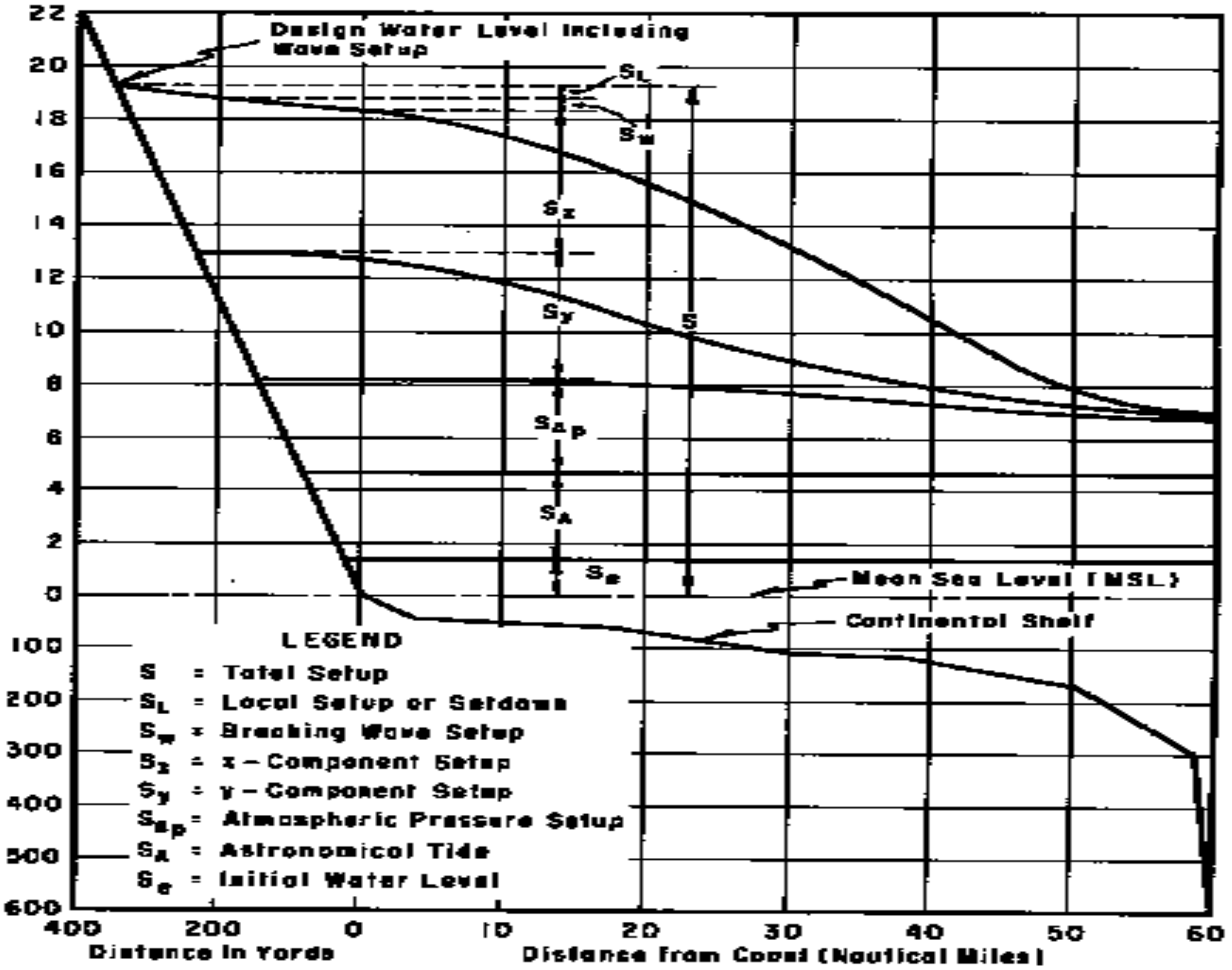
# Wave setup can compound the effect of sea level rise

Large waves moving directly onshore

Waves from Hurricane Isabel on North Carolina's coast

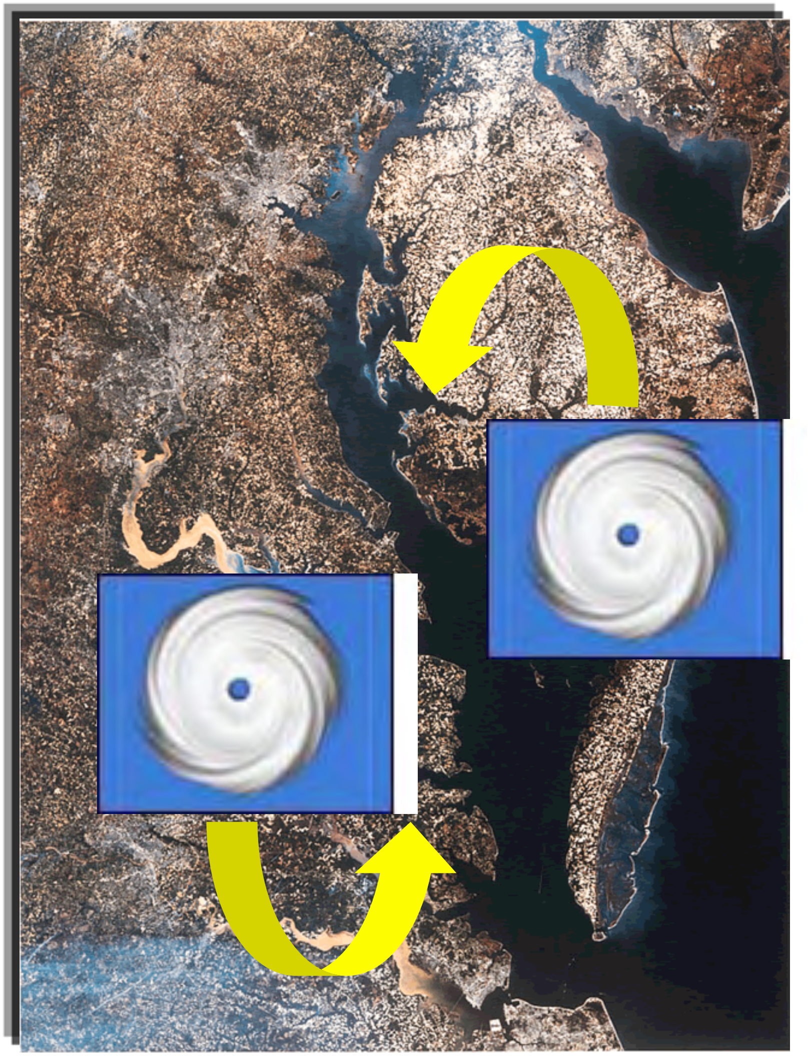
Slide from Stevenson and Kearney, 2005

# Total flood height =
# sea level + storm surge + wave setup



Track of the storm affects direction of wave generation

Also determines whether water is driven up-Bay or down-Bay



Slide from Stevenson and Kearney, 2005

From Boicourt, 2005

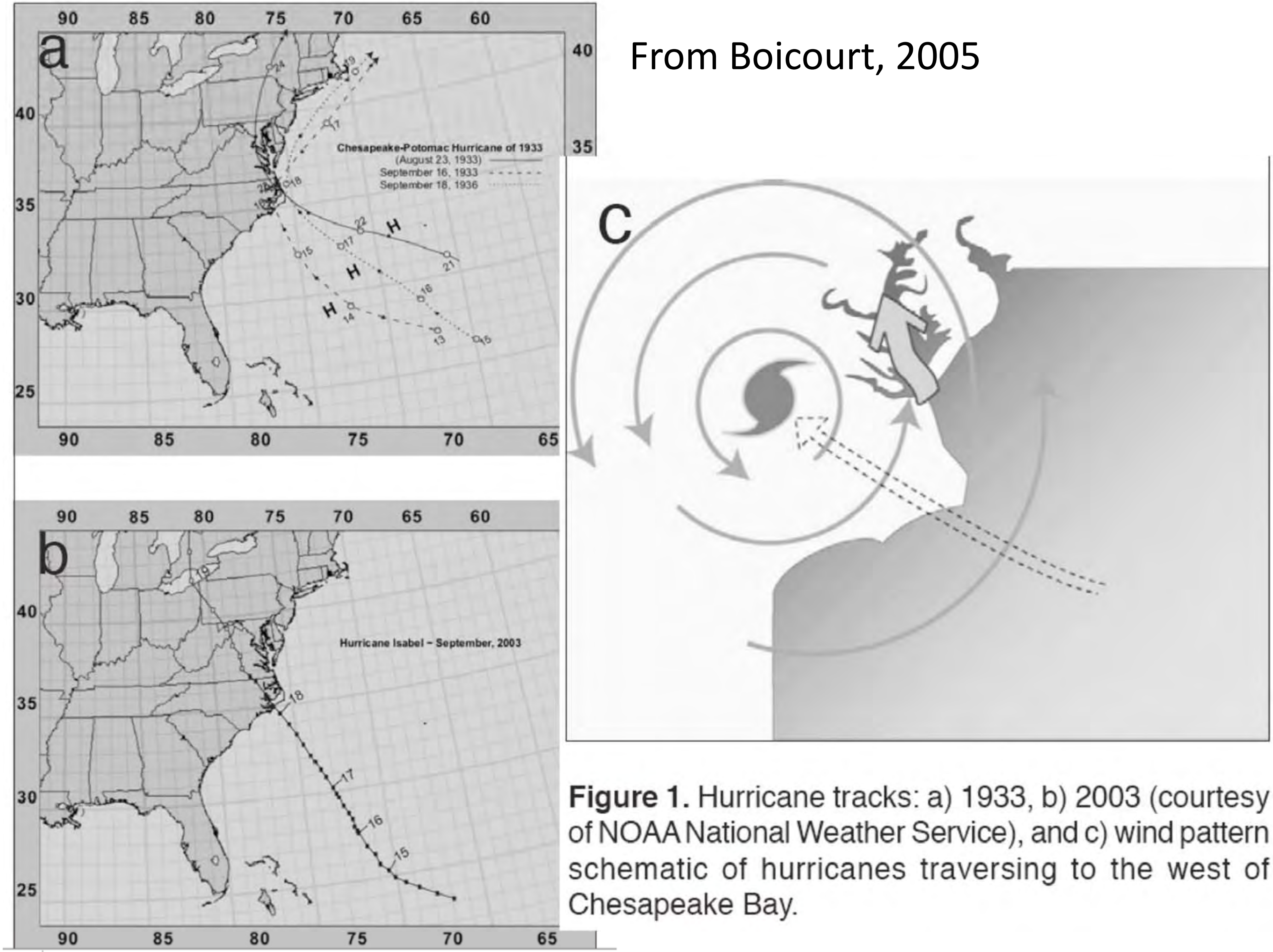


**Figure 1.** Hurricane tracks: a) 1933, b) 2003 (courtesy of NOAA National Weather Service), and c) wind pattern schematic of hurricanes traversing to the west of Chesapeake Bay.

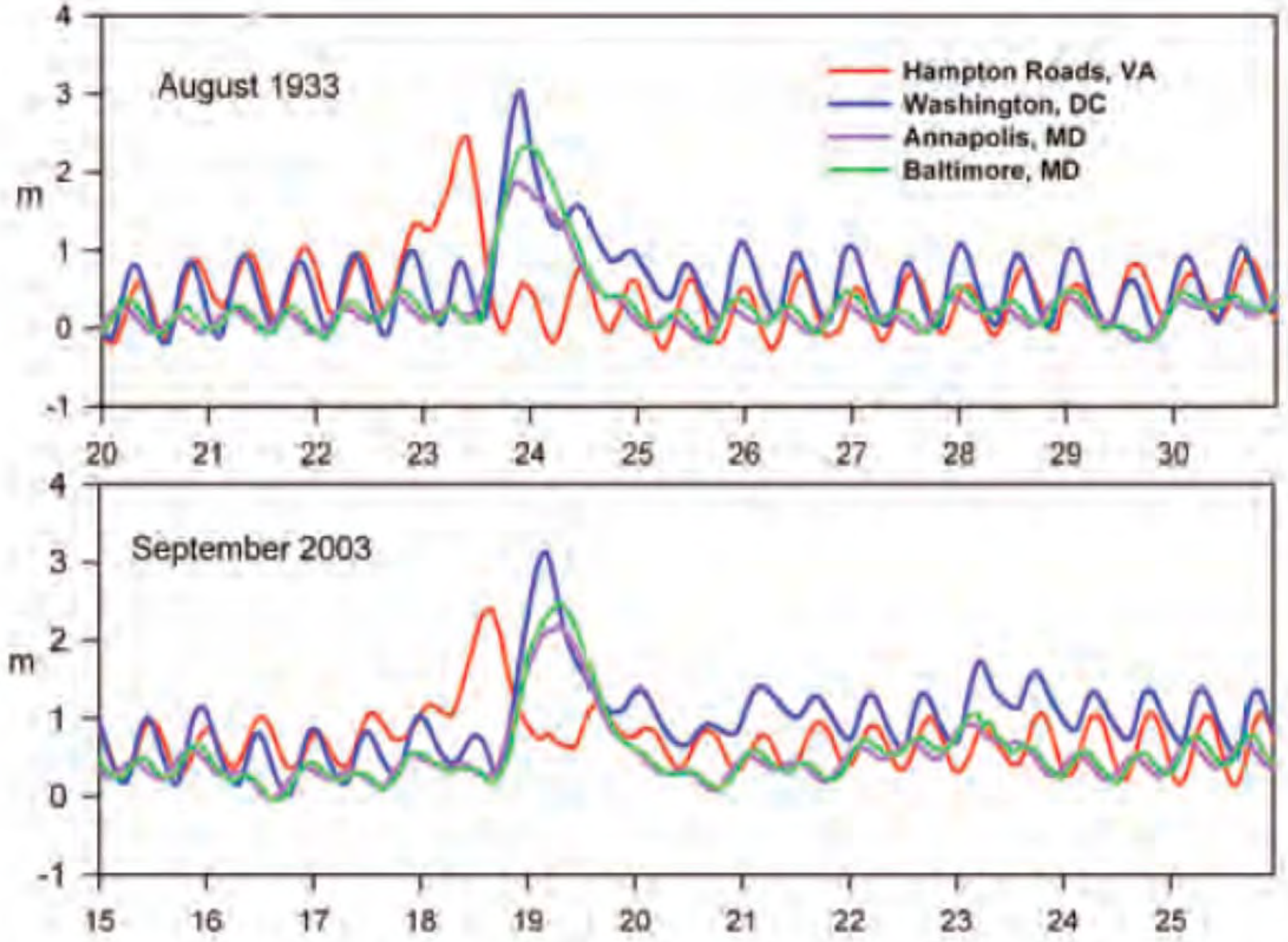
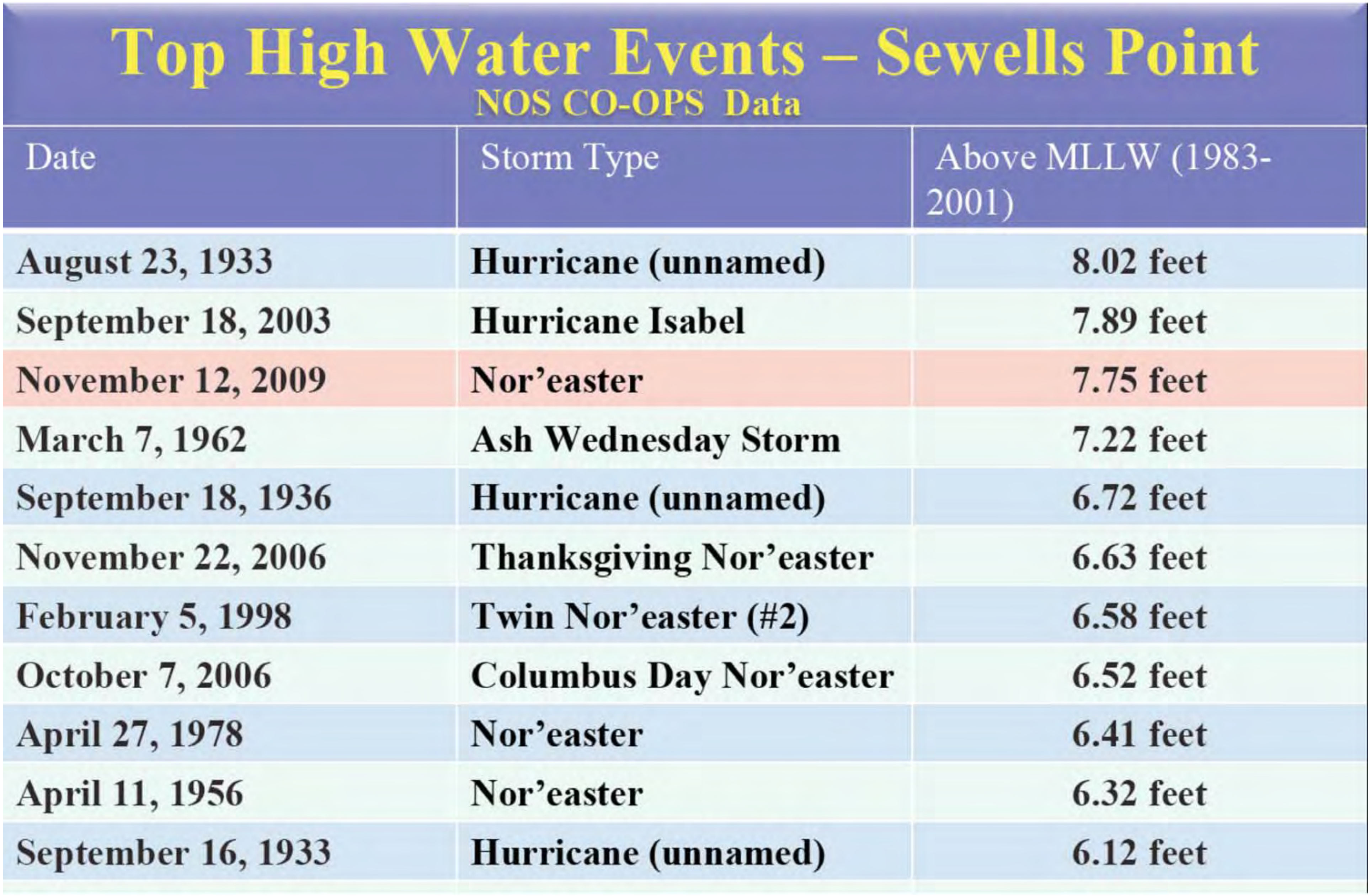


**Figure 2.** Water gauge records from Chesapeake Bay tide gauges common to 1933 and 2003. The time axis has been adjusted to facilitate comparison of the two hurricanes.

