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Final Report

Hydro-meteorological Responses to Tropical System Precipitation in Illinois

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ABSTRACT

This study sought to characterize the impact of tropical system precipitation on streamflow values measured in nine Illinois watersheds and determine whether a predictive model based on antecedent and expected rainfall conditions could be developed. Unlike smaller-scale thunderstorm complexes which are difficult to forecast beyond 24 hours, there is much greater forecast lead time associated with tropical systems. The differences in spatial and temporal scales associated with two types of heavy rain producing storms suggests that hydro-meteorologists have a better opportunity to develop timely regional precipitation and streamflow forecasts as a tropical system approaches Illinois.

During a 100-year period (1913-2012) 26 tropical systems were found to have produced an average of an inch or more precipitation within a 24-hour window (i.e., event) in one or more of Illinois' nine climate divisions. Those climate divisions impacted by an event experienced a significant increase in monthly soil moisture levels as measured by the Palmer Drought Severity Index (PDSI). When pre- versus post-tropical system streamflow (ST) values were compared for the non-event watersheds an increase in ST of less than 50% occurred, while ST changes in watersheds that experienced an event increased by more than 500%. Factors that influenced the magnitude of increase included pre-storm ST conditions (i.e., was ST below, near or above average prior to the event), timing of event (i.e., summer or fall), and total storm precipitation.

The predictive ST model, where model output (e.g., post event ST estimates) could be integrated into decision support tools used by those impacted by flooding, was of limited use. Reasons for a lack of success were related to three primary issues, a small sample of events (i.e., 26) in the study, events occurring over a long period (100-years) when changes in land use and agricultural practices altered the surface hydrology (i.e., use of tiles, no-till agriculture, expanding crops in risky environments, etc.), and different surface characteristics (e.g., basin shape and size, soils, geomorphology, etc.) among the nine watersheds.

Despite the issues that add complexity to the rainfall to ST relationships over time, those who are tasked with forecasting tropical storm precipitation and related ST values have greater knowledge of how ST values increase and can provide more lead time to regional decision makers in affected watersheds.

Chapter 1: Introduction

Background

Heavy summer rainfall events in the Midwest are typically associated with mesoscale convective systems (MCS, Parker and Johnson 2000; e.g., Maddox et al. 1979; Fritsch et al. 1986; Junker et al. 1999; Anderson and Arrit 2001; Ashley et al. 2003; Tuttle and Davis 2006; Schumacher and Johnson 2005; Schumacher 2009). Various sub-types of MCS have been intensely studied, and their contribution to Midwest warm-season rainfall is well established (Maddox 1980; Rodgers et al. 1985; Fritsch et al. 1986; Parker and Johnson 2000; Ashley et al. 2003; Houze 2004; Ashley and Ashley 2008; Gallus et al. 2008; Kunkel et al. 2012). These types of systems can produce disastrous hydro-meteorological effects in Illinois that can lead to millions of dollars in flood-related damage (Angel et al. 1997) and even loss of life (Angel et al. 1997; Ashley and Ashley 2008). Although meteorological conditions dictate when, where and how long these heavy-rain producing systems will impact an area (Doswell et al. 1996), their impacts, either positive or negative, are largely determined by antecedent conditions (Changnon et al. 2003). For example, heavy MCS rainfall on areas experiencing drought could produce beneficial effects for crops, but the same rainfall on saturated soils and swollen streams could result in flooding (Changnon et al. 2003). One may wonder: *what other types of precipitation events could produce similar hydro-meteorological impacts in Illinois?*

Tropical systems have received little recognition as heavy rain producers in the Midwest, and studies have typically viewed these systems as interesting and rare case-studies (Changnon and Changnon 2004; Changnon and Changnon 2006; Gensini et al. 2011). However, Illinois has experienced heavy tropical system rainfall (≥ 2.54 cm day^{-1}) once every 3.8 years from 1913-2012, and the period from 2005 to 2012 produced 7 such events (Haberlie et al. 2014). One such event, associated with the remnants of Hurricane Ike in 2008, produced once in 100 year rainfall and peak streamflow values in northern Illinois (Gensini et al. 2011). Tropical systems were found to produce heavy rainfall over a broader area (i.e., impacting on average three Illinois climate divisions) than MCS events. Furthermore, these tropical systems typically occur during neutral to wet conditions in Illinois. Tropical system events that occur under conditions where soils are wet and rivers are at or above average stream flow could further accentuate negative hydro-meteorological impacts in Illinois (Changnon et al. 2003). Moreover, recent studies have suggested that tropical systems in the Atlantic basin could become stronger and more numerous as anthropogenic warming continues (Emanuel 2005; Elsner et al. 2008; Bender et al. 2010), and some of those systems may increasingly impact the Midwest (Kunkel et al. 2012; Haberlie et al. 2014). Thus, there is reasonable motivation to understand the impacts of these events in Illinois, especially if their frequency increases. Building on the work of Haberlie et al. (2014), *this study will quantify the amount and impact of tropical system related precipitation in Illinois, with a focus on drought and stream flow response.*

