Assessment of Flood Risk Across Wisconsin’s Upper Fox River Basin in Response to Heavy Precipitation Events

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Assessment of Flood Risk Across Wisconsin’s Upper Fox River Basin in Response to Heavy Precipitation Events

Part 1: Analysis of Historical Observations
27 Weather Stations Within the Upper Fox River Basin from the National Climatic Data Center (NCDC) Global Historical Climate Network

<table>
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The 10 “best” stations (yellow shading) contain 19-122 years of daily precipitation (PRCP) data. For those stations, the percentage of missing data ranges from 1.9% to 61.8%. Fond du Lac and Oshkosh have 122 years of daily data from 1893 to 2014, with only 2.6% and 4.5% of missing daily precipitation observations, respectively.
5 weather stations with the longest records (61-122 years, less than 5% missing data)

Annual mean precipitation (mm)

SW to NE gradient within basin of about 3"
The seasonal cycle of the % probability of receiving measurable precipitation (0.01”+) in a day is assessed at the 10 “best” stations in the Upper Fox River Basin, which have 19-122 years of data. Wet days are most abundant in May (probability = 35.7%) and least abundant in February (probability = 22.4%).
The seasonal cycle of the % probability of receiving 1”+ precipitation in a day is assessed at the 10 “best” stations in the Upper Fox River Basin, which have 19-122 years of data. The most active period is May-September, particularly June. At these stations, a 1”+ precipitation event typically occurs once every June. Note that June was also the most active month for flooding.
The seasonal cycle of the % probability of receiving 2”+ precipitation in a day is assessed at the 10 “best” stations in the Upper Fox River Basin, which have 19-122 years of data. The most active period is May-September, particularly June. At these stations, a 2”+ precipitation event typically occurs once every five Junes. Note that June was also the most active month for flooding.
During the period of 1900s-2000s, the frequency of wet days has significantly (p<0.1) increased at both Fond du Lac and Oshkosh, most notably during January-March. Averaged between the 2 stations, the decade of 1900-1909 contained the least wet days and the decade of 2000-2009 contained the most wet days. Surprisingly, there has been no significant trend in the frequency of heavy precipitation days at either station, unlike the pattern seen across most the state.
Precipitation Extremes in the Upper Fox River Basin from the National Weather Service Gridded Advanced Hydrologic Prediction Service (AHPS), Based on Rain Gauges and Radar

Both the NWS station observations and gridded AHPS product indicate that June is the most active month for heavy precipitation events in the Upper Fox River Basin.

For 1”+ events, there is a broad peak across April-August. For 2”+ or 3”+ events, the June peak becomes much more distinct.

The AHPS dataset is short in duration but is gridded and provides full coverage across the basin, which offers some advantages over scattered weather stations.
Relating the Climatological Mean Precipitation Pattern and Total Flood Frequency Pattern

Wisconsin exhibits a modest south/southwest to northeast gradient in annual mean precipitation, with over 36” in Iowa and Green Counties and less than 31” in Florence and Brown Counties. According to the NCDC Storm Events Database, the occurrence of floods and flash floods within Wisconsin is greatest across its southern counties and along the Mississippi River. The spatial patterns of annual mean precipitation and flood frequency are quite consistent. However, the south to north gradient in flood frequency is much more pronounced, with 48 floods days in Grant County and 42 in Vernon County versus only 1 in Door County and 2 in Kewaunee County during 1996-2014. The modest precipitation gradient appears to support a sharp gradient in flood frequency. The Upper Fox River is positioned just north of the zone of greatest flooding.
The counties in the Upper Fox River Basin (Adams, Calumet, Fond du Lac, Green Lake, Marquette, Waushara, Winnebago) have experienced 39 days of floods/flash floods during 1/1996-10/2014, with a mean rate of two days per year. The most active year was 2004, with 10 days of flooding. The four most recent years only contained one day of flooding. These flood events caused $46.5 million in property damage and $183.0 million in crop damage (NCDC Storm Events Database). The 6/12/2008 flood in Oshkosh caused $18.6 million in property damage. The 6/1/2004 flood in Fond du Lac caused $63.0 million in crop damage.
Flooding typically occurs within a narrow from May to August. 37 of 39 flood days (95%) occurred during May-August. The most active month is June.

Nearly 25% of all flood days occurred in 2004. The period of 2005-2013 was relatively inactive regarding flooding.
### Surface Synoptic Forcing and Upper-Level Circulation Associated With the 39 Flood/Flash Flood Days During 1996-2013 Across the Counties of the Upper Fox River Basin