From Boicourt, 2005

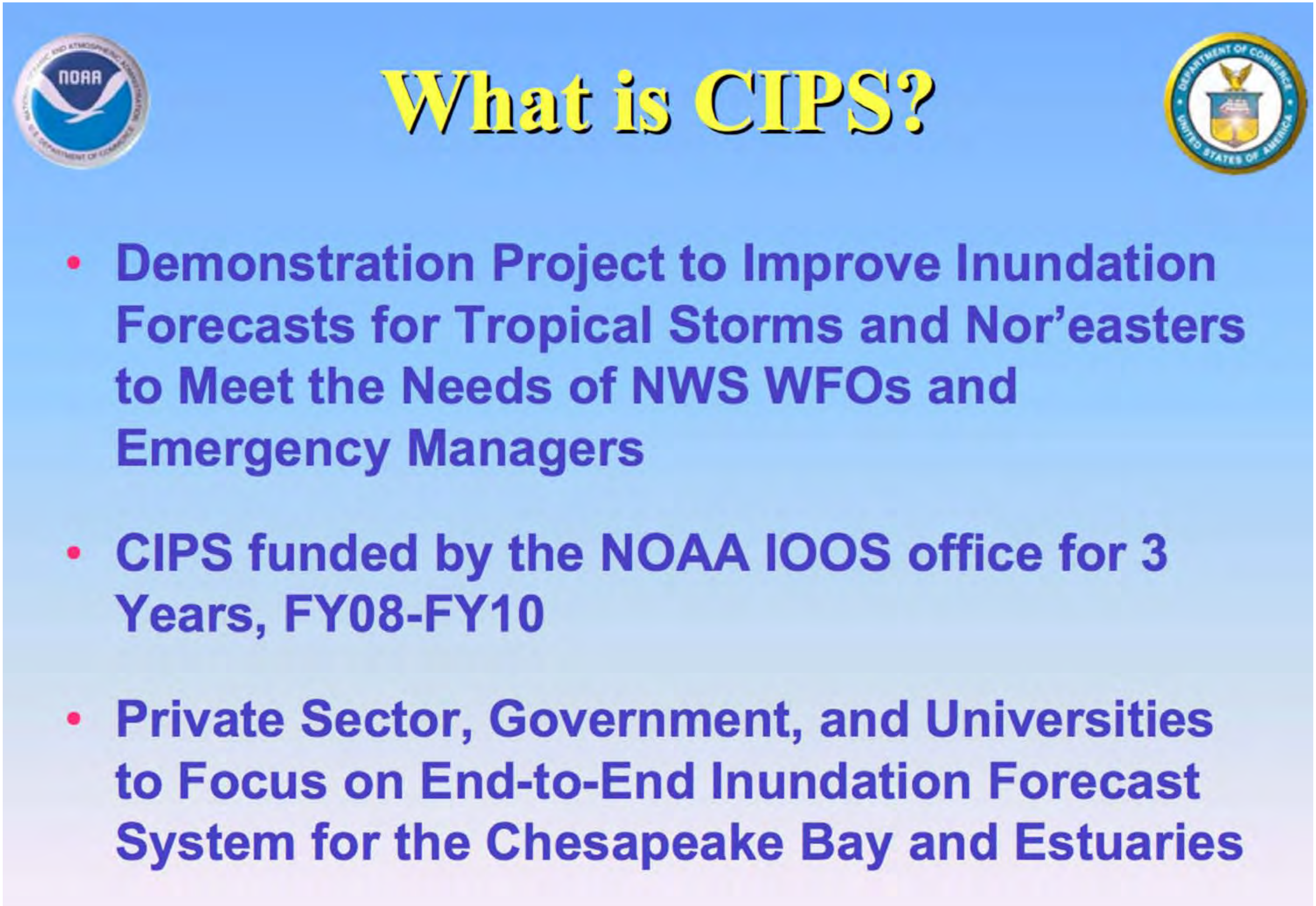


# Top High Water Events – Sewells Point

## NOS CO-OPS Data

| Date | Storm Type | Above MLLW (1983-2001) |
|---|---|---|
| **August 23, 1933** | **Hurricane (unnamed)** | **8.02 feet** |
| **September 18, 2003** | **Hurricane Isabel** | **7.89 feet** |
| **November 12, 2009** | **Nor'easter** | **7.75 feet** |
| **March 7, 1962** | **Ash Wednesday Storm** | **7.22 feet** |
| **September 18, 1936** | **Hurricane (unnamed)** | **6.72 feet** |
| **November 22, 2006** | **Thanksgiving Nor'easter** | **6.63 feet** |
| **February 5, 1998** | **Twin Nor'easter (#2)** | **6.58 feet** |
| **October 7, 2006** | **Columbus Day Nor'easter** | **6.52 feet** |
| **April 27, 1978** | **Nor'easter** | **6.41 feet** |
| **April 11, 1956** | **Nor'easter** | **6.32 feet** |
| **September 16, 1933** | **Hurricane (unnamed)** | **6.12 feet** |

Slide from Weng, Gao, Loftis and Teng, 2011, VIMS

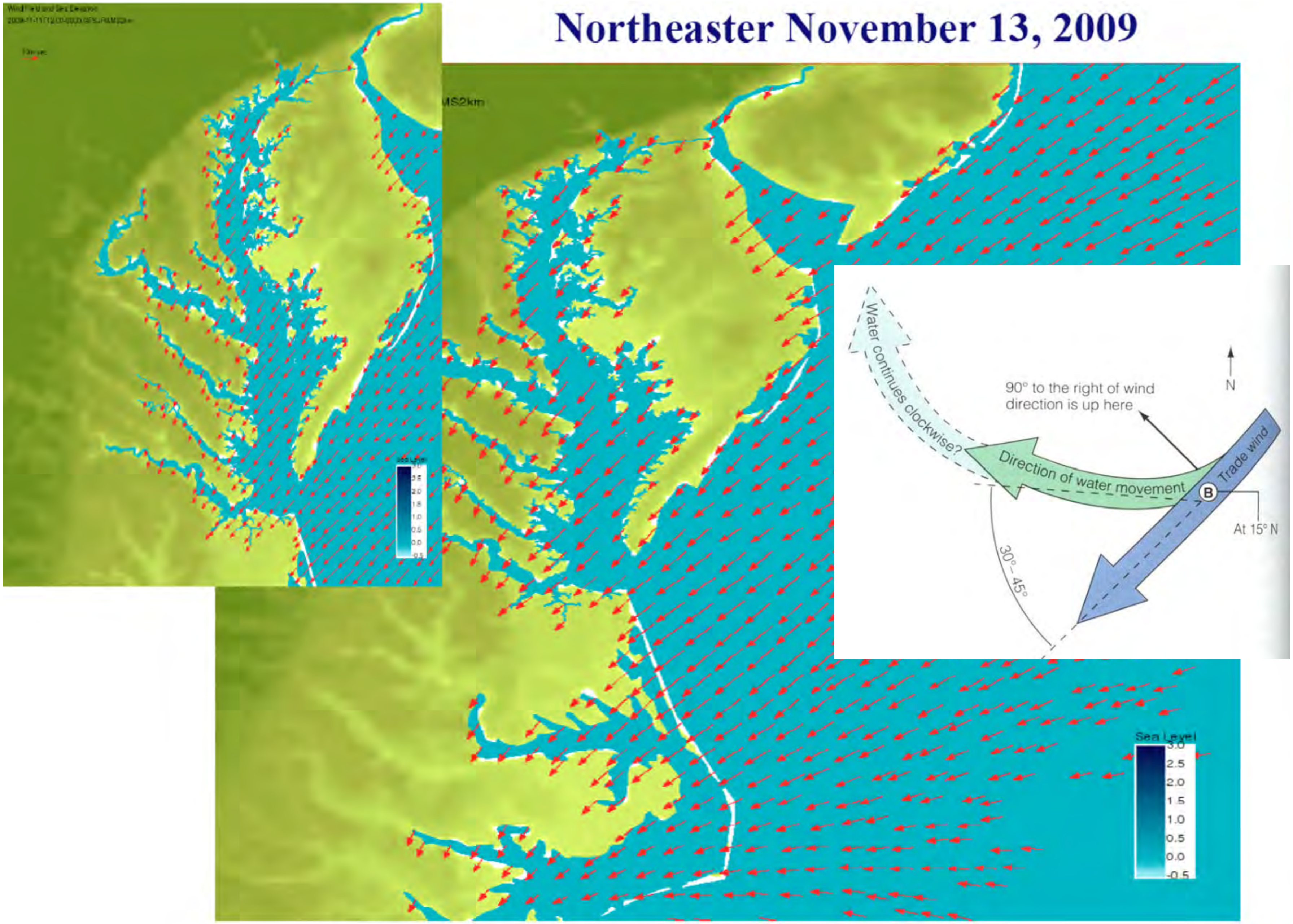


# What is CIPS?

- Demonstration Project to Improve Inundation Forecasts for Tropical Storms and Nor’easters to Meet the Needs of NWS WFOs and Emergency Managers
- CIPS funded by the NOAA IOOS office for 3 Years, FY08-FY10
- Private Sector, Government, and Universities to Focus on End-to-End Inundation Forecast System for the Chesapeake Bay and Estuaries

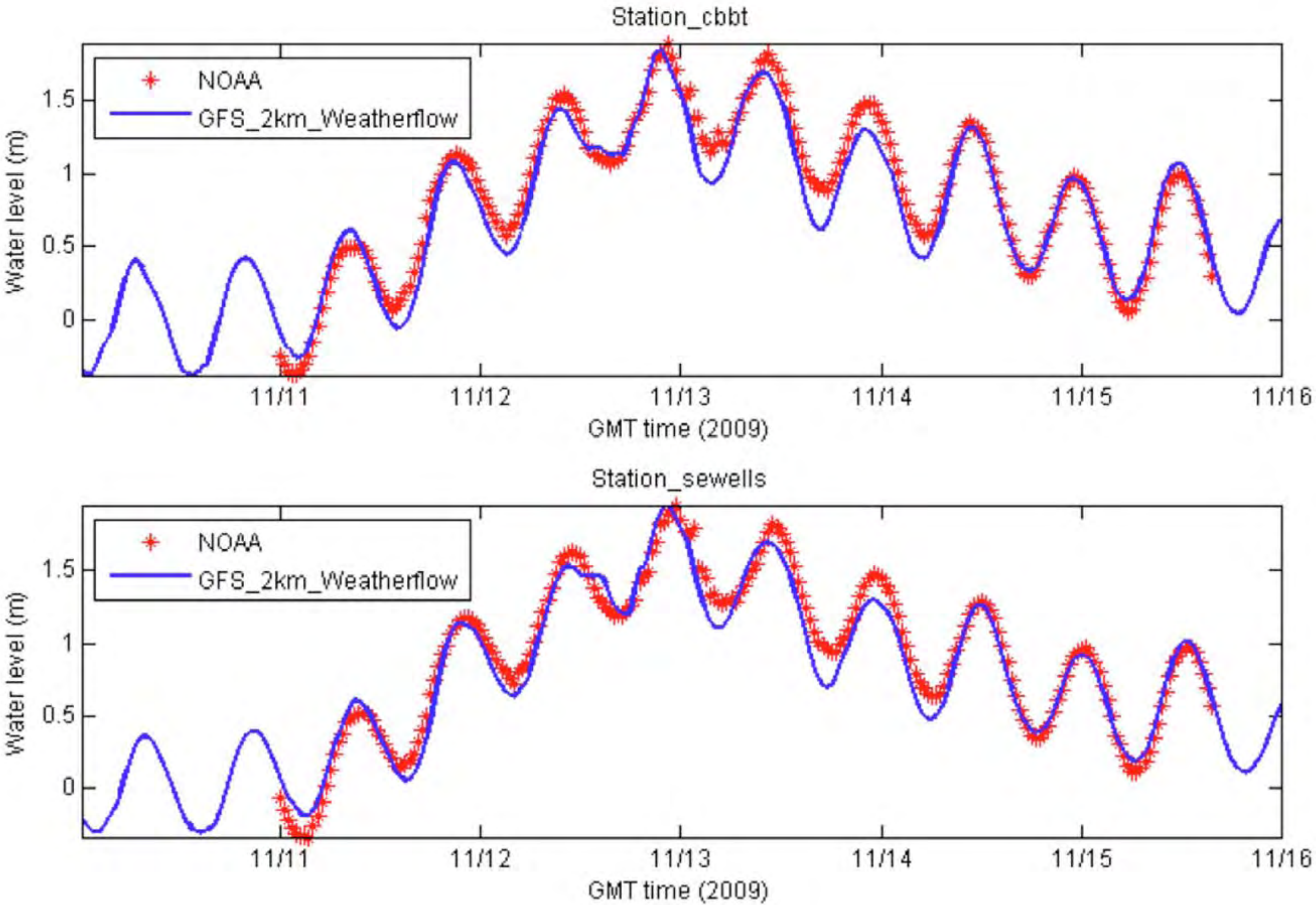
Slide from Siebers, NOAA, and CIPS Team, 2010

# Northeaster November 13, 2009



Slide from Weng, Gao, Loftis and Teng, 2011, VIMS/inset figure from Garrison, 1993

# Storm Surge Model Results - lower Chesapeake Bay



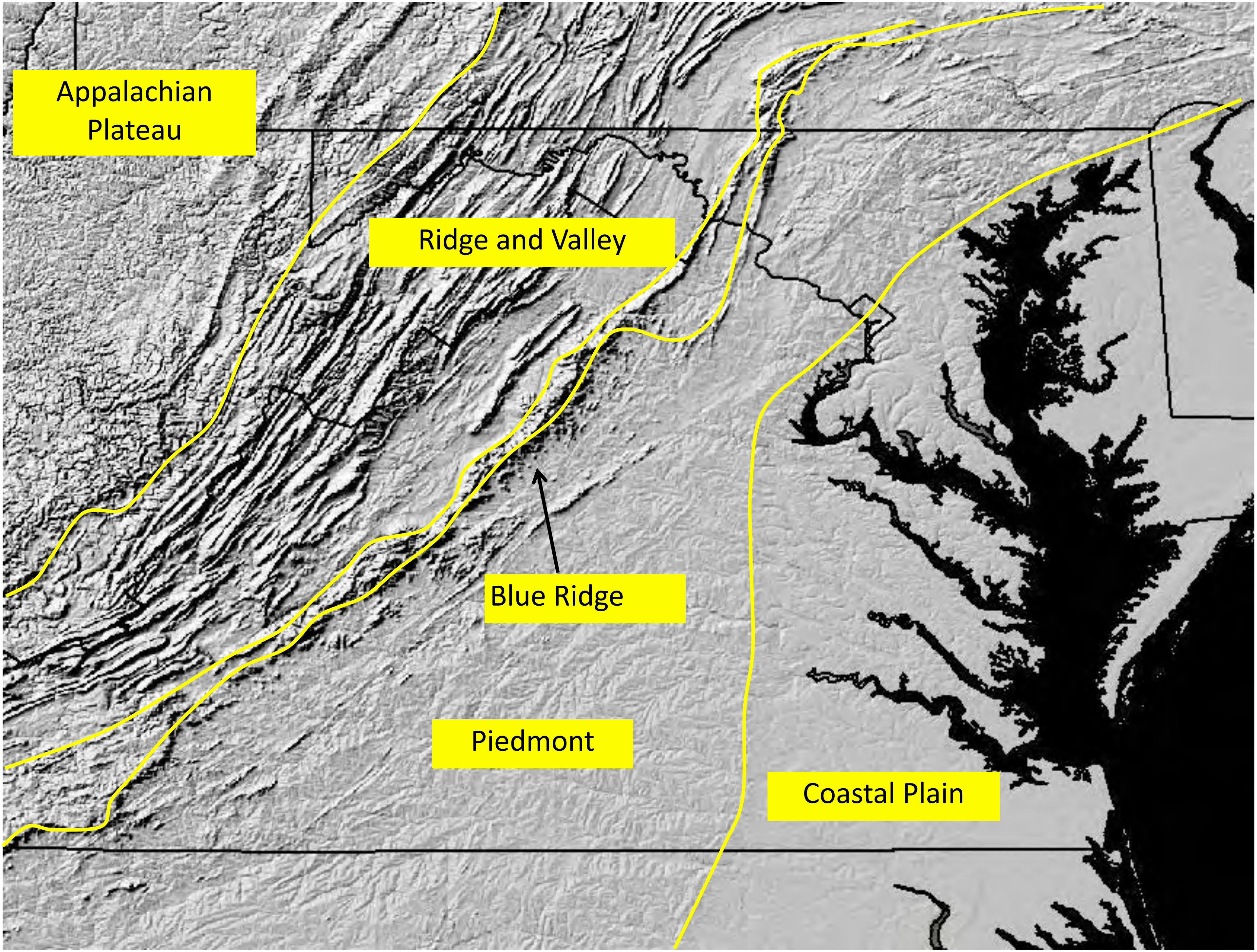
Slide from Weng, Gao, Loftis and Teng, 2011, VIMS