Objectives of the Study

1) Produce information related to Illinois-impacting tropical systems that increases situational awareness for emergency managers, operational meteorologists, and agri-business interests

2) Develop a model that could assist interested parties in anticipating the impact of tropical systems in Illinois.

Chapter 2. Data and Approach

Tropical Systems impacting Illinois

Haberlie et al. (2014) identified heavy rainfall events (≥2.54 cm per day) associated with tropical systems that impacted Illinois from1913-2012 (Table 1). Climate divisions (CDs) that experienced a heavy tropical rainfall event, the dates the storm was in the region, the total number of climate divisions (CDs) impacted by each system, precipitation data, and monthly Palmer Drought Severity Index (PDSI) values before and after each event were used in this study. There were 26 tropical system events during the 100-year period that impacted one or more Illinois CDs (Table 1). On average a tropical system impacted 3.8 Illinois CDs or more than a third of the state.

Table 1. Tropical systems that impacted one or more Illinois climate divisions (CDs).

Year	Name	Regional Date(s)	IL CD(s)
1915	2	8/20-8/22	4-9
1916	14	10/19	2
1923	8	10/17	2, 4-9
1923	9	10/18-10/19	2, 5, 7, 9
1926	1	7/31-8/2	5
1932	3	9/2-9/4	9
1941	2	9/24-9/25	2-4, 6
1947	4	9/21	1
1948	5	9/5-9/6	8, 9
1949	10	10/6	1, 4, 5, 7
1950	Baker	9/1	7, 8
1955	5	8/29	3
1957	Audrey	6/28-6/29	5-7
1960	Ethel	9/17	5
1961	Carla	9/13-9/14	1-6
1965	Betsy	9/11-9/12	8, 9
1968	Candy	6/25-6/26	1-5, 7-9
1979	Bob	7/12-7/14	1
1979	Claudette	7/28-7/29	7, 8
2005	Arlene	6/12-6/14	9
2005	Dennis	7/11-7/17	8, 9
2005	Katrina	8/30-8/31	9
2005	Rita	9/25-9/26	7
2008	Gustav	9/4-0/5	2-6
2008	Ike	9/14-9/15	1-6
2012	Isaac	8/31-9/3	3-9

Long-term Illinois Watersheds selected for Study

In each of the Illinois' nine CDs a watershed with a long-term daily discharge record was identified and used in this study (Table 2, Figure 1). These watersheds varied in size and shape, however, they were generally considered “virgin” watersheds with little or no impairments to the natural flow.