<table>
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<tr>
<th>EVENT</th>
<th>SURFACE SYNOPTIC FORCING</th>
<th>UPPER LEVEL (500 hPa)</th>
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<td>6/16/1996 Calumet, Winnebago, Waushara</td>
<td>Slow-moving cyclone approaching from southwest with warm front</td>
<td>Weak approaching upper-level low</td>
</tr>
<tr>
<td>6/17/1996 Fond du Lac</td>
<td>Slow-moving cyclone approaching from southwest with warm front</td>
<td>Weak approaching upper-level low</td>
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<tr>
<td>6/21/1997 Fond du Lac</td>
<td>Stationary front advancing southward</td>
<td>Mostly zonal</td>
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<tr>
<td>7/16/1997 Adams, Waushara</td>
<td>Stationary front over Wisconsin</td>
<td>Mostly zonal, slight ridging to the west</td>
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<tr>
<td>6/27/1998 Marquette</td>
<td>Cyclone to the northwest following US-Canadian border</td>
<td>Upper-level low to the northwest</td>
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<td>6/10/1999 Fond du Lac, Winnebago, Waushara</td>
<td>Approaching cold front stalls around Wisconsin</td>
<td>Upper-level trough to the west</td>
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<td>6/27/1999 Calumet, Winnebago</td>
<td>Cold front crosses through Wisconsin and becomes a stationary front</td>
<td>Weak trough approaching from the west</td>
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<td>7/18/1999 Waushara</td>
<td>Stationary front advances northward into Wisconsin</td>
<td>Mostly zonal</td>
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<tr>
<td>6/1/2000 Fond du Lac, Marquette</td>
<td>Weak cyclone moves northeastward through Wisconsin</td>
<td>Weak trough passes through Wisconsin</td>
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<td>8/14/2000 Winnebago</td>
<td>Stationary front passing through Wisconsin becomes a cold front</td>
<td>Weak trough develops to northwest</td>
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<tr>
<td>8/22/2000 Fond du Lac</td>
<td>Cold front passing over Wisconsin becomes a stationary front</td>
<td>Weak trough passes through Wisconsin</td>
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<td>8/18/2001 Green Lake</td>
<td>Cyclone and occluded front head southeastward through Wisconsin</td>
<td>Upper-level trough passes through Wisconsin</td>
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<td>6/2/2002 Waushara</td>
<td>Stationary front over Wisconsin becomes a warm front</td>
<td>Mostly zonal</td>
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<td>6/22/2002 Adams, Green Lake, Marquette, Waushara</td>
<td>Warm front over Wisconsin becomes a stationary front</td>
<td>Mostly zonal</td>
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<td>7/8/2002 Fond du Lac</td>
<td>Stationary front over Wisconsin becomes a cold front</td>
<td>Weak ridging developing to the southwest</td>
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<td>8/21/2002 Fond du Lac</td>
<td>Developing cyclone and cold front pass over Wisconsin from southwest</td>
<td>Zonal flow becoming western US trough</td>
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<td>7/30/2003 Calumet, Winnebago</td>
<td>Weak occluded cyclone becomes a stationary front</td>
<td>Upper-level low to the northwest</td>
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<td>Weak surface cyclone/trough</td>
<td>Upper level low over Wisconsin</td>
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<td>5/5/2004 Winnebago</td>
<td>Occluded low passes through Wisconsin, heading to the northeast</td>
<td>Upper level trough passes through Wisconsin</td>
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<td>Cold front stalls over Wisconsin as a stationary front</td>
<td>Trough building over western U.S.</td>
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<td>Approaching cyclone and warm front from the southwest</td>
<td>Western-central US trough</td>
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<td>Weak low heads to the northeast through Wisconsin</td>
<td>Weak trough passes through Midwest</td>
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<td>6/1/2004 Fond du Lac, Green Lake, Marquette</td>
<td>Weak cyclone and cold front passes through Wisconsin</td>
<td>Upper-level trough passes through Wisconsin</td>
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<td>Stationary front to south of Wisconsin</td>
<td>Upper level low approaching from west</td>
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<td>Mostly zonal become weak trough to west</td>
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<td>Low develops along cold front over Wisconsin</td>
<td>Weak trough over western U.S.</td>
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<td>7/1/2004 Green Lake, Winnebago</td>
<td>Stationary front advances from the north through Wisconsin</td>
<td>Ridge building to Midwest from the west</td>
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<td>6/4/2007 Fond du Lac</td>
<td>Cold front pushes through Wisconsin from north</td>
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<td>Weak low develops over Great Lakes</td>
<td>Northwest flow with ridge over southwest U.S.</td>
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<td>Weak surface low pass through Wisconsin from west with cold front</td>
<td>Upper-level low to the east</td>
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<td>6/17/2008 Green Lake, Marquette</td>
<td>Weak surface low and stationary front approaching from southwest</td>
<td>Approaching trough from the west</td>
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<td>6/8/2008 Fond du Lac, Winnebago</td>
<td>Developing low and cold front pass over Wisconsin from southwest</td>
<td>Approaching trough from the west</td>
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<td>Approaching cold front with slow moving low to the northwest</td>
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<td>7/16/2008 Calumet</td>
<td>Cold front becomes stationary front over Wisconsin</td>
<td>Mostly zonal</td>
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<td>7/14/2010 Winnebago</td>
<td>Deepening cyclone to north, with cold and warm fronts crossing Wisconsin</td>
<td>Upper-level low to the northwest</td>
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<td>7/24/2010 Calumet</td>
<td>Cold front passes through Wisconsin</td>
<td>Weak upper-level trough crosses Wisconsin</td>
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<td>9/24/2010 Adams</td>
<td>Cyclone passes to the northeast through the Great Lakes Basin</td>
<td>Upper-level trough dissipates over Wisconsin</td>
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<td>5/3/2012 Calumet, Winnebago</td>
<td>Stationary front over Wisconsin becomes cold front</td>
<td>Mostly zonal with trough over west coast</td>
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Flood events were typically triggered by cold fronts (17 days) or stationary fronts (16 days).
Composite of sea-level pressure (hPa) and 10-meter wind (m/s) anomalies for 39 flood days in counties of Upper Fox River Basin using MERRA Reanalysis

Composite of sea-level pressure (hPa) and 2-meter specific humidity (g/kg) anomalies for 39 flood days in counties of Upper Fox River Basin using MERRA Reanalysis

Shading=Sea-level pressure; Vectors=10-m wind

Shading=2-m specific humidity; Contours=Sea-level pressure

Cyclone approaching from southwest to northeast, with southerly flow from the Gulf of Mexico providing moisture to Wisconsin.

MERRA = Modern-Era Retrospective Analysis for Research and Applications
Composite of 250-hPa upper-tropospheric zonal u-wind (m/s) and 500-hPa mid-tropospheric vertical motion (omega, Pa/day) anomalies for 39 flood days in counties of Upper Fox River Basin using MERRA Reanalysis.