# Coastal flooding as a future hazard

- Given the range of projected sea-level rise over the remainder of this century, it is fairly certain that even a modest storm-surge event should be able to cause flood inundation farther inland than would occur today
- Impacts such as those seen during Isabel would be more common
- Therefore we should be planning for these effects superimposed on the direct effects of sea-level rise in populated areas
- This is a probably a more reliable prediction than any we can currently make about impact of climate change on rainfall-runoff flood hazards

# Rainfall-runoff flooding

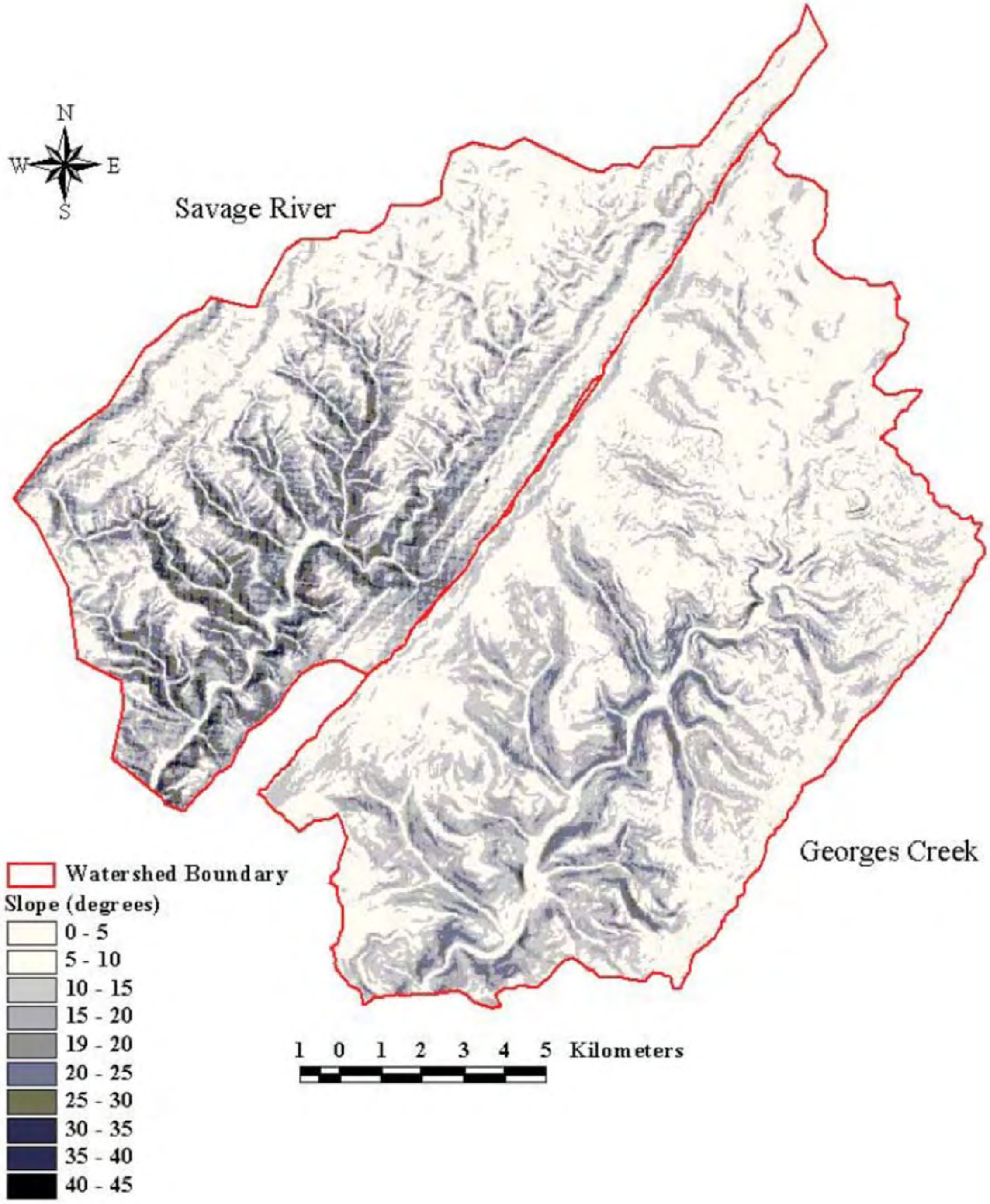
- Interaction of storm magnitude, duration and intensity with watershed scale and geomorphic properties: steep headwater basins vs. large lowland rivers
- Flood-generating storm types:
  - High-intensity convective systems – maximum rainfall rates, highest peak discharge at small drainage areas, downstream attenuation of flood peaks
  - Tropical cyclones, often with extratropical transition – largest rainfall accumulations over largest areas; capable of generating record floods at intermediate to large watershed scales Examples: Agnes, June 1972; Lee, Sept. 2011
  - Extratropical cyclones/Nor'easters – long-duration moderate-intensity precipitation, rain on snow/ice, smaller flood peaks at small drainage area but large contributing area Examples: March 1936, January 1996



Appalachian Plateau
Ridge and Valley
Blue Ridge
Piedmont
Coastal Plain

Flood-prone watersheds on the Appalachian Plateau of Maryland

Floods in Jan. 1996 – rain on snow – and in Sept. 1996 – Hurricane Fran



Flooding on Georges Creek

“I always say that these valleys have--at best--enough space for a road, a railroad track, and the river!” – Keith Eshleman, UMCES

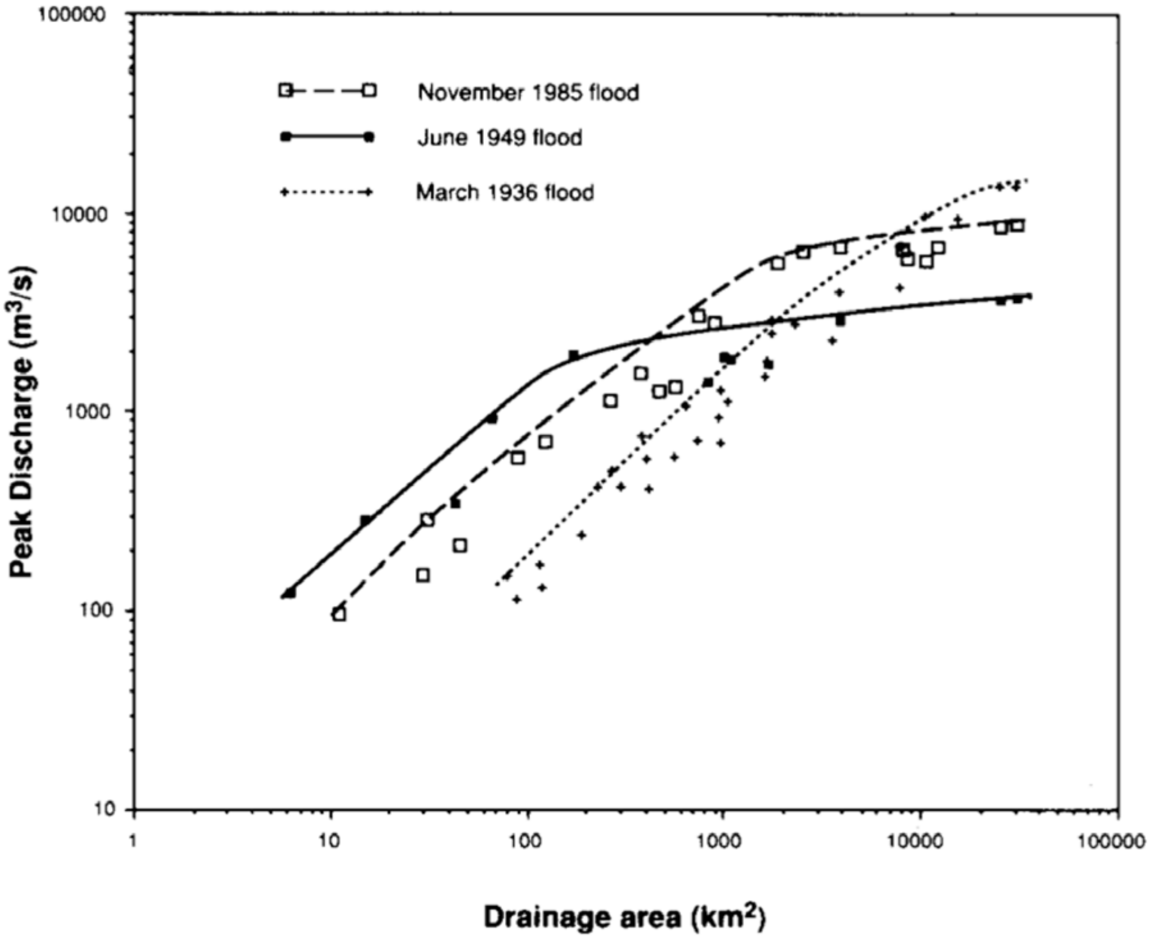
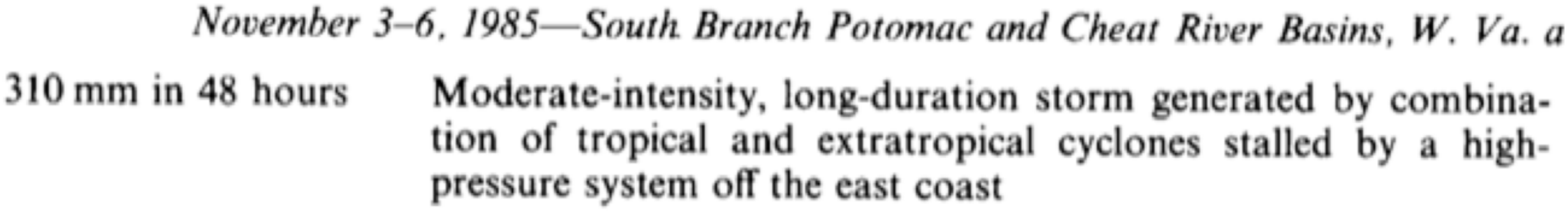


Figure 4. Envelope curves illustrating trends in the relationship between peak discharge and drainage area for three great floods in the Potomac River basin and adjacent drainage basins. Data from Lescinsky (1987), Grover (1937), and Mussey (1950)

From Miller, 1990

| Maximum recorded precipitation for selected duration | Hydrologic characteristics of storm and flood |
|---|---|
| | *March 9–22, 1936—Potomac, James, and upper Ohio River basins (Grover, 1937)* |
| 127 mm in 24 hours<br>285 mm in 14 days | Low-intensity, long-duration storm; large contributing area, enhanced by frozen ground; record-breaking discharge at large drainage areas |
| | *July 18, 1942—Susquehanna and Allegheny River Basins, centered around Smethpo* |
| 909 mm in 12 hours<br>780 mm in 4.75 hours | High-intensity, short-duration storm; extremely high discharge at small drainage areas; limited contributing area |
| | *June 17–18, 1949—North River Basin, Va. and South Branch Potomac River Basin* |
| 413 mm in 24 hours | High-intensity, short-duration storm; extremely high discharge in small basins; limited contributing area |
| | *August 19–20, 1969—Hurricane Camille, Tye and Rockfish River Basins, Nelson C* |
| 711 mm in <12 hours | High-intensity, short-duration precipitation delivered by tropical cyclone; small contributing areas, but with enough water to generate record-breaking peaks at drainage areas up to 1500 km$^2$ |
| | *June 21–24, 1972—Susquehanna, Potomac, James, and other river basins draining* |
| 269 mm in 12 hours<br>442 mm in 48 hours | Moderate to high-intensity, long-duration precipitation caused by remnants of tropical cyclone combined with extratropical cyclone; extreme discharge peaks in small basins and in large basins; large contributing area |

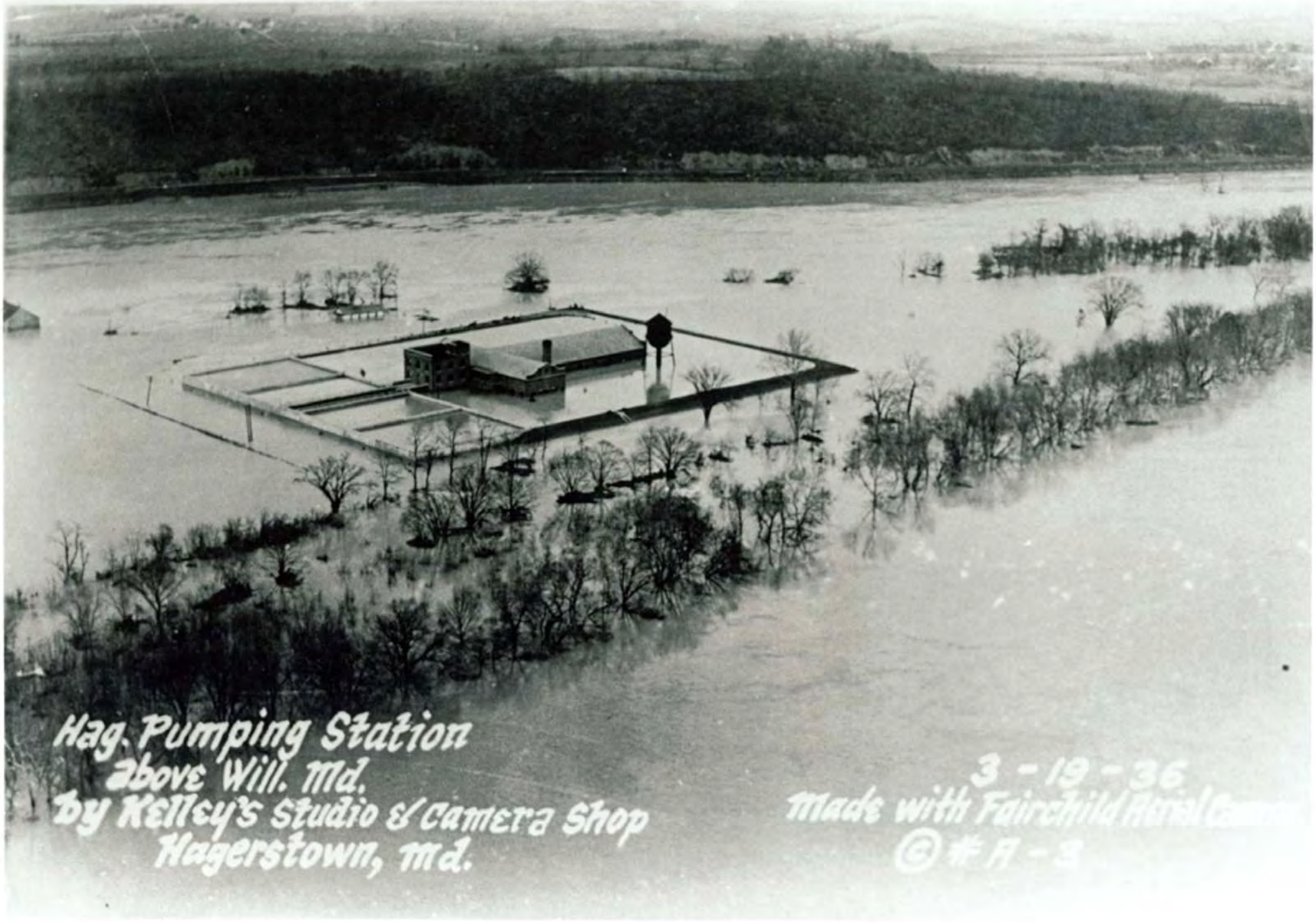


*November 3–6, 1985—South Branch Potomac and Cheat River Basins, W. Va.*[a]

| | |
|---|---|
| 310 mm in 48 hours | Moderate-intensity, long-duration storm generated by combination of tropical and extratropical cyclones stalled by a high-pressure system off the east coast |

*June 27, 1995 – Rapidan River Basin, Virginia*

| | |
|---|---|
| 623 mm in 6 hours | “Upslope” or terrain-locked convective storm: Orographic effects were dominant in a series of storm cells capturing tropical moisture flowing at low altitude from the southeast and trapping it against the foothills of the Blue Ridge. Peak discharge is on the envelope curve of historic floods for the U.S. east of the Mississippi River |



Hag. Pumping Station
above Will. Md.
by Kelley's Studio & Camera Shop
Hagerstown, Md.