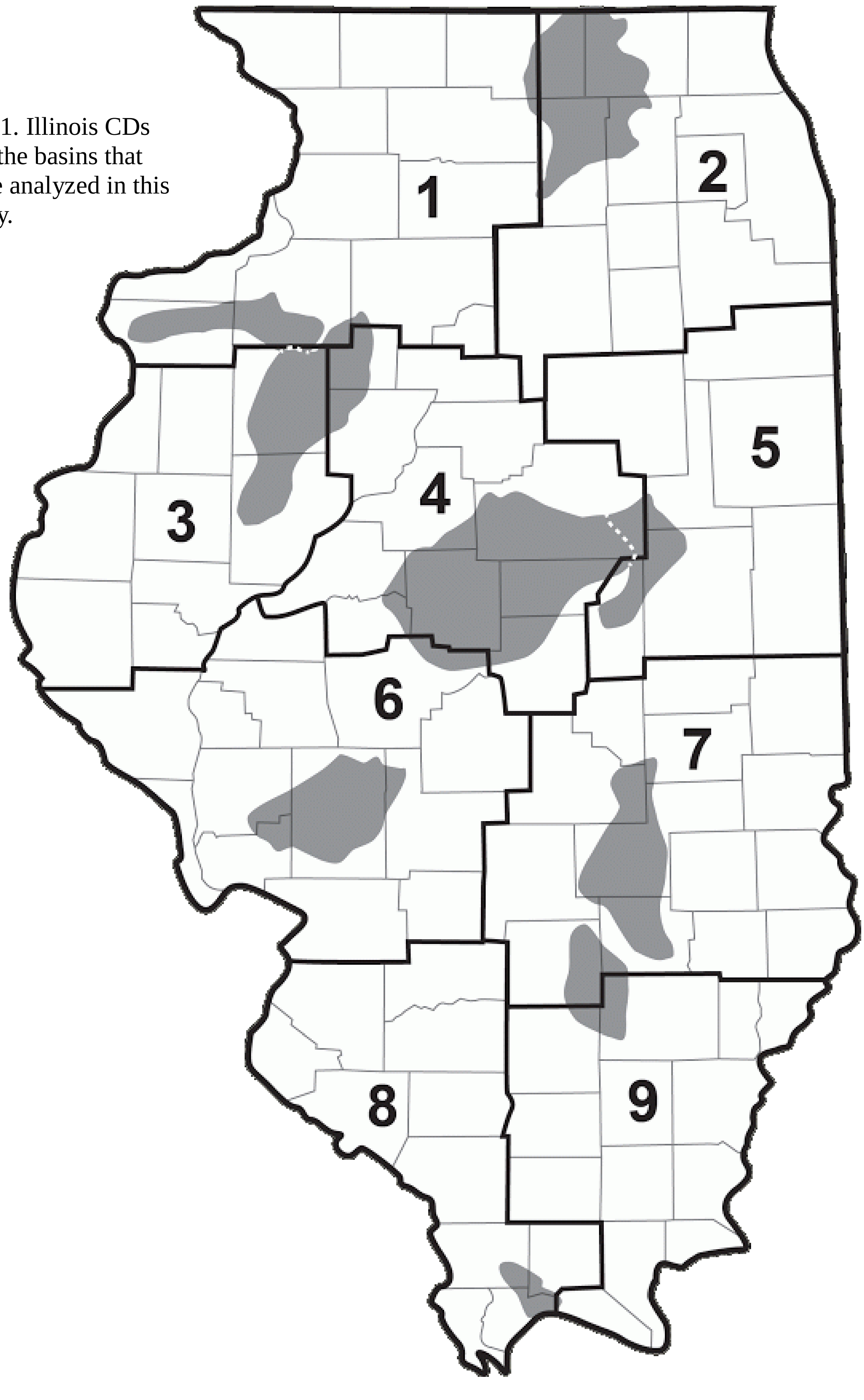

Fig. 1. Illinois CDs and the basins that were analyzed in this study.

Table 2. Characteristics of Illinois basins used in study.

Climate Division	Streamflow Gage Number	Gage Site Location	Basin Size (mi^2)	Period of Record
CD1	05466500	Edwards near New Boston	445	1934-present
CD2	05440000	Kishwaukee near Perryville	1,099	1939-present
CD3	05570000	Spoon near Seville	1,636	1914-present
CD4	05582000	Salt Cr. near Greenview	1,804	1941-present
CD5	05572000	Sangamon near Monticello	550	1914-present
CD6	05587000	Macoupin near Kane	868	1921-33;1940-present
CD7	03379500	Little Wabash near Clay City	1,131	1914-present
CD8	03612000	Cache near Forman	244	1922-present
CD9	03380500	Skillet Fork near Wayne City	464	1914-21;1928-present

Examining the Impact of Tropical System Precipitation on Streamflow

Discharge data in feet per second from the USGS-NSIP (2014) were gathered for the day before and the last day of each tropical system passage in Illinois. These values were then compared to assess the impact of tropical systems on streamflow (ST) in Illinois. Average differences in post-tropical storm ST minus pre-tropical storm ST values were compared for two groups of watersheds, those that were impacted by a tropical system event (CD that experienced >2.54 cm per day rainfall from a tropical system) and those that were not.

Identifying Factors Contributing to Changes in Streamflow

Further multi-regression analysis was performed to assess the importance of antecedent soil moisture conditions, storm total rainfall, maximum 24-hour rainfall, basin size, time of year, days the tropical system was over Illinois, and the mean amount of rain per day produced by these systems. These variables were used to ascertain whether a predictive model could be developed to forecast potential tropical system-related ST for the state and the selected watersheds.