**Day -2**

Day -1

Day 0

**Composite of 500-hPa geopotential height (m) anomalies for 39 flood days in counties of Upper Fox River Basin using MERRA Reanalysis**

**Day -2: 500-hPa Hts**

**Day -1**

**Day 0**

**Day 0: 250-hPa U Wind, 500-hPa Omega**

Shading=250-hPa u-wind; Contours=500-hPa omega (jet stream winds)  (negative=ascent)

Anomalous trough-ridge pattern (zonal flow), supporting southerly flow from the Gulf of Mexico and ascending motion over Wisconsin.

Northward shifted upper-level jet stream.

Shading=500-hPa geopotential height (mid-tropospheric wave pattern)
Robustness of Synoptic Weather Patterns from MERRA Reanalysis Among 39 Flood Events in Counties of Upper Fox River Basin

- % events with + anomalies in 850-hPa v-wind
- % events with - anomalies in sea-level pressure
- % events with + anomalies in 850-hPa specific humidity
- % events with + anomalies in 500-hPa geopotential height
- % events with - anomalies in 500-hPa omega
- % events with + anomalies in 250-hPa u-wind

List of patterns from most robust to least robust:

- Anomalous southerly winds
- Approaching low pressure
- Increased moisture
- Anomalous trough-ridge
- Ascending motion
- Northward shift of jet
Primary tracks:

1. Moist southerly flow from the Gulf of Mexico (41% of events)
2. Local weather system within the Great Lakes region (33% of events)
3. West-northwesterly storm track from southern Canada (25% of events)

Floods in the Upper Fox River Basin are produced by a variety of meteorological forcings.
Available USGS Data of Daily Streamflow and Gage Height Within the Upper Fox River Basin

USGS Daily Streamflow Stations for Upper Fox River Basin

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<td>Fox River at Princeton, WI</td>
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<td>Silver Creek at Spaulding Road Near Green Lake, WI</td>
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<td>Roy Creek at Roy Creek Road Near Green Lake, WI</td>
<td>43.75°N</td>
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<td>Green Lake SW Inlet @ CT Highway K NR Green Lake, WI</td>
<td>43.77°N</td>
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USGS Daily Gage Height Stations for Upper Fox River Basin

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<td>Lake Winnebago at Oshkosh, WI</td>
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<td>7/10/1882-8/13/2014</td>
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<tr>
<td>04084255</td>
<td>Lake Winnebago Near Stockbridge, WI</td>
<td>44.07°N</td>
<td>88.32°W</td>
<td>11/1/1982-8/13/2014</td>
</tr>
</tbody>
</table>
Discharge on the Upper Fox River typically peaks in March-May (likely related to snowmelt). Gage height on Lake Winnebago typically peaks in May-July (likely related to greatest precipitation). Flooding is most common when water levels are high, rather than river discharge is most rapid.
The year 2004 contained 33 days with discharge exceeding 8000 ft³/s, while 2006 contained only 6.

In recent years, 2004 and 2008 displayed high discharge. Both years produced frequent flood events.
Some flood events within the Upper Fox River Basin counties corresponded with high streamflow at the Fox River at Berlin and some did not. In some cases, the heavy precipitation events were quite localized and may not have directly impacted the river. The flood events of March-July 2004 corresponded with exceptionally high discharge.
### 39 Flood Days in Counties of Upper Fox River Basin (from NCDC Storm Events Database) and Daily Precipitation (mm) on Day-2 to Day 0 for Fond du Lac, Oshkosh, Ripon 5 NE, Dalton, Montello, and the Mean of 27 Within-Basin Stations

<table>
<thead>
<tr>
<th></th>
<th>Day-2</th>
<th>Day-1</th>
<th>Day 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/16/1996 Calumet, Winnebago, Waushara</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>6/17/1996 Fond du Lac</td>
<td>0</td>
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</tr>
<tr>
<td>6/21/1997 Fond du Lac</td>
<td>1.3</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>7/16/1997 Adams, Waushara</td>
<td>1.5</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>6/27/1998 Marquette</td>
<td>5.8</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>6/10/1999 Fond du Lac, Winnebago, Waushara</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>6/27/1999 Calumet, Winnebago</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>7/18/1999 Waushara</td>
<td>6.9</td>
<td>0</td>
<td>3.7</td>
</tr>
<tr>
<td>6/1/2000 Fond du Lac, Marquette</td>
<td>3.8</td>
<td>11.2</td>
<td>1.3</td>
</tr>
<tr>
<td>8/14/2000 Winnebago</td>
<td>2.3</td>
<td>3.0</td>
<td>8.4</td>
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<tr>
<td>8/22/2000 Fond du Lac</td>
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<tr>
<td>8/18/2001 Green Lake</td>
<td>9.4</td>
<td>16.0</td>
<td>10.7</td>
</tr>
<tr>
<td>6/21/2002 Waushara</td>
<td>0</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>6/22/2002 Adams, Green Lake, Marquette, Waushara</td>
<td>0.8</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>7/8/2002 Fond du Lac</td>
<td>2.5</td>
<td>2.0</td>
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</tr>
<tr>
<td>7/30/2003 Calumet, Winnebago</td>
<td>3.2</td>
<td>2.9</td>
<td>1.8</td>
</tr>
<tr>
<td>8/2/2004 Winnebago</td>
<td>7.1</td>
<td>29.2</td>
<td>4.8</td>
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<tr>
<td>5/8/2004 Fond du Lac, Green Lake</td>
<td>0.3</td>
<td>15.0</td>
<td>0.5</td>
</tr>
<tr>
<td>5/21/2004 Winnebago</td>
<td>5.0</td>
<td>26.4</td>
<td>2.5</td>
</tr>
<tr>
<td>5/23/2004 Marquette</td>
<td>29.0</td>
<td>8.8</td>
<td>2.5</td>
</tr>
<tr>
<td>5/25/2004 Green Lake</td>
<td>42.9</td>
<td>38.9</td>
<td>43.2</td>
</tr>
<tr>
<td>6/1/2004 Fond du Lac, Green Lake, Marquette</td>
<td>34.5</td>
<td>4.7</td>
<td>2.5</td>
</tr>
<tr>
<td>6/11/2004 Winnebago, Waushara</td>
<td>8.4</td>
<td>0.5</td>
<td>43.2</td>
</tr>
<tr>
<td>6/15/2004 Winnebago</td>
<td>2.5</td>
<td>10.2</td>
<td>3.5</td>
</tr>
<tr>
<td>6/16/2004 Adams</td>
<td>4.1</td>
<td>3.3</td>
<td>7.6</td>
</tr>
<tr>
<td>7/1/2004 Green Lake, Winnebago</td>
<td>0</td>
<td>0</td>
<td>6.8</td>
</tr>
<tr>
<td>6/4/2007 Fond du Lac</td>
<td>3.3</td>
<td>7.9</td>
<td>4.8</td>
</tr>
<tr>
<td>7/3/2007 Marquette</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>7/26/2007 Waushara</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>6/7/2008 Green Lake, Marquette</td>
<td>0</td>
<td>12.7</td>
<td>15.7</td>
</tr>
<tr>
<td>6/8/2008 Fond du Lac, Winnebago</td>
<td>0</td>
<td>3.6</td>
<td>8.4</td>
</tr>
<tr>
<td>6/12/2008 Calumet, Fond du Lac, Winnebago</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>7/16/2008 Calumet</td>
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<td>0.0</td>
</tr>
<tr>
<td>7/14/2010 Winnebago</td>
<td>3.6</td>
<td>32.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7/24/2010 Calumet</td>
<td>0</td>
<td>0</td>
<td>6.8</td>
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<tr>
<td>9/24/2010 Adams</td>
<td>0</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>5/3/2012 Calumet, Winnebago</td>
<td>0.3</td>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Limitations of this approach:** (1) Flooding may have occurred away from the rain gauges; (2) Need to consider Day+1 given the 2 datasets define a day (range of hours) differently.