3 - 19 - 36
Made with Fairchild Aerial Cam
© #A - 3

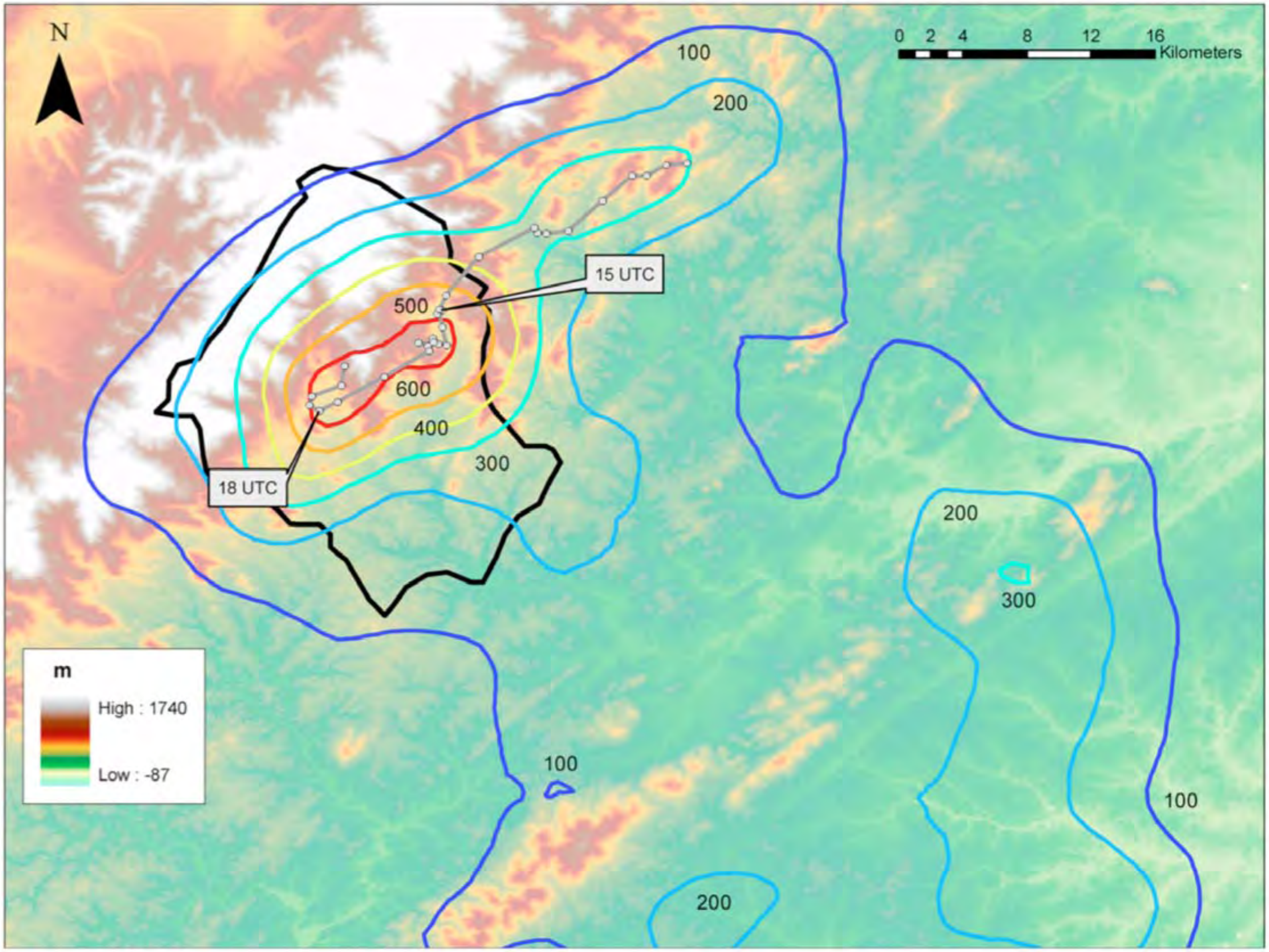
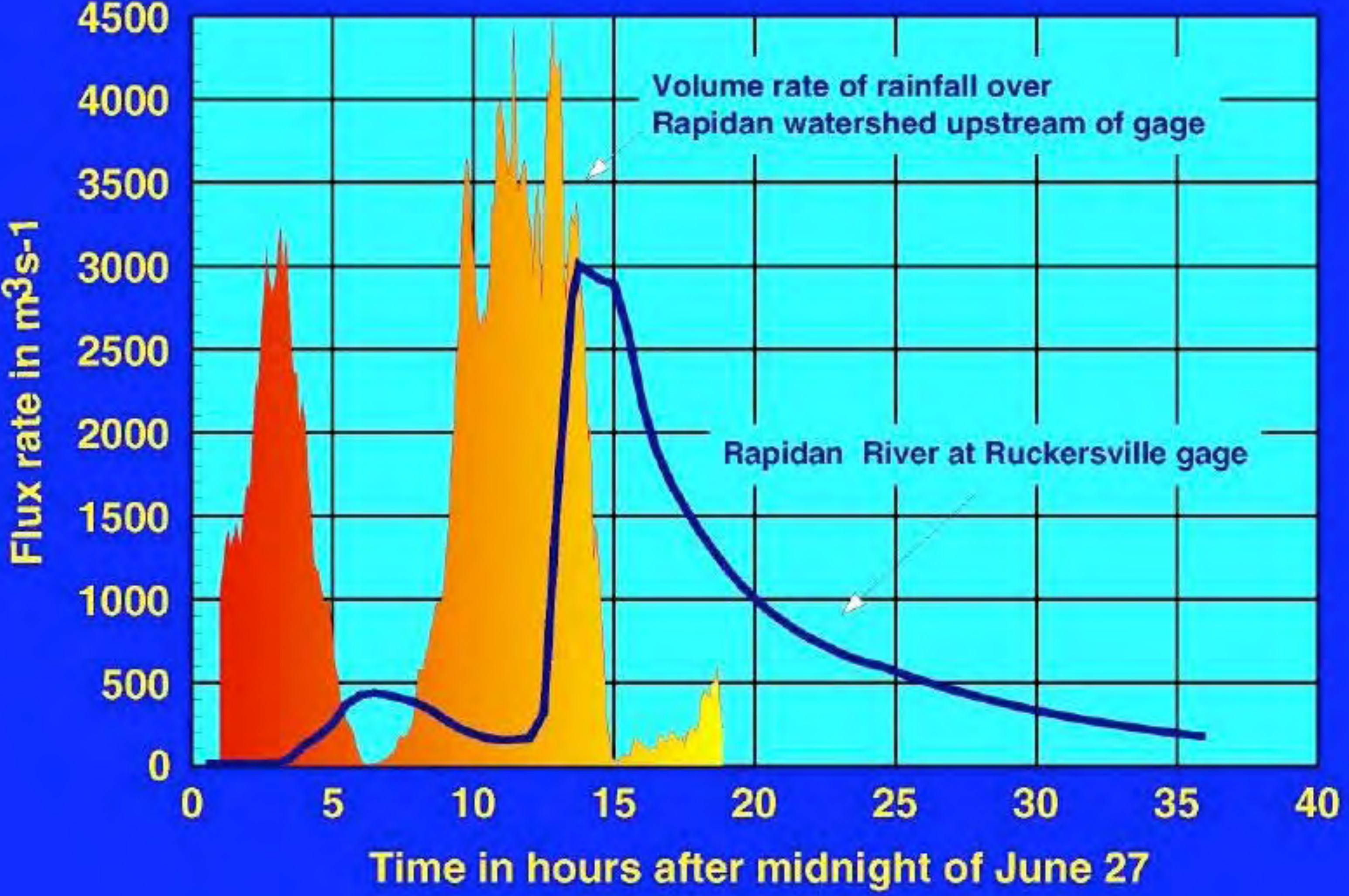
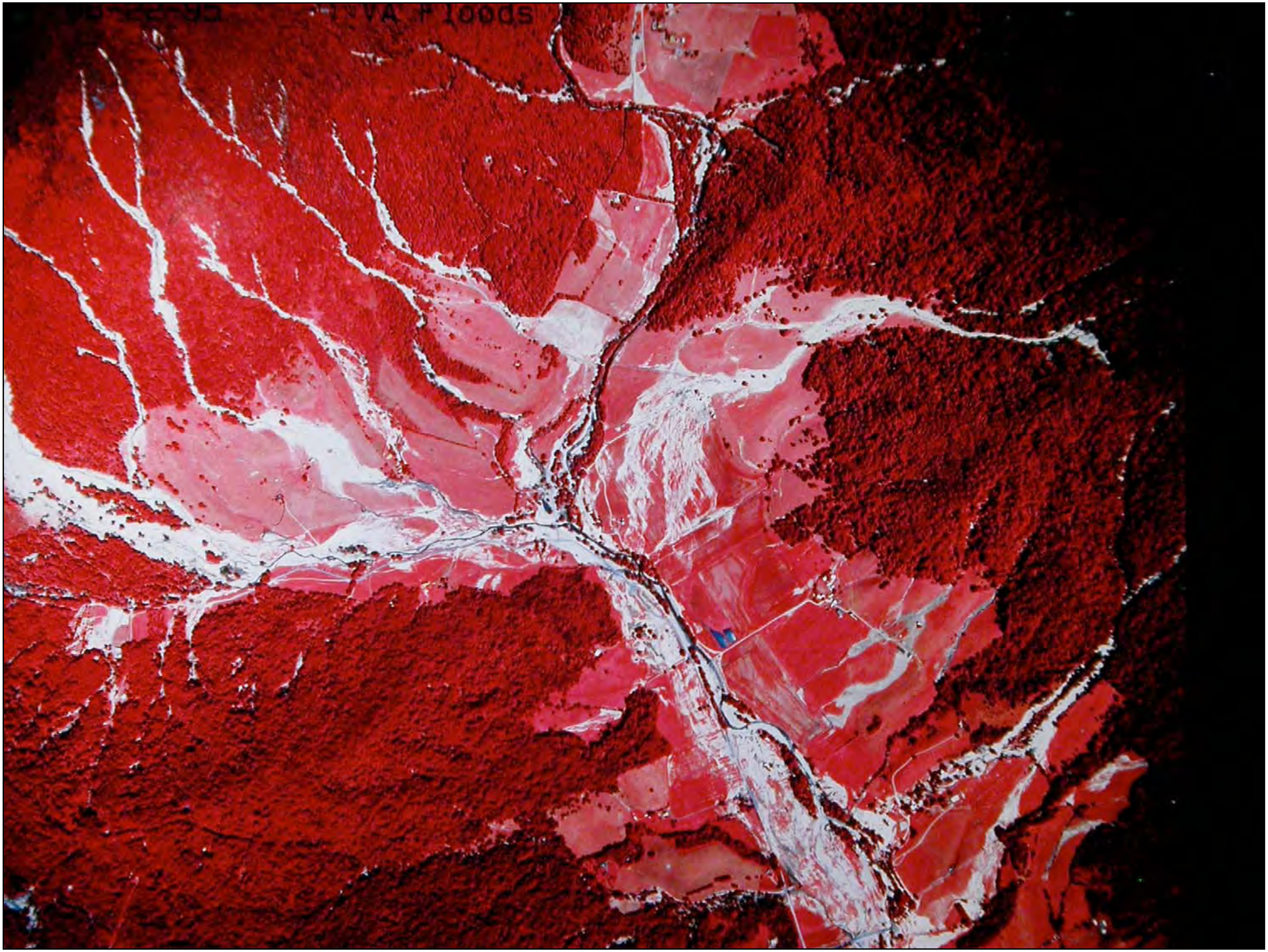


**Figure 8.** Storm total rainfall (millimeters) for the 27 June 1995 storm (0000–2100 UTC) from bias-corrected radar rainfall estimates. Storm centroid locations for the Rapidan storm are shown, with time labels at 1500 and 1800 UTC. The Rapidan basin boundary is outlined in a solid black line.

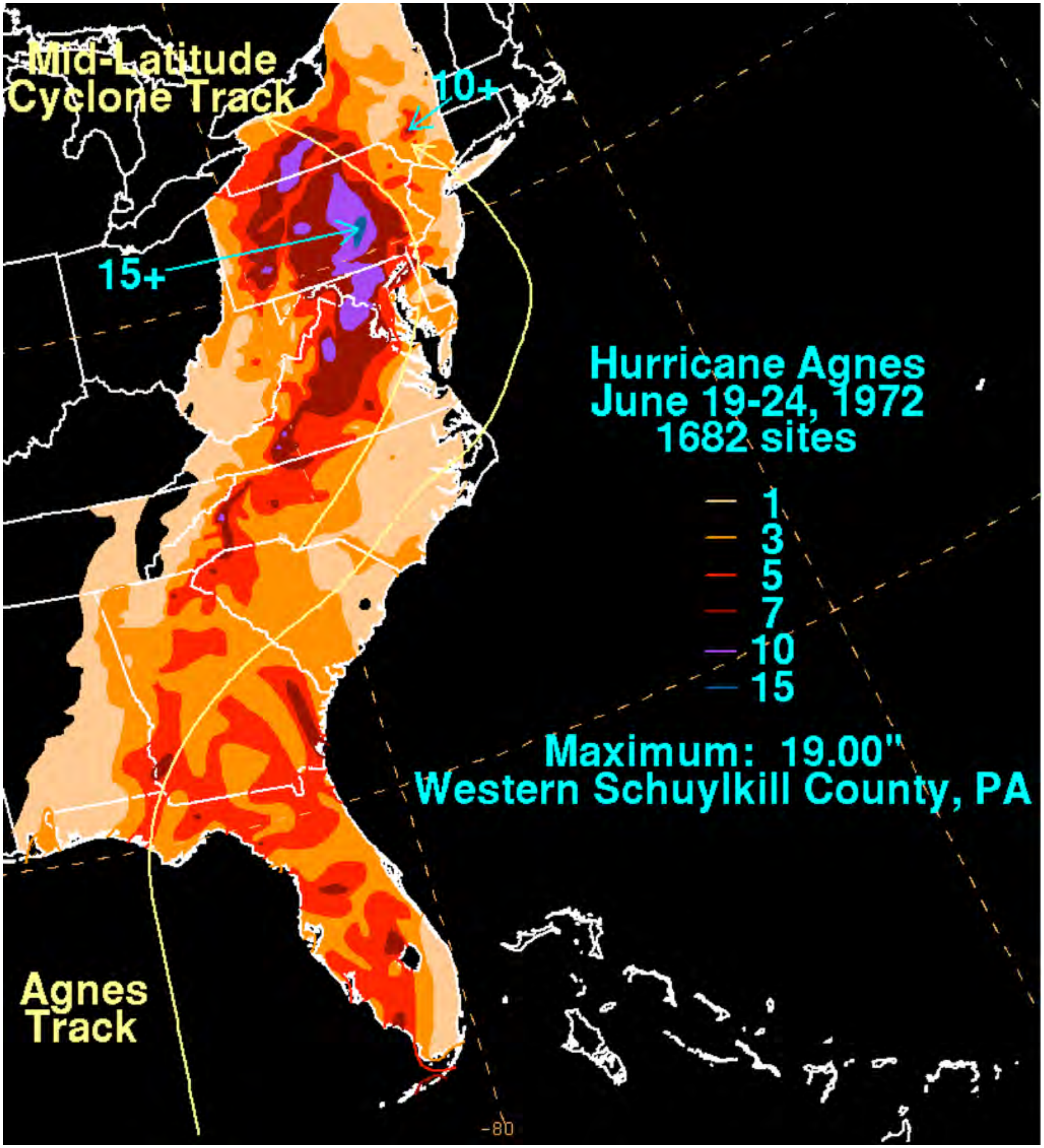
Smith et al, 2011

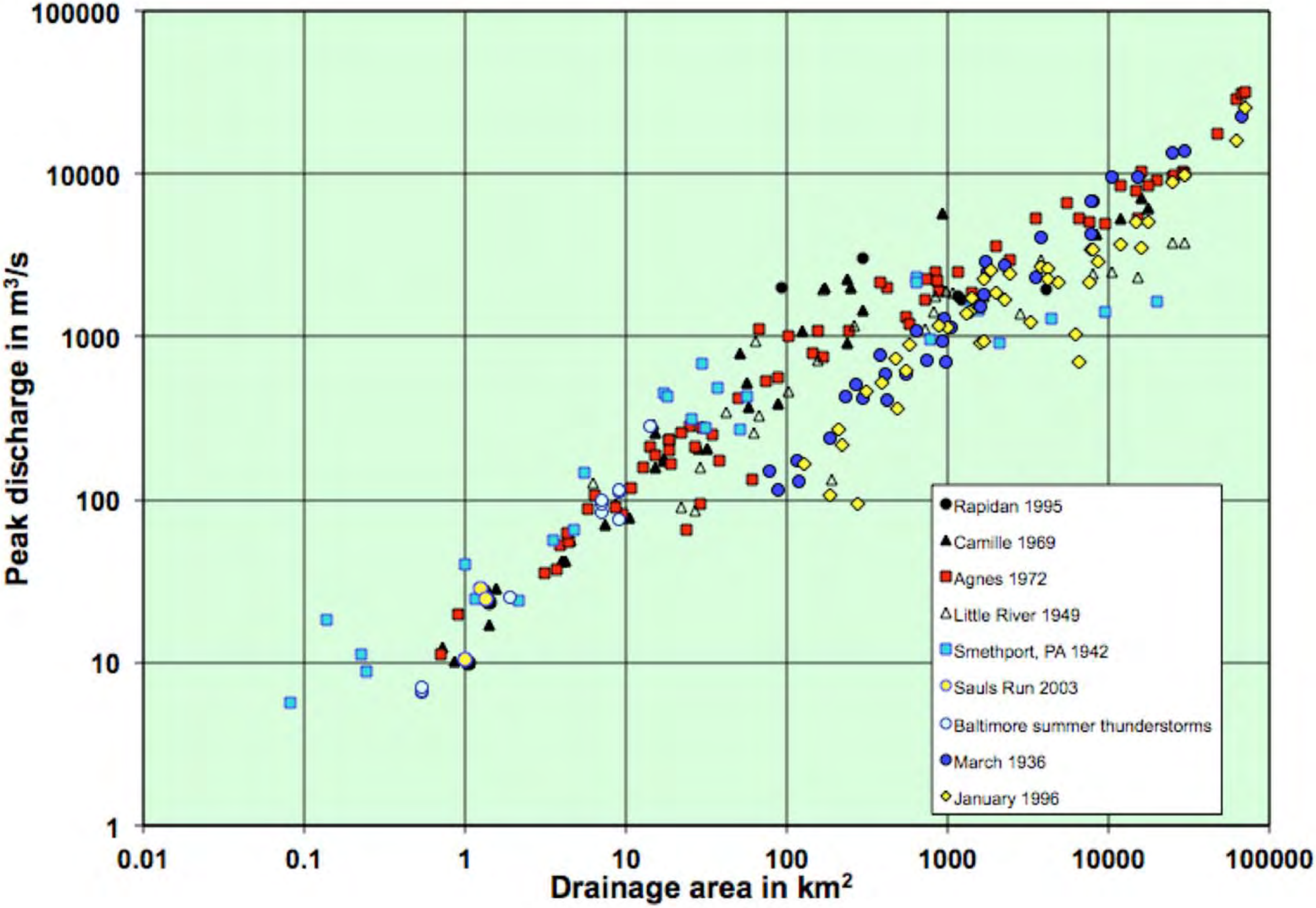

Rapidan River, Virginia
Route 29 Bridge
June 27, 1995

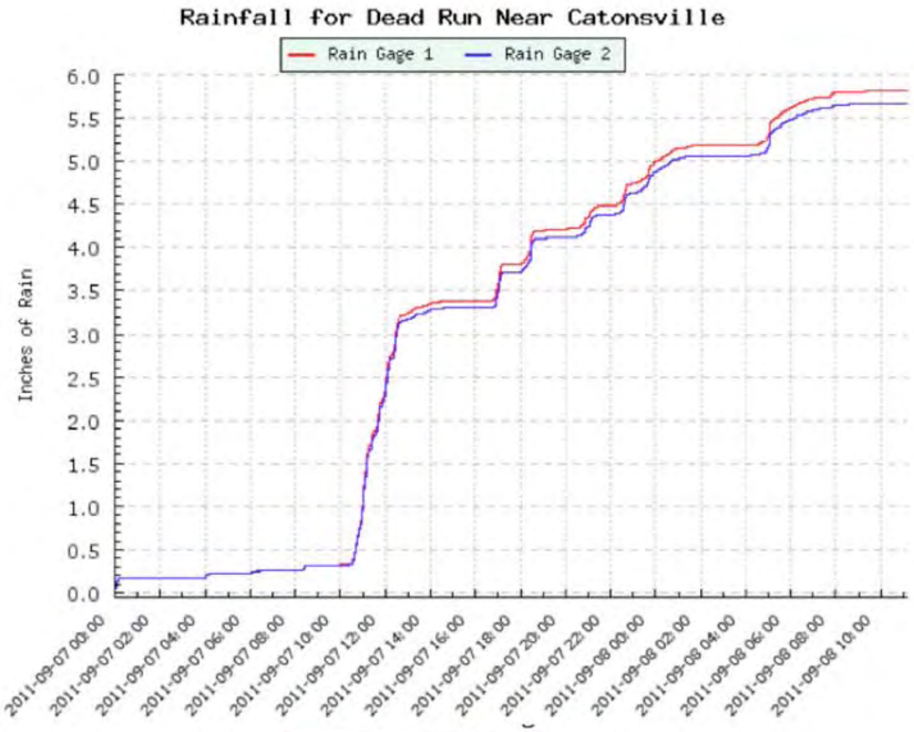

4500
4000
3500
3000
2500
2000
1500
1000
500
0
Flux rate in m3s-1
0
5
10
15
20
25
30
35
40
Time in hours after midnight of June 27
Volume rate of rainfall over
Rapidan watershed upstream of gage
Rapidan River at Ruckersville gage


06-22-95
VA Floods

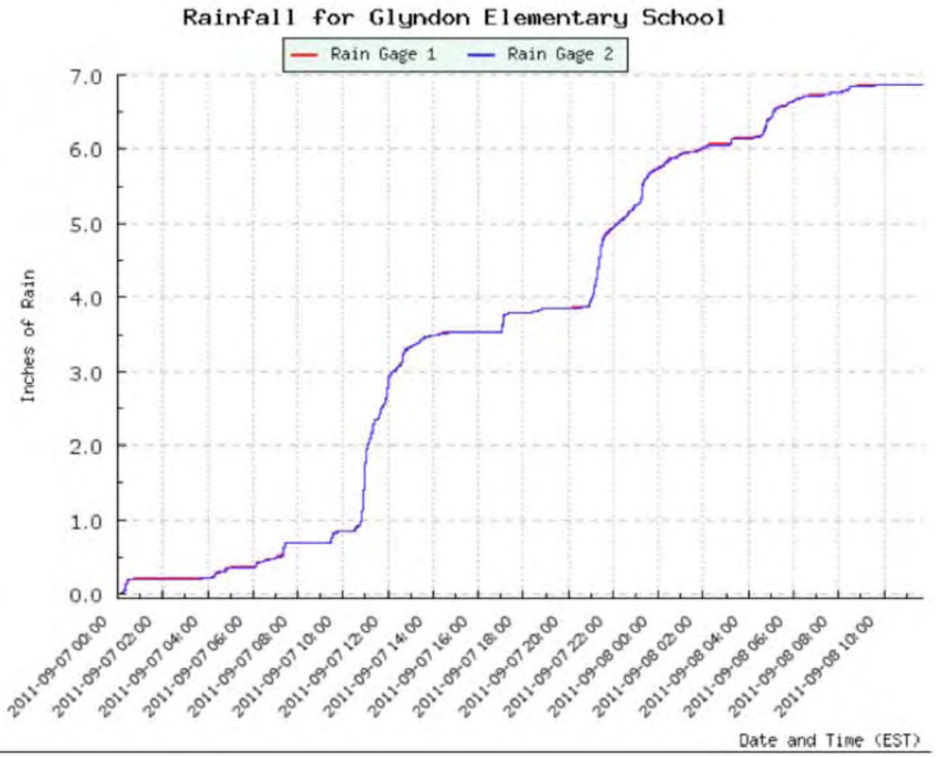

Tropical Storm Agnes
June 1972


Mid-Latitude
Cyclone Track
10+
15+
Hurricane Agnes
June 19-24, 1972
1682 sites
1
3
5
7
10
15
Maximum: 19.00"
Western Schuylkill County, PA
Agnes
Track
-80

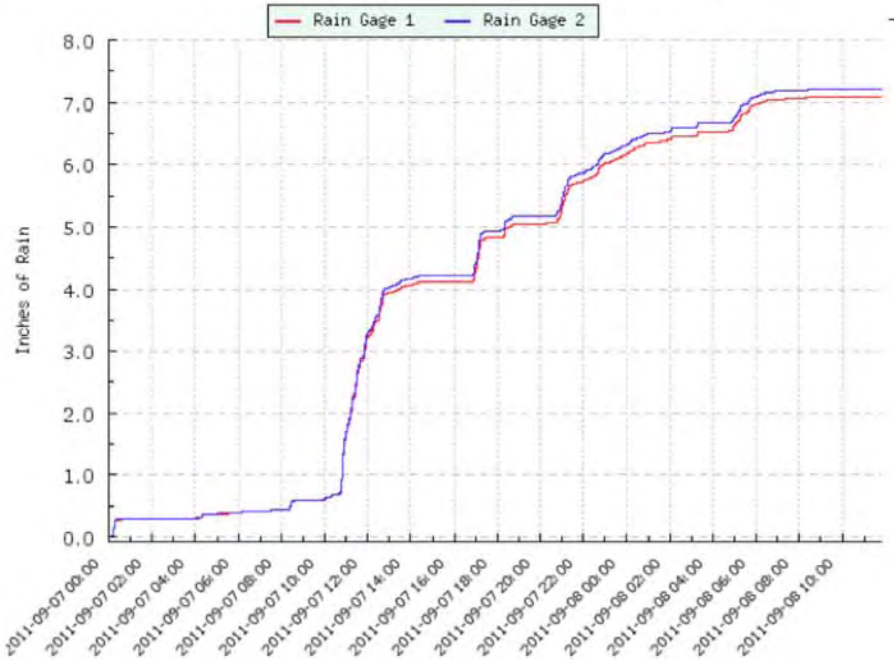

100000
10000
1000
100
10
1
Peak discharge in m³/s
0.01
0.1
1
10
100
1000
10000
100000
Drainage area in km²
● Rapidan 1995
▲ Camille 1969
■ Agnes 1972
△ Little River 1949
■ Smethport, PA 1942
○ Sauls Run 2003
○ Baltimore summer thunderstorms
● March 1936
◆ January 1996



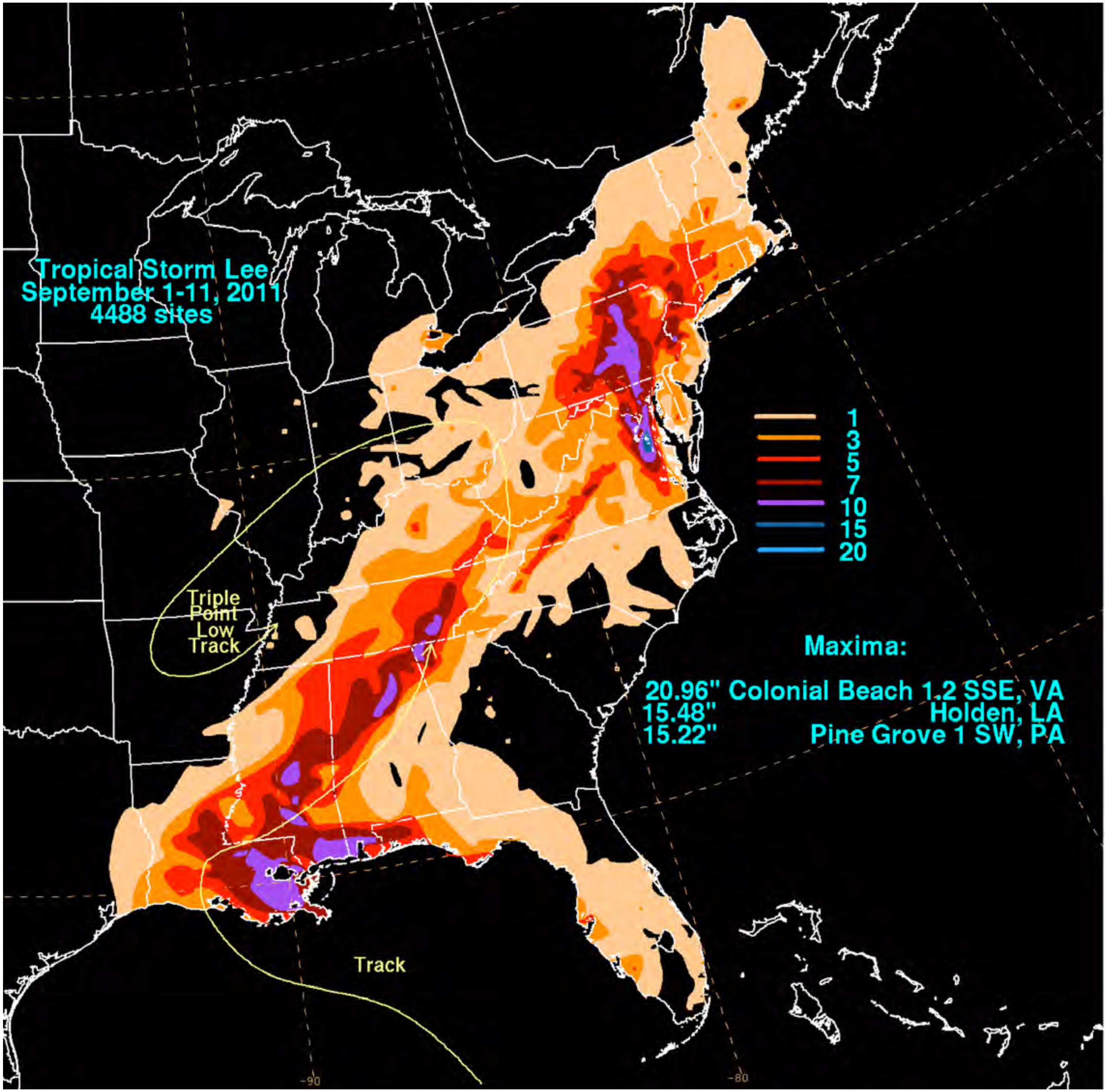
Rainfall for Dead Run Near Catonsville



Rainfall for Glyndon Elementary School



7 September 2011


Tropical Storm Lee
September 1-11, 2011
4488 sites
1
3
5
7
10
15
20
Triple Point Low Track
Track
Maxima:
20.96" Colonial Beach 1.2 SSE, VA
15.48" Holden, LA
15.22" Pine Grove 1 SW, PA
-90
-80

# Urban floods

- High-intensity convective storms are often associated with orographic precipitation, but the relief and width of the Blue Ridge in Maryland is much less than in Virginia and events comparable to the 1995 Rapidan flood are rare if they occur at all
- Intensive convective storms do occur over small watersheds of the mid-Atlantic Piedmont and Coastal Plain
- Initiated by air flow coming over the Blue Ridge, interact with urban canopy and landscape features as well as Chesapeake Bay
- Examples: August 1971, July 2004

**AUGUST 5, 2011**

# 17 died in Md. thunderstorms 40 years ago

FROM TODAY'S PRINT EDITIONS:

It was one of **Maryland's worst natural disasters**, claiming 17 lives. But few remember after 40 years. **Bruce Sullivan** does. A senior forecaster at the National Center for Environmental Prediction, he said a line of severe thunderstorms formed along a stalled front over **Baltimore** and **Harford** counties on Sunday afternoon, Aug. 1, 1971. They dumped more than 12 inches of rain in six hours. Rivers and creeks flooded. Most of the dead drowned. Scores more needed rescue.

The thunderstorm of August 1-2, 1971, was one of the most damaging in the Baltimore metropolitan area during the past 50 years. A "bucket" survey indicated an unofficial rainfall total of 11 inches in less than 10 hours. The National Weather Service gage in Baltimore recorded 5.5 inches in 3 hours. The storm and resultant floods are documented in a report by Carpenter (1974). Floods at stations along the Gunpowder and Back River basins had recurrence intervals equivalent to or in excess of 100 years. Fourteen people died as a result of the flooding. Bridge and roadway washouts were widespread. Total damage attributable to the flood was estimated at $6.5 million (U.S. Environmental Data Service, 1971).

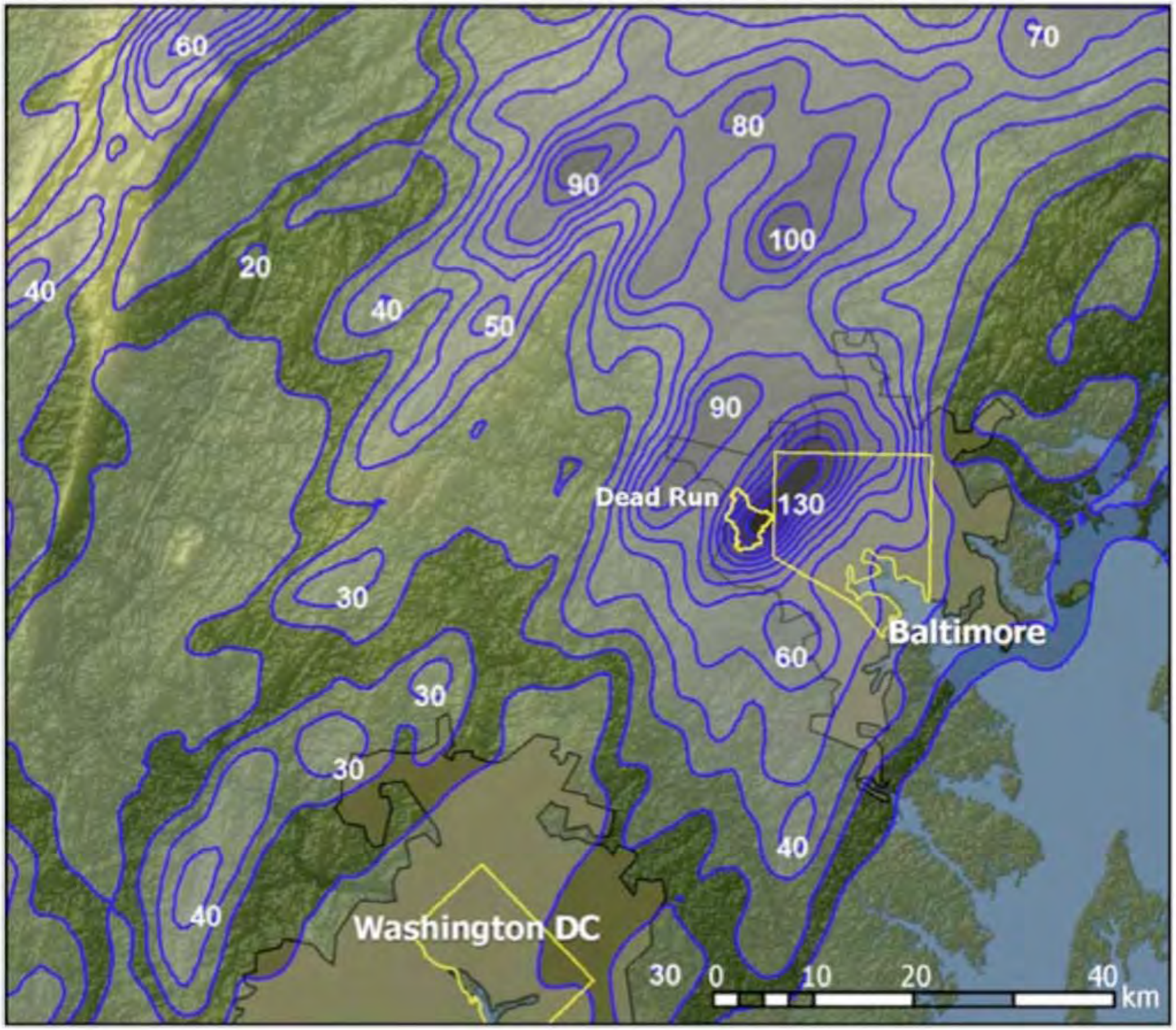
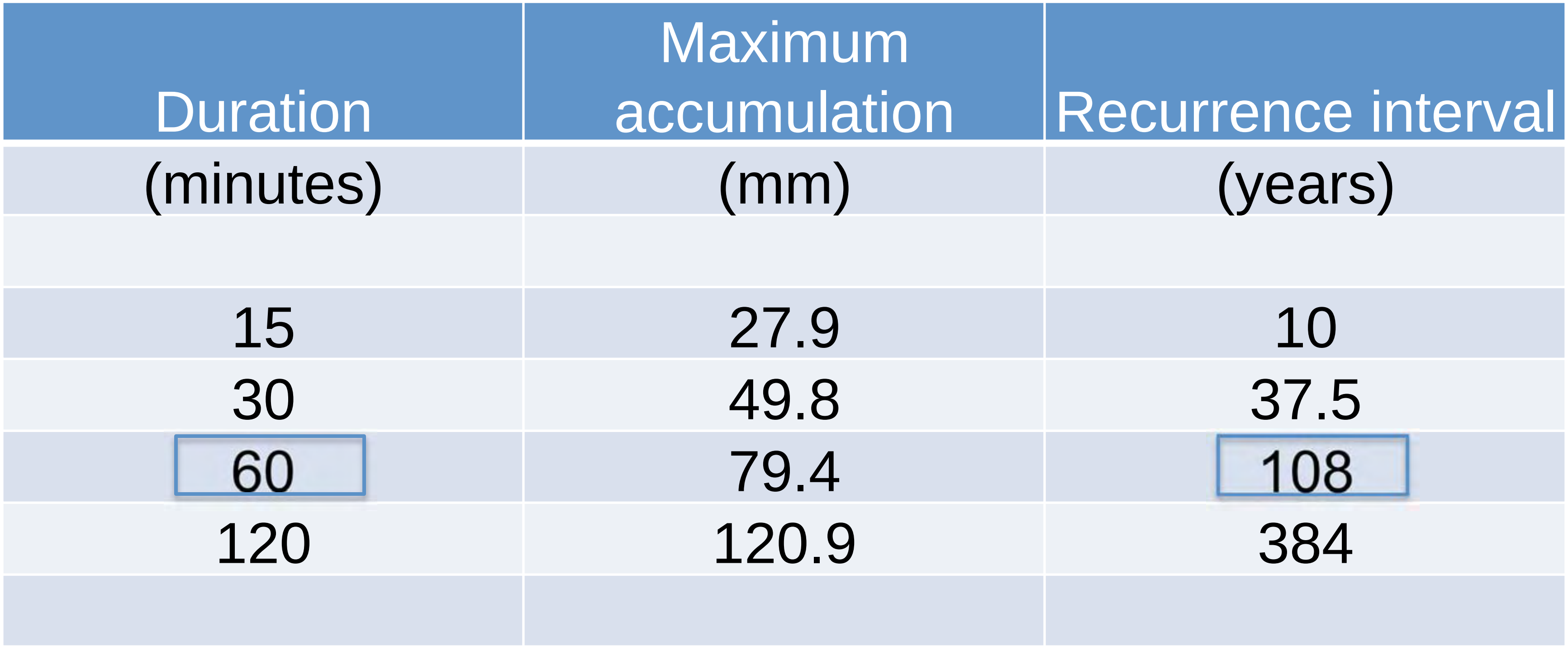


**Figure 6.** Storm total bias-corrected radar-rainfall contours from the Sterling, VA WSR-88D station over the "urban focus" domain (in mm).