Day-2: 4.3±7.2 mm  
Day-1: 8.6±11.7 mm  
Day 0: 20.1±19.6 mm
### Summary of 11 Flood Events Within Upper Fox River Counties, Including Daily Basinwide Precipitation from AHPS for Day-2, Day-1, Day 0, and Day+0 and the Meteorological Forcings

<table>
<thead>
<tr>
<th>Flood Event Day 0</th>
<th>Day-2 Mean±1 std (Range)</th>
<th>Day-1 Mean±1 std (Range)</th>
<th>Day 0 Mean±1 std (Range)</th>
<th>Day +1 Mean±1 std (Range)</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>20070604</td>
<td>0.21±0.14 (0.02 -&gt; 0.66)</td>
<td>0.36±0.23 (0.08 -&gt; 1.45)</td>
<td>0.94±0.70 (0.11 -&gt; 3.48)</td>
<td>0.10±0.08 (0.00 -&gt; 0.68)</td>
<td>Persistent rains; repeated rounds of thunderstorms</td>
</tr>
<tr>
<td>20070703</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.03±0.03 (0.00 -&gt; 0.20)</td>
<td>1.10±0.40 (0.33 -&gt; 2.69)</td>
<td>MCS, short wave trough, cold front</td>
</tr>
<tr>
<td>20070726</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.00±0.00 (0.00 -&gt; 0.05)</td>
<td>0.12±0.21 (0.00 -&gt; 1.56)</td>
<td>0.78±0.75 (0.00 -&gt; 4.36)</td>
<td>Thunderstorms, upper low, cold front</td>
</tr>
<tr>
<td>20080607</td>
<td>0.70±0.30 (0.18 -&gt; 1.75)</td>
<td>0.10±0.07 (0.00 -&gt; 0.40)</td>
<td>0.02±0.02 (0.00 -&gt; 0.13)</td>
<td>1.87±1.20 (0.11 -&gt; 4.18)</td>
<td>Slow surface boundary, strong low-level jet</td>
</tr>
<tr>
<td>20080608</td>
<td>0.10±0.07 (0.00 -&gt; 0.40)</td>
<td>0.02±0.02 (0.00 -&gt; 0.13)</td>
<td>1.87±1.20 (0.11 -&gt; 4.18)</td>
<td>3.18±0.53 (1.70 -&gt; 4.42)</td>
<td>Heaviest rains; slow surface boundary, strong low-level jet</td>
</tr>
<tr>
<td>20080612</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.01±0.01 (0.00 -&gt; 0.10)</td>
<td>0.05±0.05 (0.00 -&gt; 0.26)</td>
<td>3.36±1.08 (1.24 -&gt; 5.23)</td>
<td>Quick burst of rain; warm, moist, unstable air ahead of cold front</td>
</tr>
<tr>
<td>20080716</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.00±0.00 (0.00 -&gt; 0.10)</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.77±0.33 (0.16 -&gt; 3.01)</td>
<td>Thunderstorms, slow warm front</td>
</tr>
<tr>
<td>20100714</td>
<td>0.21±0.20 (0.00 -&gt; 1.16)</td>
<td>0.03±0.16 (0.00 -&gt; 1.86)</td>
<td>0.00±0.00 (0.00 -&gt; 0.01)</td>
<td>2.85±0.40 (1.77 -&gt; 3.98)</td>
<td>Thunderstorms along cold front</td>
</tr>
<tr>
<td>20100724</td>
<td>0.06±0.01 (0.00 -&gt; 0.04)</td>
<td>2.15±0.36 (1.26 -&gt; 4.40)</td>
<td>0.65±0.30 (0.32 -&gt; 1.95)</td>
<td>0.00±0.00 (0.00 -&gt; 0.01)</td>
<td>Isolated thunderstorm</td>
</tr>
<tr>
<td>20100924</td>
<td>0.01±0.02 (0.00 -&gt; 0.12)</td>
<td>0.39±0.39 (0.01 -&gt; 1.89)</td>
<td>0.53±0.28 (1.14 -&gt; 1.46)</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>Stationary front, wet soil</td>
</tr>
<tr>
<td>20120503</td>
<td>0.00±0.00 (0.00 -&gt; 0.00)</td>
<td>0.44±0.16 (0.19 -&gt; 1.03)</td>
<td>2.30±0.88 (0.44 -&gt; 3.81)</td>
<td>0.61±0.45 (0.01 -&gt; 1.80)</td>
<td>Thunderstorms</td>
</tr>
<tr>
<td>Mean</td>
<td>0.12&quot;</td>
<td>0.32&quot;</td>
<td>0.59&quot;</td>
<td>1.33&quot;</td>
<td></td>
</tr>
</tbody>
</table>