July 7, 2004 storm and flood. Figure from Ntelekos, et al., 2008

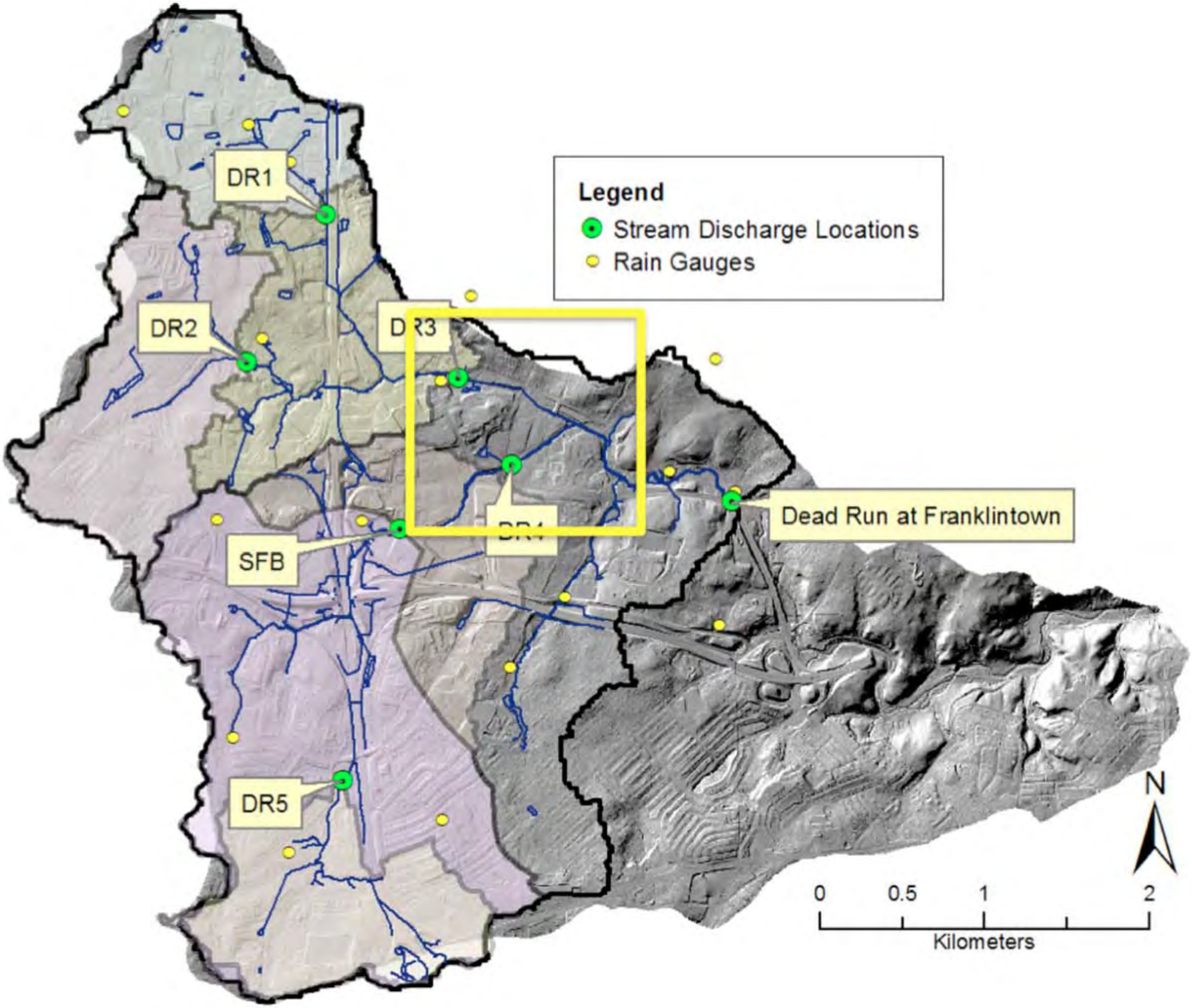
# Maximum precipitation accumulation and recurrence intervals
# Dead Run Watershed, July 7, 2004

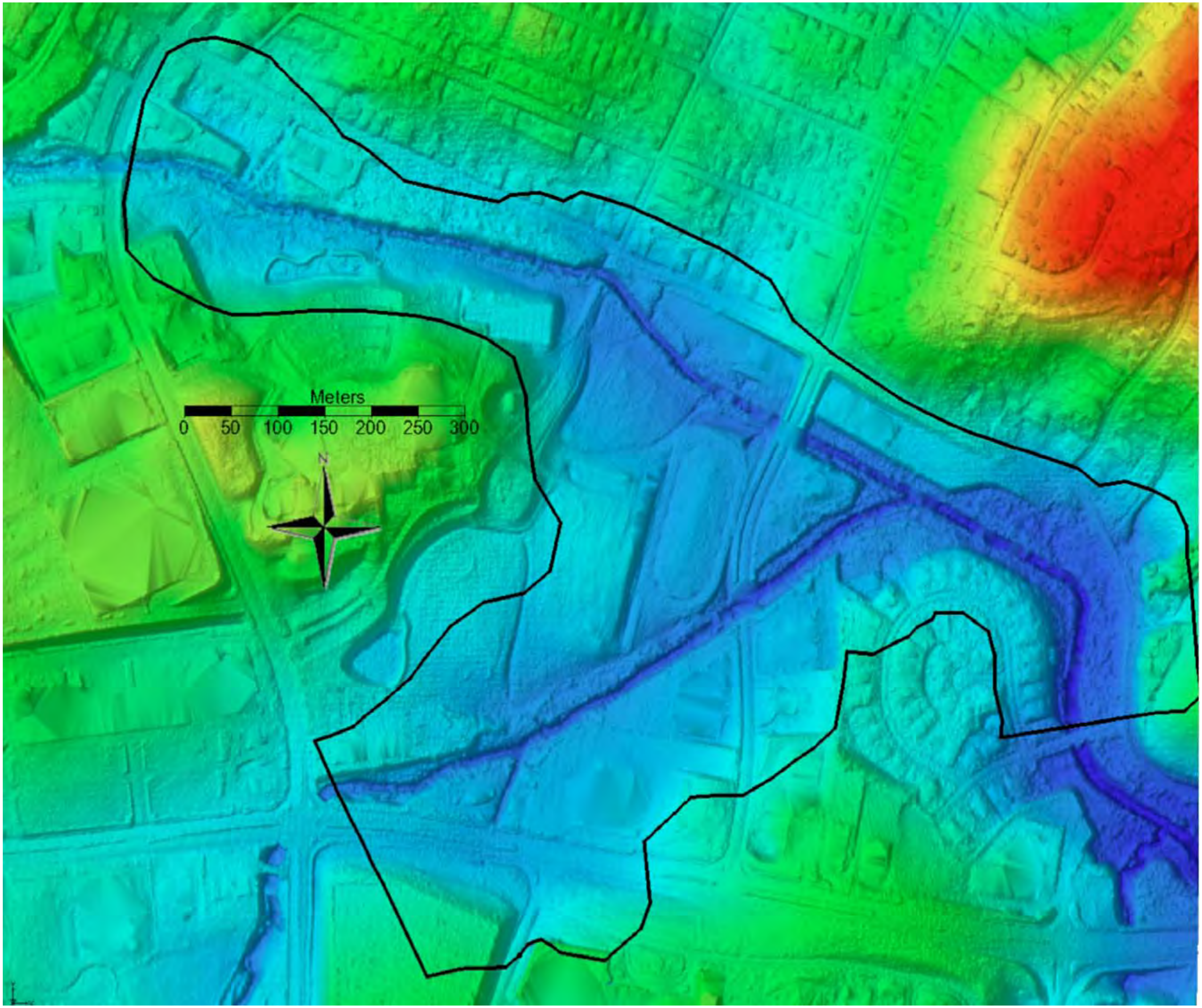


| Duration | Maximum accumulation | Recurrence interval |
|---|---|---|
| (minutes) | (mm) | (years) |
| | | |
| 15 | 27.9 | 10 |
| 30 | 49.8 | 37.5 |
| 60 | 79.4 | 108 |
| 120 | 120.9 | 384 |
| | | |

Dead Run at Franklintown stream gauge characteristic hydrograph response to a rainfall pulse is 60-75 minutes

Suggests that flood peak most likely responds to the 60-minute maximum accumulation and may have comparable recurrence interval


Legend
Stream Discharge Locations
Rain Gauges
DR1
DR2
DR3
DR4
SFB
DR5
Dead Run at Franklintown
N
0
0.5
1
2
Kilometers


Meters
0
50
100
150
200
250
300
N


7 July 2004

Yellow – July 7 Inundation Area
Light blue – FEMA 500-yr Floodplain
Dark blue – FEMA 100-yr Floodplain

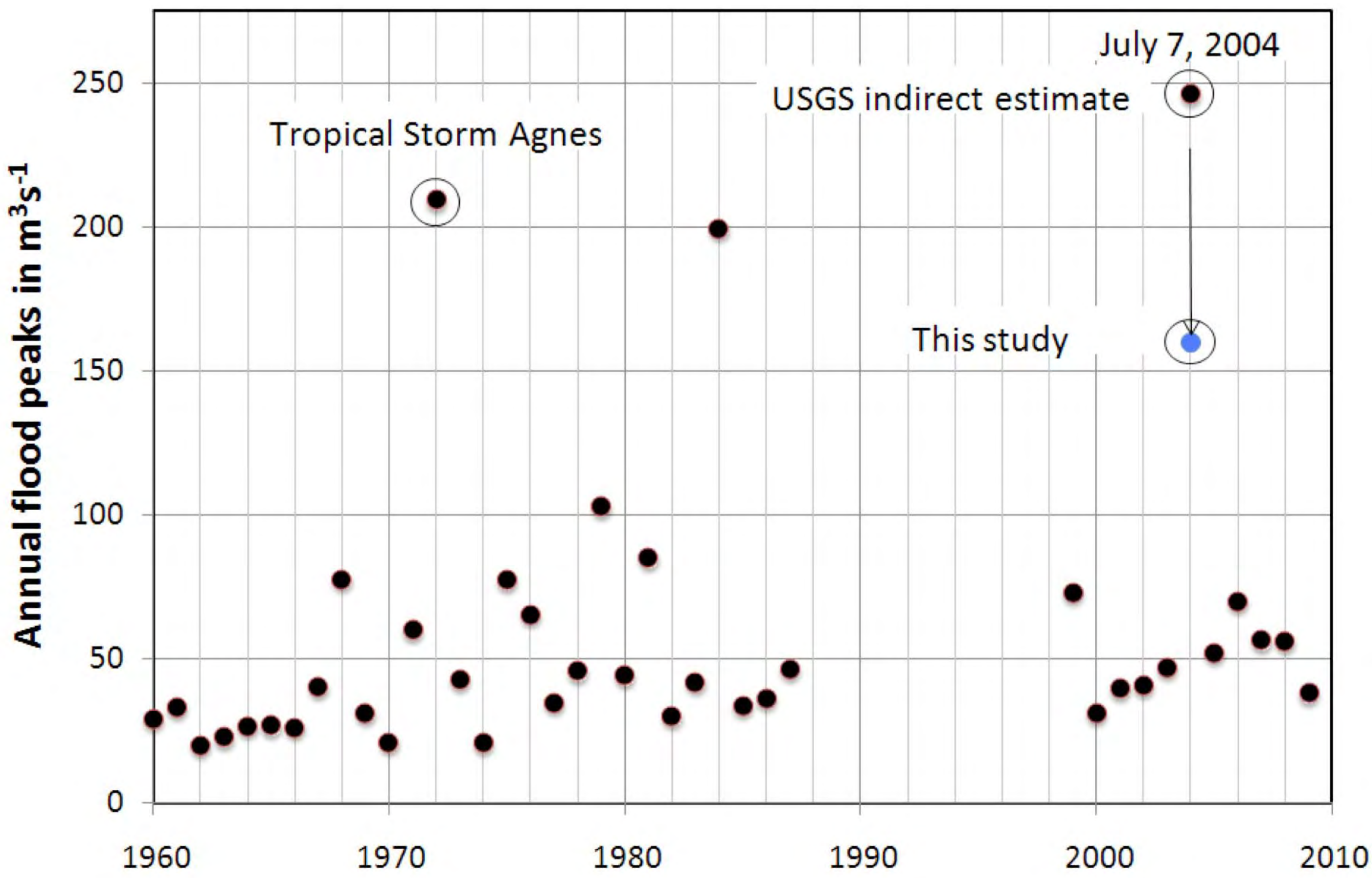
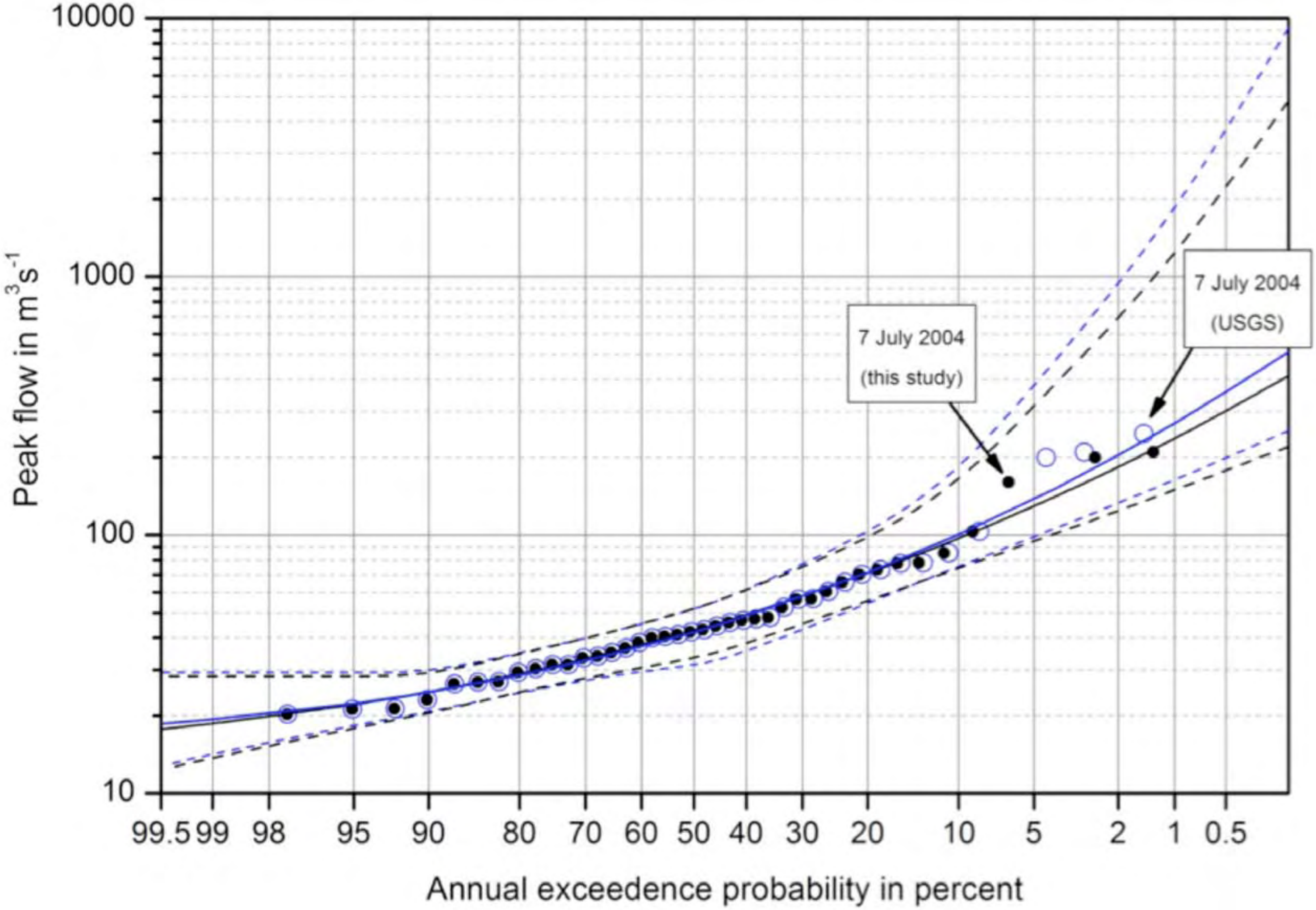