**Shading = Heaviest day of precipitation for each event**

All of the above events occurred during May-September. Typically, flooding within the counties of the Upper Fox River occurred with basin-wide average rainfall of about 2", summed across 4-day periods (day -3 to day +1). In some cases, flooding was attributed to short-duration downbursts (e.g. 6/12/2008), while in other cases, it was caused by prolonged heavy rains (e.g. 6/4/2007).
### Daily Precipitation (Inches) for Day-2 to Day+1 for Select Flood Events in the Upper Fox River Counties Using AHPS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Circles = Locations of flooding from NCDC Storm Events Database</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Flooding in Fond du Lac**
- **4-day within-basin rainfall range: 0.34” to 4.17”**
- **Persistent multi-day rain event due to repeated rounds of thunderstorms**

#### Flood Event: 6/7/2008
- **Flooding in Dalton and Endeavor**
- **4-day within-basin rainfall range: 0.41” to 5.55”**
- **Sharp 4-day rainfall gradient across the basin, with totals ranging from 0.41” to 5.55”. Rainfall produced by a slow-moving surface boundary and strong low-level jet.**

#### Flood Event: 6/12/2008
- **Flooding in St. Anna, Ripon, and Oshkosk**
- **4-day within-basin rainfall range: 1.31” to 5.28”**
- **Sudden 1-day burst of rain due to warm, moist, unstable air ahead of a cold front**

---

In general, flood events are **LOCALLY** associated with 4-day rainfall totals of 1.7” to 5”, with a mean of 3.5”. Rainfall patterns within the basin are highly heterogeneous for flood events.
### 20 wettest 1-day periods (40 mm+) in Upper Fox River Basin from Daymet, 1996-2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/13/2008</td>
<td>77 mm *</td>
</tr>
<tr>
<td>7/15/2010</td>
<td>74 mm *</td>
</tr>
<tr>
<td>6/17/1996</td>
<td>70 mm *</td>
</tr>
<tr>
<td>6/9/2008</td>
<td>69 mm *</td>
</tr>
<tr>
<td>6/11/2004</td>
<td>62 mm *</td>
</tr>
<tr>
<td>6/8/2008</td>
<td>61 mm *</td>
</tr>
<tr>
<td>3/31/1998</td>
<td>59 mm</td>
</tr>
<tr>
<td>7/26/2005</td>
<td>56 mm</td>
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<tr>
<td>8/19/2007</td>
<td>54 mm</td>
</tr>
<tr>
<td>7/21/1999</td>
<td>53 mm</td>
</tr>
<tr>
<td>5/3/2012</td>
<td>50 mm *</td>
</tr>
<tr>
<td>5/18/2000</td>
<td>47 mm</td>
</tr>
<tr>
<td>9/14/2003</td>
<td>47 mm</td>
</tr>
<tr>
<td>4/10/2013</td>
<td>47 mm</td>
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<tr>
<td>6/12/2001</td>
<td>45 mm *</td>
</tr>
<tr>
<td>6/10/2004</td>
<td>44 mm *</td>
</tr>
<tr>
<td>7/23/2010</td>
<td>43 mm *</td>
</tr>
<tr>
<td>11/4/2003</td>
<td>42 mm</td>
</tr>
<tr>
<td>5/22/2004</td>
<td>41 mm *</td>
</tr>
<tr>
<td>10/15/2012</td>
<td>41 mm</td>
</tr>
</tbody>
</table>

50% of heaviest 1-day precipitation events caused flooding.

### 20 wettest 3-day periods (60 mm+) in Upper Fox River Basin from Daymet, 1996-2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/9/2008</td>
<td>133 mm *</td>
</tr>
<tr>
<td>6/11/2004</td>
<td>116 mm *</td>
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<td>104 mm *</td>
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<tr>
<td>10/15/2012</td>
<td>96 mm</td>
</tr>
<tr>
<td>4/1/1998</td>
<td>91 mm</td>
</tr>
<tr>
<td>7/21/1999</td>
<td>81 mm *</td>
</tr>
<tr>
<td>5/4/2012</td>
<td>78 mm *</td>
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<td>77 mm</td>
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<td>7/26/2005</td>
<td>76 mm</td>
</tr>
<tr>
<td>6/2/2000</td>
<td>75 mm *</td>
</tr>
<tr>
<td>7/17/2010</td>
<td>74 mm *</td>
</tr>
<tr>
<td>5/18/2000</td>
<td>66 mm</td>
</tr>
<tr>
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<td>61 mm</td>
</tr>
<tr>
<td>9/9/2001</td>
<td>60 mm</td>
</tr>
<tr>
<td>6/23/2002</td>
<td>58 mm *</td>
</tr>
</tbody>
</table>

45% of heaviest 3-day precipitation events caused flooding.

### 20 wettest 7-day periods (73 mm+) in Upper Fox River Basin from Daymet, 1996-2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/13/2008</td>
<td>226 mm *</td>
</tr>
<tr>
<td>6/14/2004</td>
<td>137 mm *</td>
</tr>
<tr>
<td>8/25/2007</td>
<td>127 mm</td>
</tr>
<tr>
<td>5/8/2012</td>
<td>123 mm *</td>
</tr>
<tr>
<td>7/22/1999</td>
<td>119 mm *</td>
</tr>
<tr>
<td>10/19/2012</td>
<td>113 mm</td>
</tr>
<tr>
<td>6/22/1996</td>
<td>112 mm *</td>
</tr>
<tr>
<td>6/5/2000</td>
<td>107 mm *</td>
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<tr>
<td>7/27/2005</td>
<td>99 mm</td>
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<tr>
<td>4/3/1998</td>
<td>94 mm</td>
</tr>
<tr>
<td>7/17/2010</td>
<td>94 mm *</td>
</tr>
<tr>
<td>6/18/2001</td>
<td>87 mm</td>
</tr>
<tr>
<td>6/22/1997</td>
<td>82 mm *</td>
</tr>
<tr>
<td>4/15/2013</td>
<td>82 mm</td>
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<tr>
<td>4/9/1999</td>
<td>79 mm</td>
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<tr>
<td>9/19/2003</td>
<td>79 mm</td>
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<td>9/11/2001</td>
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<td>6/18/2001</td>
<td>75 mm</td>
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<tr>
<td>5/11/2003</td>
<td>76 mm *</td>
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<tr>
<td>6/22/1997</td>
<td>76 mm</td>
</tr>
<tr>
<td>4/19/2013</td>
<td>75 mm</td>
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<tr>
<td>4/9/1999</td>
<td>74 mm</td>
</tr>
<tr>
<td>5/11/2003</td>
<td>74 mm</td>
</tr>
<tr>
<td>6/26/2002</td>
<td>73 mm *</td>
</tr>
</tbody>
</table>

45% of heaviest 7-day precipitation events caused flooding.

### 20 wettest 14-day periods (101 mm+) in Upper Fox River Basin from Daymet, 1996-2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/13/2008</td>
<td>268 mm *</td>
</tr>
<tr>
<td>6/12/2004</td>
<td>187 mm *</td>
</tr>
<tr>
<td>7/24/2010</td>
<td>168 mm *</td>
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<tr>
<td>7/22/1999</td>
<td>159 mm *</td>
</tr>
<tr>
<td>8/25/2007</td>
<td>151 mm</td>
</tr>
<tr>
<td>5/9/2012</td>
<td>145 mm *</td>
</tr>
<tr>
<td>10/26/2012</td>
<td>131 mm</td>
</tr>
<tr>
<td>6/19/1996</td>
<td>130 mm *</td>
</tr>
<tr>
<td>6/18/2001</td>
<td>123 mm</td>
</tr>
<tr>
<td>6/8/2000</td>
<td>119 mm *</td>
</tr>
<tr>
<td>6/16/2010</td>
<td>113 mm</td>
</tr>
<tr>
<td>6/30/1998</td>
<td>109 mm *</td>
</tr>
<tr>
<td>7/20/2008</td>
<td>109 mm *</td>
</tr>
<tr>
<td>6/25/2013</td>
<td>109 mm</td>
</tr>
<tr>
<td>4/19/2013</td>
<td>107 mm</td>
</tr>
<tr>
<td>5/13/2003</td>
<td>106 mm *</td>
</tr>
<tr>
<td>8/24/1997</td>
<td>103 mm</td>
</tr>
<tr>
<td>4/10/1998</td>
<td>103 mm</td>
</tr>
<tr>
<td>9/14/2000</td>
<td>101 mm</td>
</tr>
<tr>
<td>8/1/2005</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

45% of heaviest 14-day precipitation events caused flooding.

**Only May-July heavy precipitation events caused flooding.**

Bold = Heavy precipitation events in May-July, * = flooding reported in Counties of Upper Fox River Basin in NCDC Storm Events Database
Flooding is primarily confined to May-August.

One-day rainfall totals in excess of 1” (averaged across basin) during May-July often lead to flooding.

Seven-day rainfall totals in excess of 1.5” (averaged across basin) during June-July often lead to flooding.
Conclusions, Part 1

- Upper Fox River Basin is located between the wettest part of Wisconsin (southwest) and the driest part (northeast)
- May-September is the most active period for heavy precipitation in the region
- June is the month with the most frequent occurrences of extreme rainfall
- No significant century-long trend in heavy precipitation at Fond du Lac or Oshkosh
- Instances of flooding occur almost exclusively during May through August
- Most floods are a consequence of clearly identifiable weather patterns
- Heavy rainfalls during May-July are much more likely to trigger flooding
- Floods are most common when water levels are high, rather than when rivers are most rapid
What does the future hold?

Part 2: Analysis of Future Projections
Global climate models suggest considerable changes in future precipitation patterns. Wisconsin is likely to become wetter in most seasons.
Heavy precipitation has increased in recent decades over all of the continental U. S., especially in the North and Northeast.
The observed trend toward heavier precipitation events is probably being driven in part by greenhouse warming. This trend will likely strengthen in the future.
Downscaling Global Climate Model Data

Global Climate Models (GCMs) simulate large-scale atmospheric processes with grid cells approximately $2^\circ \times 2^\circ$ latitude/longitude.

Methods used to render large-scale GCM output at finer scales for applications:

1. Statistical Downscaling

2. Dynamical Downscaling (Regional Climate Models)
Statistical Downscaling

Translate coarse simulations of climate from global models to finer scales by using observed relationships between large-scale weather and local weather.