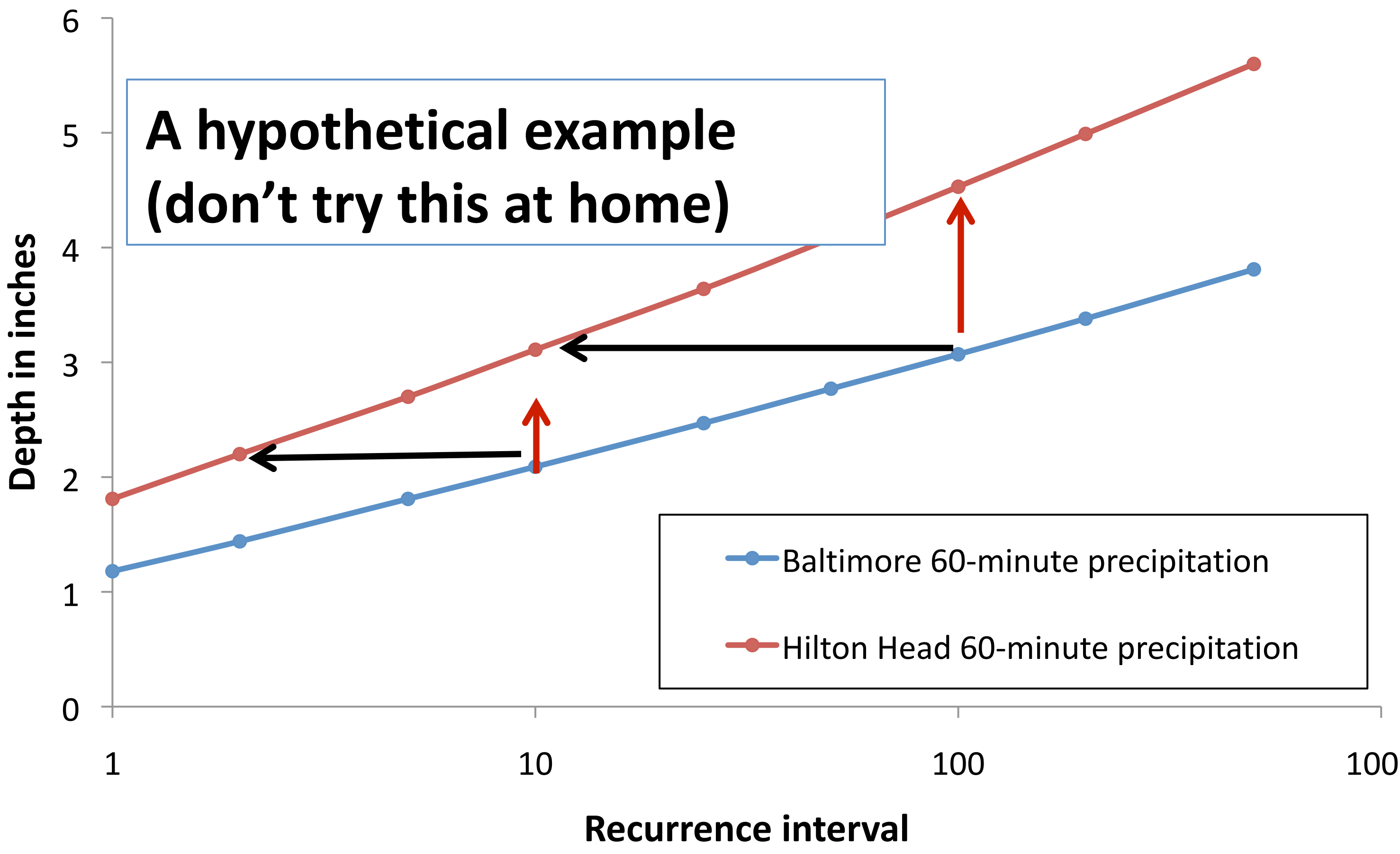
Figure 29. Time series of annual flood peaks for the Dead Run at Franklintown gage.

From Miller et al., in review


10000
1000
100
10
Peak flow in $m^3 s^{-1}$
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
Annual exceedence probability in percent
7 July 2004
(this study)
7 July 2004
(USGS)

# What about nonstationarity and climate change?

- Frequency and intensity of extreme precipitation is expected by some to increase over the next century
- Some observations in nearby states show this trend is already in progress, though modest for MD thus far; stronger for WV, DE, PA
- Percent of total rainfall coming in extreme events is also expected to increase
- However GCM projections of rainfall maxima are not accurate because the models do not incorporate dynamics of local convective storms



**A hypothetical example (don’t try this at home)**

If we posit that Baltimore conditions by late 21st century are comparable to those at Hilton Head, SC today, the current 100-yr 60-minute rainfall in Baltimore would become the 10-yr 60-minute rainfall; the current 10-yr 60-min rainfall would become the 1.8-yr 60-min rainfall; the local 10-yr 60-min rainfall (2.09 in) and the local 100-yr 60-min rainfall (3.07 in) would both increase by 50%.

(data from NOAA Precipitation Frequency Atlas 14)

# What about nonstationarity and flood frequency?

- Notwithstanding the thought experiment on the preceding slide, there is considerable uncertainty in current flood frequency estimates and there are multiple potential causes of nonstationarity
- We don’t know with any degree of reliability how the frequency distribution of extreme precipitation will change
- And we don’t really know how an altered frequency distribution of precipitation would affect the frequency distribution of floods
- Therefore any climate signal is unlikely to emerge from the noise within the next several decades

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# IF STATIONARITY IS DEAD, WHAT DO WE DO NOW?[1]

*Gerald E. Galloway*[2]

# A PERSPECTIVE ON NONSTATIONARITY AND WATER MANAGEMENT[1]

*Robert M. Hirsch*[2]

# NONSTATIONARY WATER PLANNING: AN OVERVIEW OF SEVERAL PROMISING PLANNING METHODS[1]

*Marc D. Waage and Laurna Kaatz*[2]

# STATIONARITY: WANTED DEAD OR ALIVE?[1]

*Harry F. Lins and Timothy A. Cohn*[2]

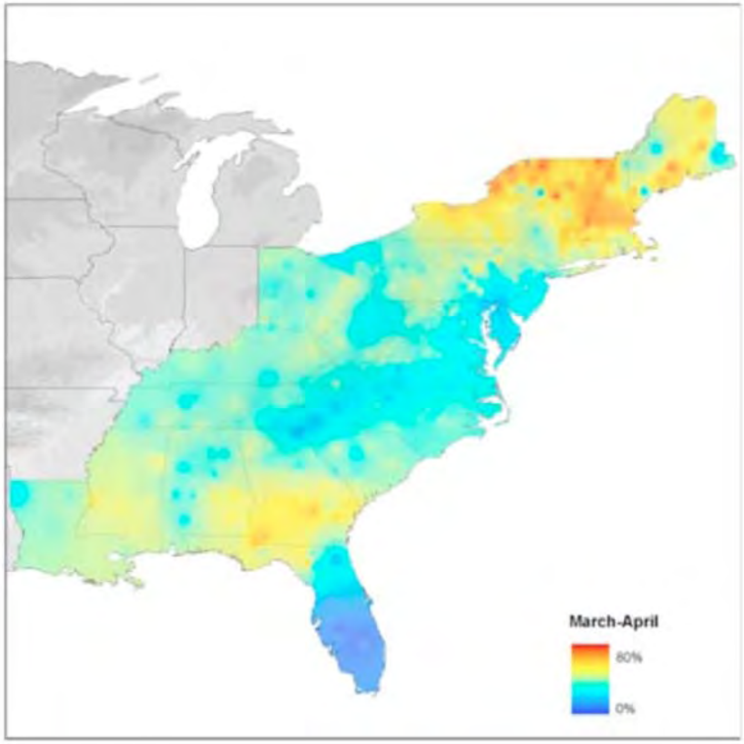
# What about nonstationarity and flood frequency?

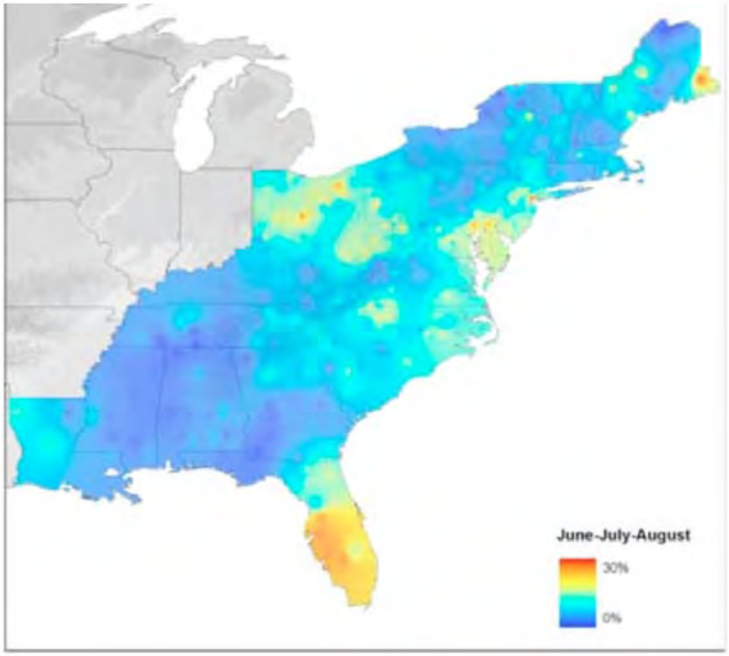
- The closest to a consensus argument made in papers published in the special June 2011 issue of JAWRA is that stationarity probably never did exist but that the records we have are still useful and should not be abandoned;
- And that we need a better understanding of all forms of uncertainty affecting our assessment of flood risk
- Nonstationarity in flood series associated with land-use change, urbanization and river regulation has been demonstrated in the literature;
- But thus far no reliable trends toward increasing flood frequency have been established solely as a result of global climate change

# What about nonstationarity and flood frequency?

- The last few slides focus on illustrating
  - That we are still learning about considerable fine-scale spatial variability in the types of events associated with annual maximum floods
  - That there is considerable local variability in the frequency distribution of extreme rainfall that has not previously been appreciated
  - That the effect of land-use change probably dwarfs any likely change attributable solely to climate in the near term;
  - That uncertainties in current flood frequency estimates are extremely large and we need to focus on understanding their implications before worrying about the magnitude of change

From Villarini and Smith, 2010
Note relatively low percentage of annual flood peaks in the mid-Atlantic occurring in March-April; higher percentage occurring in June-July-August; and local maximum in tropical cyclone-generated floods compared to areas immediately north and south





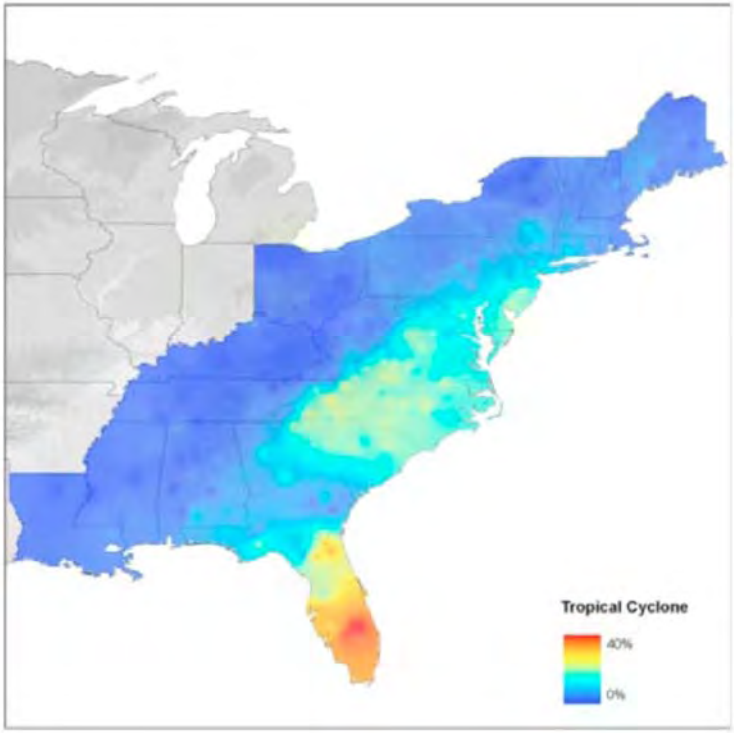
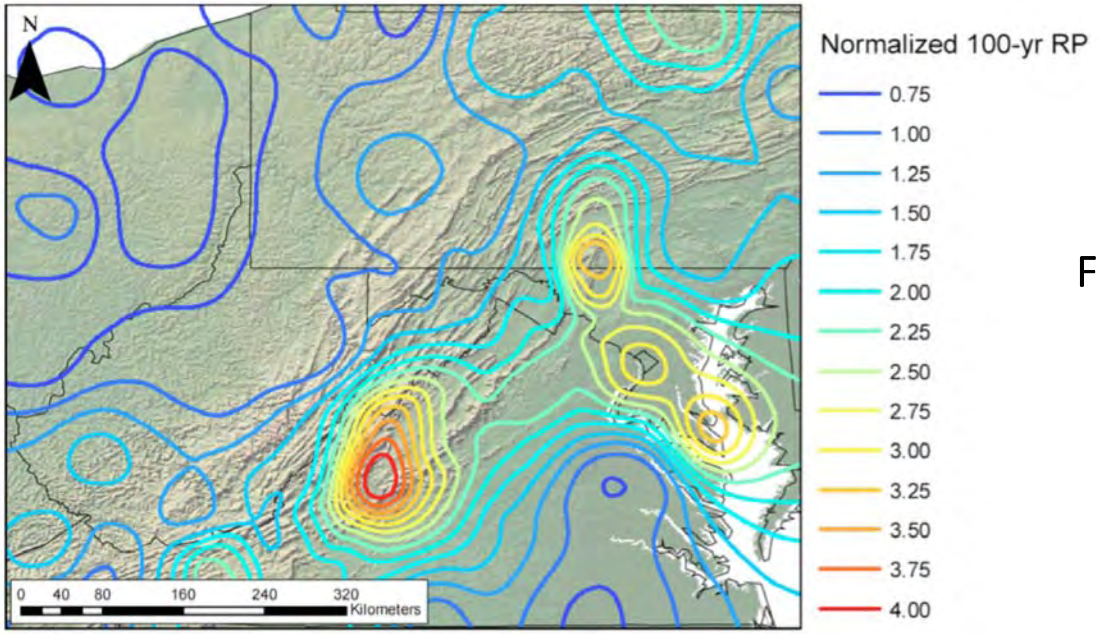


**Figure 7.** Maps showing the frequency of the annual maximum peak discharge (interpolation performed by means of inverse distance weighted method) for (top) March–April and (middle) June–July–August and (bottom) caused by tropical cyclones.

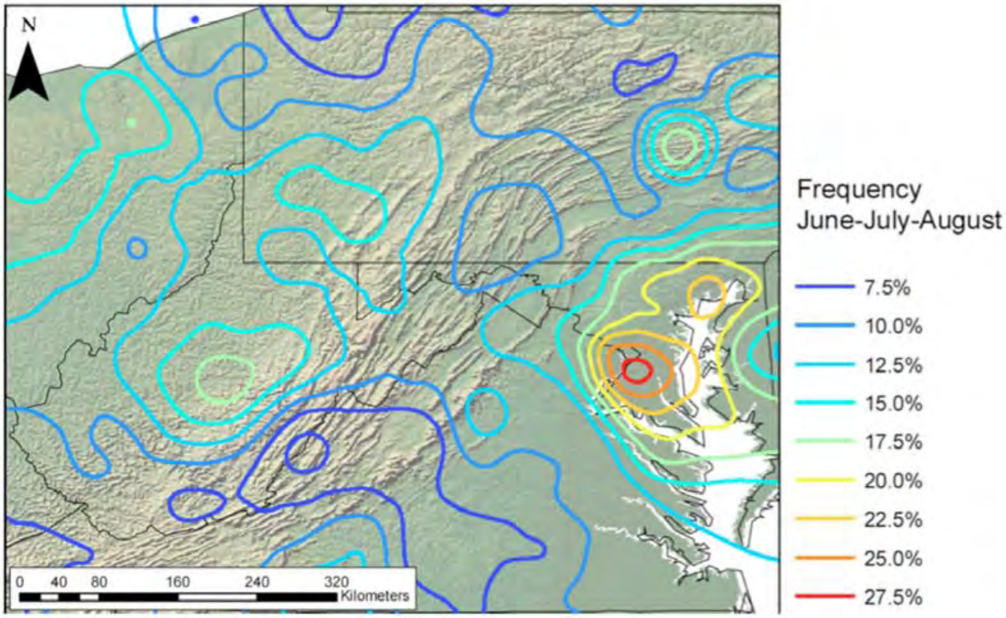


From Smith et al., 2011

**Figure 4.** (top) Normalized 100 year return period magnitude and (bottom) fraction of annual flood peaks that occur during June, July, and August. The normalized 100 year flood magnitude is computed as the ratio of the at-site 100 year flood magnitude to the regional 100 year magnitude (see text for details).