A diverse team from the institutions below has statistically downscaled GCM simulations from 1950 to 2100 using the BCCA translation method for the mid- and late-21st centuries under two greenhouse gas emissions scenarios: the high-end “RCP8.5” and the low-end “RCP4.5”.

Images Courtesy of David Lorenz, UW-Madison
Dynamical Downscaling (Regional Climate Models)

A coordinated effort to dynamically downscale North American climate change by mid-century, using six regional climate models (RCMs) driven at their boundaries by four global models.

Caveats: Provides projections for the middle 21st century only and assumes a single (high-end) greenhouse gas emissions scenario.

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**NARCCAP**
North American Regional Climate Change Assessment Program

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![Dynamical Downscaling Map](image)

<table>
<thead>
<tr>
<th>RCMs</th>
<th>GCMs</th>
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<tr>
<td></td>
<td>CCSM3</td>
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<td>RCM3</td>
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<tr>
<td>WRFG</td>
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</table>
We assess future changes in precipitation over the Upper Fox River Basin using both types of
downscaling methods.

Comparisons are made for the middle (2041-2070) and late (2071-2100) 21st century, relative to
the late 20th century (1971-2000).

Unless noted otherwise, results are from the high-end, RCP8.5 emissions scenario.
Projected Changes in Total Precipitation

Dynamically Downscaled
“NARCCAP”

Mid-21st Century

Mean: 8.5%, 2.9”

A modestly wetter climate in the future (5-10% more precipitation)

Consistent with global climate model projections

Better agreement among dynamically downscaled than statistically downscaled models

Statistically Downscaled
“BCCA”

Mid-21st Century

Mean: 5.9%, 1.9”

Late-21st Century

Mean: 8.7%, 2.7”
Uncertainty Assessment using Bootstrapping

1,000 random resamples of all the model projections within each data set (NARCCAP, BCCA)

Considerably larger range of uncertainty in BCCA model projections of annual precipitation

Considerably larger range of uncertainty in BCCA model projections of annual precipitation
Projected Changes in Total Precipitation, RCP4.5 vs. RCP8.5

- Similar model-average increase in both emissions scenarios (5-9% more annual precip)
- Slightly stronger response with more greenhouse emissions (RCP8.5)
- Larger difference between mid- and late-century changes in RCP8.5 than RCP4.5
Projected Changes in Wet Days

**Dynamically Downscaled**

“NARCCAP”

**Statistically Downscaled**

“BCCA”

**Mid-21st Century**

- Slightly fewer wet days in the future (only about a 1% change)
- Consistent with global climate model projections
- Better agreement among dynamically downscaled than statistically downscaled models
Projected Changes in Heavy Daily Precipitation Amount

Dynamically Downscaled
“NARCCAP”

Statistically Downscaled
“BCCA”

- Fairly robust increase in heavy precipitation amount (9 to 13% more in model averages)
- Consistent with global climate model projections
- Similar agreement among dynamically downscaled and statistically downscaled models
Uncertainty Assessment using Bootstrapping

1,000 random resamples of all the model projections within each data set (NARCCAP, BCCA)

Similar uncertainty bounds in projections of heavy precipitation intensity
Projected Changes in Heavy Precipitation Intensity, RCP4.5 vs. RCP8.5

- **Robust increase in heavy precipitation amounts in both scenarios and time periods**
- **Stronger response with more greenhouse emissions (RCP8.5)**
- **Larger difference between mid- and late-century changes in RCP8.5 than RCP4.5**
Projected Changes in Heavy Daily Precipitation Frequency

Dynamically Downscaled  
“NARCCAP”

Statistically Downscaled  
“BCCA”

Mid-21st Century  
Mid-21st Century  
Late-21st Century

- Even more robust increase in heavy precipitation frequency (~ 1/3 to 1/2 more in model ave)
- Consistent with global climate model projections
- Better agreement in magnitude among dynamically downscaled models
Uncertainty Assessment using Bootstrapping

1,000 random resamples of all the model projections within each data set (NARCCAP, BCCA)

Greater uncertainty in projected changes in extreme precipitation frequency in BCCA models, especially for late century.
Projected Changes in Heavy Precipitation Frequency, RCP4.5 vs. RCP8.5

- Robust increase in heavy precipitation frequency in both scenarios and time periods
- Stronger response with more greenhouse emissions (RCP8.5)
- Much larger difference between mid- and late-century changes in RCP8.5 than RCP4.5

RCP4.5 = Conservative greenhouse gas emissions scenario
RCP8.5 = Higher-end greenhouse gas emissions scenario
Projected Changes in Heavy Weekly Precipitation Frequency

Dynamically Downscaled “NARCCAP”

- Mean: 65.0%
- Even more robust increase in heavy precipitation frequency on weekly timescale
- No model simulates less extreme weekly precipitation in future
- Better agreement in magnitude among dynamically downscaled models

Statistically Downscaled “BCCA”

- Mean: 65.0%
- Mean: 91.0%

Change in Mid-21st Century Heavy Precip Weeks
NARCCAP Models, Upper Fox River Basin

Change in Mid-21st Century Heavy Precip Weeks
BCCA Models, Upper Fox River Basin

Change in Late-21st Century Heavy Precip Weeks
BCCA Models, Upper Fox River Basin
Projected Changes in Heaviest 100 Daily Events

Dynamically Downscaled
“NARCCAP”

Statistically Downscaled
“BCCA”

- Increased intensity of top 100 daily precipitation events (typically 10-20%)
- Consistent with global climate model projections
- Less agreement in projections of very heaviest rainfalls
Intermodel Spread in Projected Heaviest 100 Events

- Intermodel spread increases with the intensity of the event
- Considerably higher intermodel spread for the handful of heaviest rainfalls
Signal-to-Noise Ratio, Projected Heaviest 100 Events

Dynamically Downscaled
“NARCCAP”

Statistically Downscaled
“BCCA”

- Signal-to-Noise ratio decreases with the intensity of the event
- Considerably lower Signal-to-Noise ratios for the handful of heaviest rainfalls
What are the implications?

Assessing the Effects of Climate Change on Precipitation and Flood Damage in Wisconsin

Zachary T. Schuster¹; Kenneth W. Potter²; and David S. Liebl³

Journal of Hydrologic Engineering, August 2012

applied “Generalized Risk Analysis”

Damage = (Daily Precipitation – Precipitation Threshold)^Y

Three different assumptions of damage:

#1: Relatively greater sensitivity to small precipitation events (Y = 0.5)

#2: Equal sensitivity to small and large events (Y = 1)

#3: Relatively greater sensitivity to large events (Y = 2)

Slack et al. (1975), Merz et al. (2009)
Estimated Changes in Flood Damage

\[ \text{Damage} = (\text{Daily Precipitation} - \text{Precipitation Threshold})^Y = (\text{Daily Precipitation} - 1.02 \text{ inches})^Y \]

Three different assumptions of damage:

#1: Relatively greater sensitivity to small precipitation events \((Y = 0.5)\)
#2: Equal sensitivity to small and large events \((Y = 1)\)
#3: Relatively greater sensitivity to large events \((Y = 2)\)

Estimated Future Flood Damage (mid-21\textsuperscript{st} century, regional climate models):

1. Identify the top 100 actual precip events at a station in basin (Oshkosh) in late 20\textsuperscript{th} century
Estimated Changes in Flood Damage

\[ \text{Damage} = (\text{Daily Precipitation} - \text{Precipitation Threshold})^Y \]
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Estimated Future Flood Damage (mid-21\(^{st}\) century, regional climate models):

1. Identify the top 100 actual precip events at a station in basin (Oshkosh) in late 20\(^{th}\) century

1. Identify the top 100 simulated precip events averaged over the Upper Fox River basin in the late 20\(^{th}\) and middle 21\(^{st}\) centuries (NARCCAP intermodel average)
Daily Precipitation Amount: Oshkosh observed, Late-20th and Mid-21st Century NARCCAP basin-mean

**Legend:**
- **Oshkosh observed (1971-2000)**
- **Late 20th C Model Mean**
- **Mid 21st C Model Mean**

**Axes:**
- **Y-axis:** Daily Precipitation Amount (inches)
- **X-axis:** Rank of Precipitation Event
Estimated Changes in Flood Damage

Damage = (Daily Precipitation – Precipitation Threshold)\(^Y\)
= (Daily Precipitation – 1.02 inches)\(^Y\)

Three different assumptions of damage:
#1: Relatively greater sensitivity to small precipitation events (Y = 0.5)
#2: Equal sensitivity to small and large events (Y = 1)
#3: Relatively greater sensitivity to large events (Y = 2)

Estimated Future Flood Damage (mid-21\(^{st}\) century, regional climate models):

1. Identify the top 100 actual precip events at a station in basin (Oshkosh) in late 20\(^{th}\) century

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3. Multiply the observed magnitude of Oshkosh’s top 100 events by the basin-wide percentage increase simulated by the NARCCAP intermodel average for all 100 events
Daily Precipitation Amount: Oshkosh observed, Late-20th and Mid-21st Century NARCCAP basin-mean

- Oshkosh observed (1971-2000)
- Late 20th C Model Mean
- Mid 21st C Model Mean

Rank of Precipitation Event

Daily Precipitation Amount (inches)
Estimated Changes in Flood Damage

\[ \text{Damage} = (\text{Daily Precipitation} - \text{Precipitation Threshold})^Y \]
\[ = (\text{Daily Precipitation} - 1.02 \text{ inches})^Y \]

Three different assumptions of damage:

#1: Relatively greater sensitivity to small precipitation events (\(Y = 0.5\))
#2: Equal sensitivity to small and large events (\(Y = 1\))
#3: Relatively greater sensitivity to large events (\(Y = 2\))

Estimated Future Flood Damage (mid-21\text{st} century, regional climate models):

1. Identify the top 100 actual precip events at a station in basin (Oshkosh) in late 20\text{th} century
2. Identify the top 100 simulated precip events averaged over the Upper Fox River basin in the late 20\text{th} and middle 21\text{st} centuries (NARCCAP intermodel average)
3. Multiply the observed magnitude of Oshkosh’s top 100 events by the basin-wide percentage increase simulated by the NARCCAP intermodel average for all 100 events
4. Use these scaled projections of future heavy rainfalls to calculate estimated flood damage
Estimated Changes in Flood Damage (Oshkosh)

Damage = \((\text{Daily Precipitation} - \text{Precipitation Threshold})^Y\)

= \((\text{Daily Precipitation} - 1.02 \text{ inches})^Y\)

Three different assumptions of damage:

- #1: Relatively greater sensitivity to small precipitation events \((Y = 0.5)\)
- #2: Equal sensitivity to small and large events \((Y = 1)\)
- #3: Relatively greater sensitivity to large events \((Y = 2)\)

Much higher damage AND uncertainty for the very heaviest events
Conclusions, Part 2

• Heavy precipitation events have been increasing nationally, including in Wisconsin.

• This upward trend will probably continue into the future.

• Over central Wisconsin (Upper Fox River Basin), climate models suggest:
  (1) a slightly wetter future,
  (2) a modest increase in the intensity of heavy daily rainfalls,
  (3) a larger increase in the frequency of heavy daily rainfalls, and
  (4) an even greater rise in the frequency of heavy rainfalls on weekly time scales.

• Model uncertainty in projected heavy precipitation is highest for heaviest events.

• Estimated uncertainty in resulting damage is also highest for the heaviest events.

• Much greater uncertainty between mid- and late-21st century under the high-end (RCP8.5) emissions scenario than the more optimistic RCP4.5 scenario.