Note that there are regions along the Blue Ridge in VA and along the Baltimore-Washington corridor with elevated 100-year floods compared to regional estimates.

Also the Baltimore-Washington corridor has a higher percent of annual flood peaks in June, July and August compared to the region.



From Smith et al. (in review)

Note the large gradients in monthly rainfall and mean daily rainfall for days of heavy rain over a relatively short distance

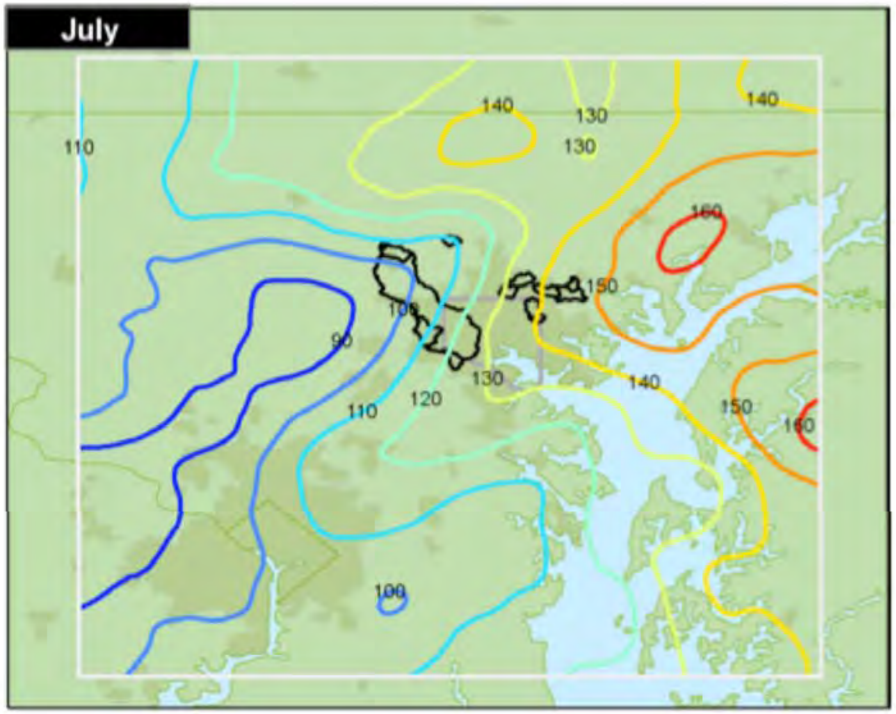


**Figure 7:** Mean monthly rainfall (mm) for July (top panel) panel) based on the 10-year data set.

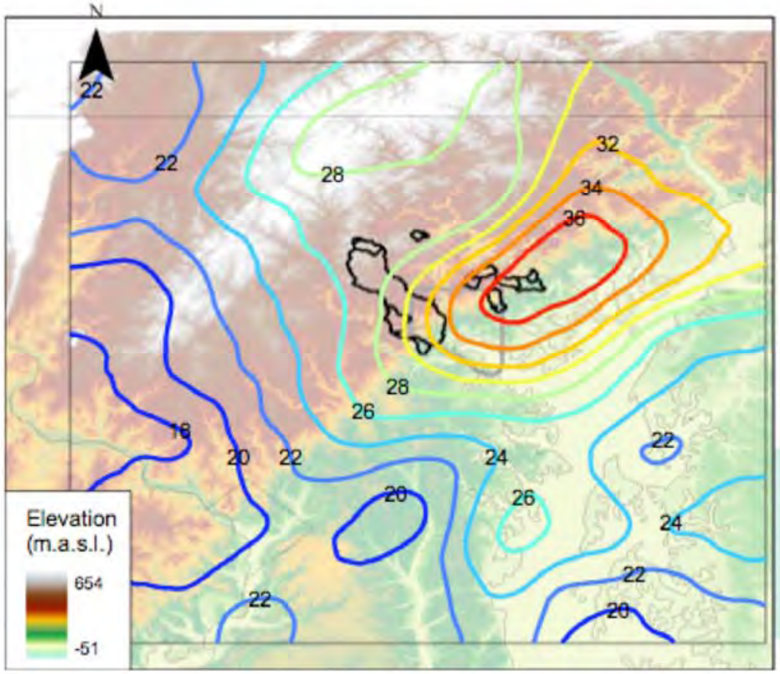


**Figure 10:** Mean daily rainfall (mm) for the 25 largest rain days in Baltimore City (gray line; see also Fig. 1). Background map illustrates topography of the study region.

From Villarini et al. 2009

Shows effect of urbanization on flood frequency distributions

The urban signal is still much stronger than the climate signal

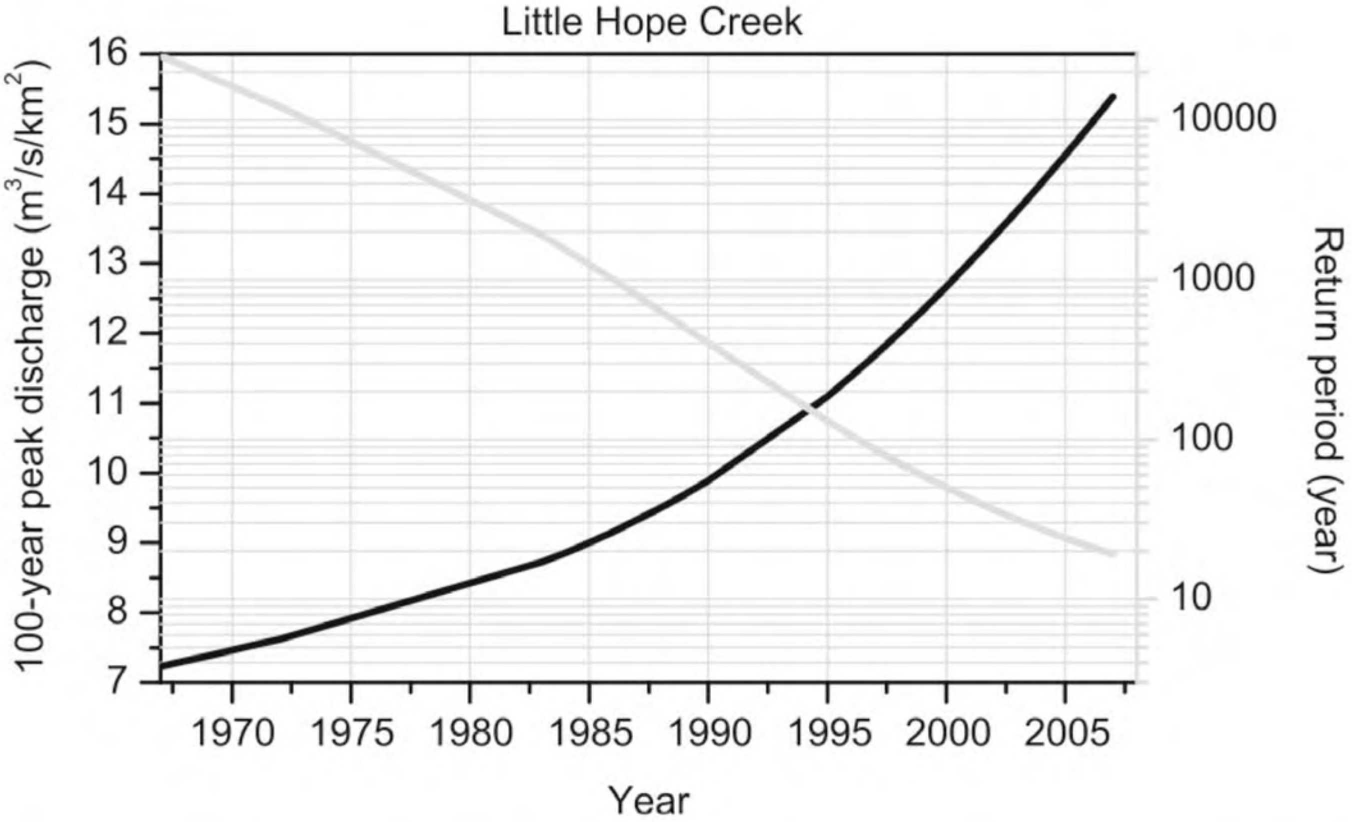


**Fig. 8.** Time trends in the value of peak discharge with 0.01 annual exceedance probability (black line) and in the estimated return period of the 0.01 annual exceedance flood peak derived from the 83-year gage record (gray line). These results are based on the GAMLSS model for Little Sugar Creek at Archdale (top panel) and Little Hope Creek (bottom panel). For reference, the Bulletin 17B 100-year peak estimates are 4.3 and 15.0 $m^3\ s^{-1}\ km^{-2}$, respectively, for Little Sugar Creek and Little Hope Creek, based on the 20-year record from 1987 through 2006.

1264 *G. Villarini et al. / Advances in Water Resources 32 (2009) 1255–1266*

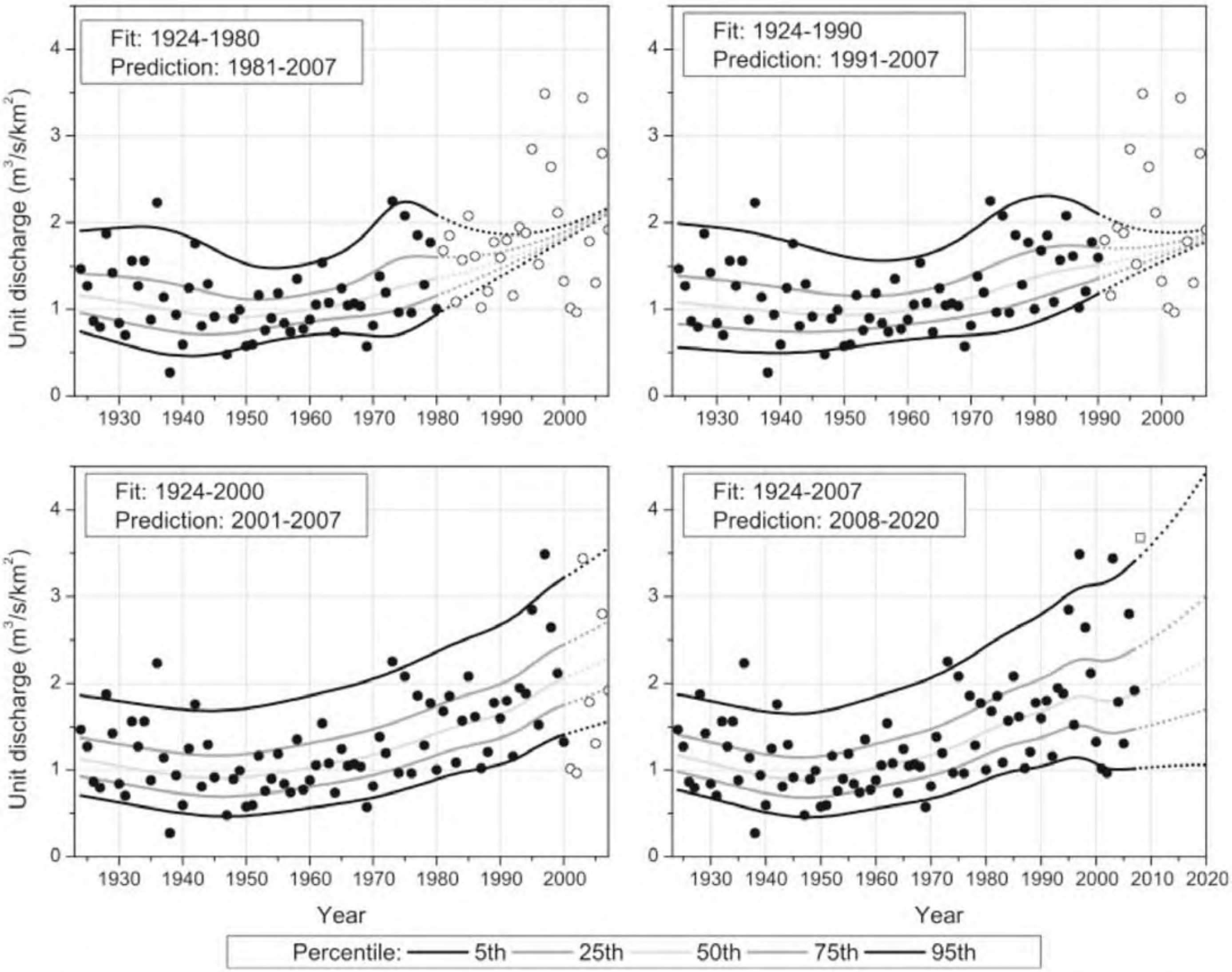
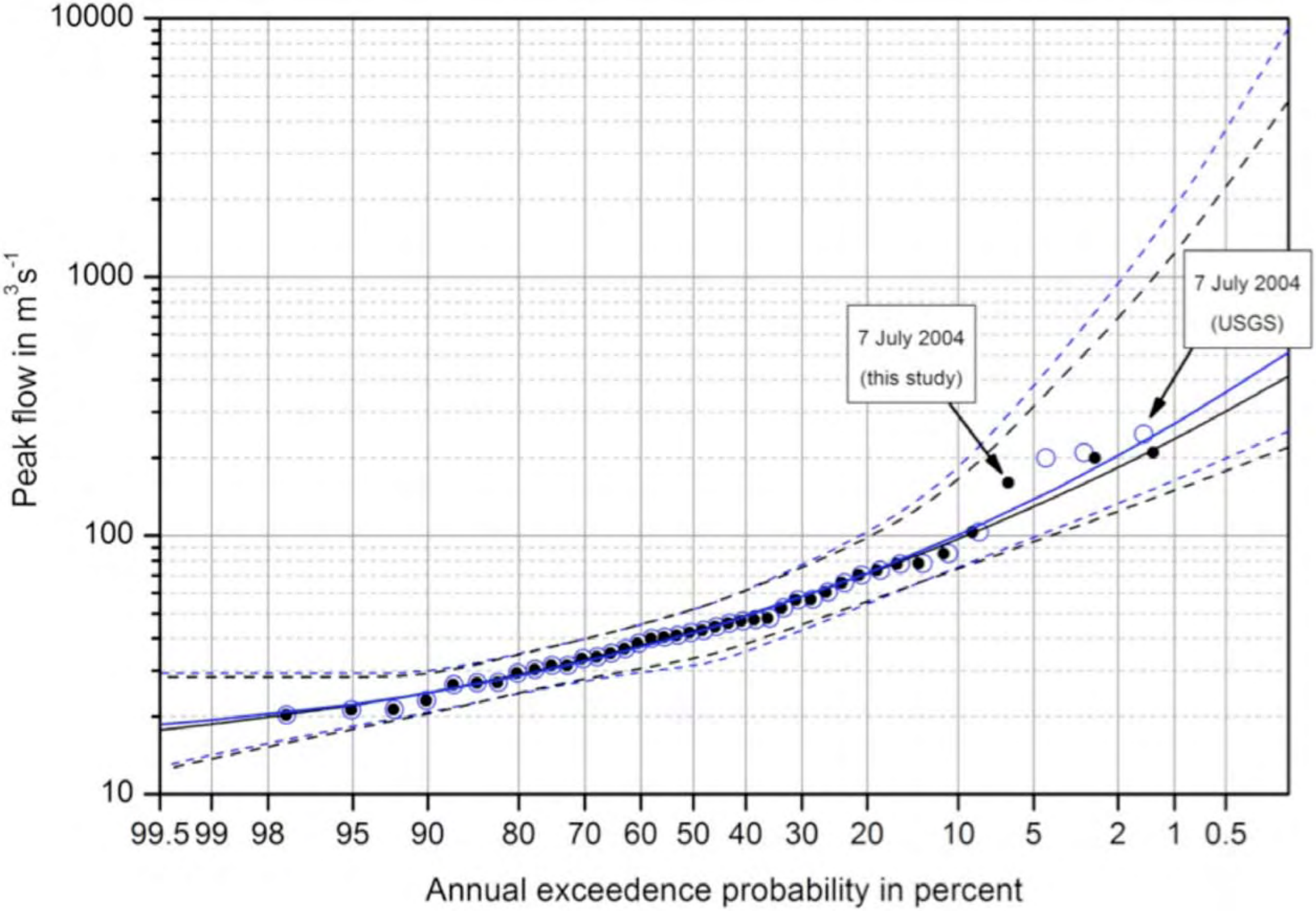


**Fig. 12.** Modeling of annual maximum peak discharge using daily maximum rainfall and population as covariates. In each of the panels, we have used part of the data for fitting (solid circles) and the modeling results are represented with solid lines. The model is then used as a predictive tool (dotted lines) and the observations not included in the fitting step are represented by hollow circles. These results refer to the data from Little Sugar Creek at Archdale. The empty square in the bottom right panel refers to the peak discharge measured by USGS on 27 August 2008.

The modeling approach shown here illustrates how flood frequency distributions have changed and might change further in response to urban development



10000
1000
100
10
Peak flow in $m^3s^{-1}$
99.5
99
98
95
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80
70
60
50
40
30
20
10
5
2
1
0.5
Annual exceedence probability in percent
7 July 2004
(this study)
7 July 2004
(USGS)

- The estimated recurrence interval of the generating precipitation for the 7 July 2004 flood is 100-400 years
- The flood peak is comparable to floods in rural watersheds of the same size with recurrence intervals of ~100-500 years
- The estimated recurrence interval of the flood peak based on the gage record is about 35 years
- However the 95% confidence limits for the 100-year flood span about an order of magnitude
- FEMA flood maps do not capture this level of uncertainty, which probably exceeds the uncertainty associated with potential climate change