Chapter 3. Results

Descriptive Results: Impact of Tropical Precipitation on Selected Watersheds

Streamflow characteristics associated with the 26 tropical system events were evaluated individually for each watershed and averaged across the state. Each of these tropical system events evolved differently but all tracked from the Gulf of Mexico toward the eastern Midwest (Haberlie et al. 2014). The most recent tropical system was associated with Hurricane Isaac in 2012. Figures 2 and 3 show the rain bands associated with the remnants of Isaac as the tropical system began to impact parts of Illinois. This tropical system spent approximately two days over the Midwest. Figure 4 shows how precipitation associated with Isaac impacted the selected Illinois watersheds, especially those in CD 3-9. Although most watersheds in the southern three-quarters of Illinois exhibit a large response to the heavy rainfall associated with Isaac's remnants, the ST response appears to vary significantly from one watershed to another. The percent change in ST values were very large primarily due to the drought conditions experienced at the time of tropical system rainfall.

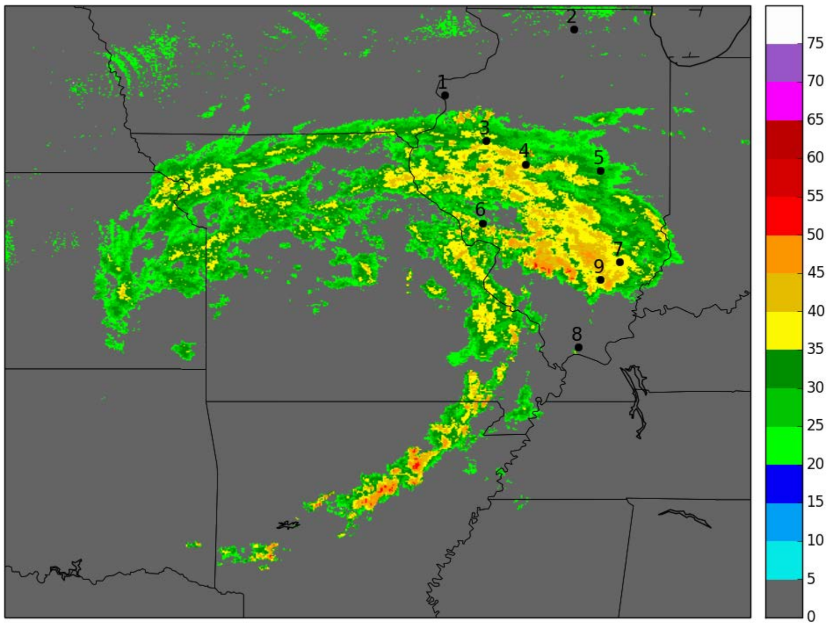

Figure 2. Radar image valid 1 Sep 2012 at 12:00 am CST.

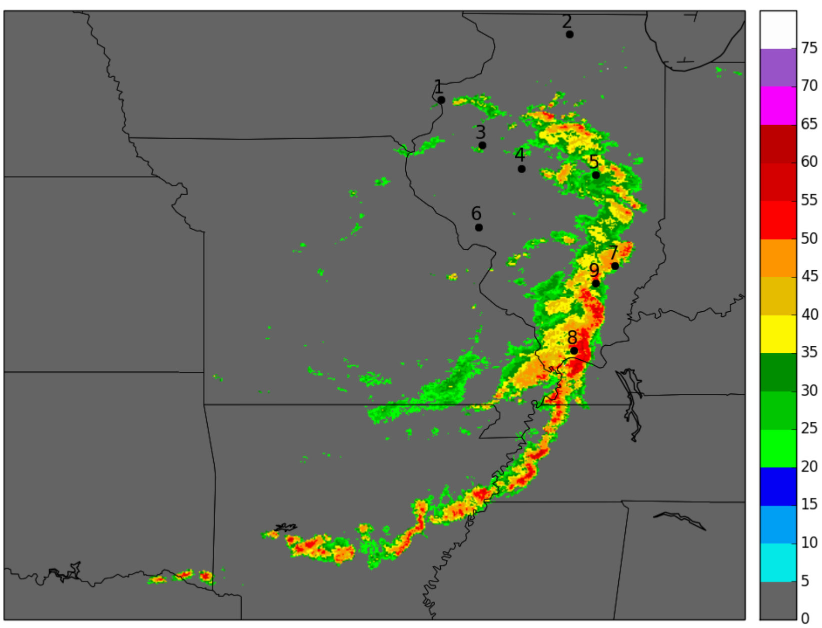

Figure 3. Radar image valid 1 Sep 2012 at 8:00 pm CST

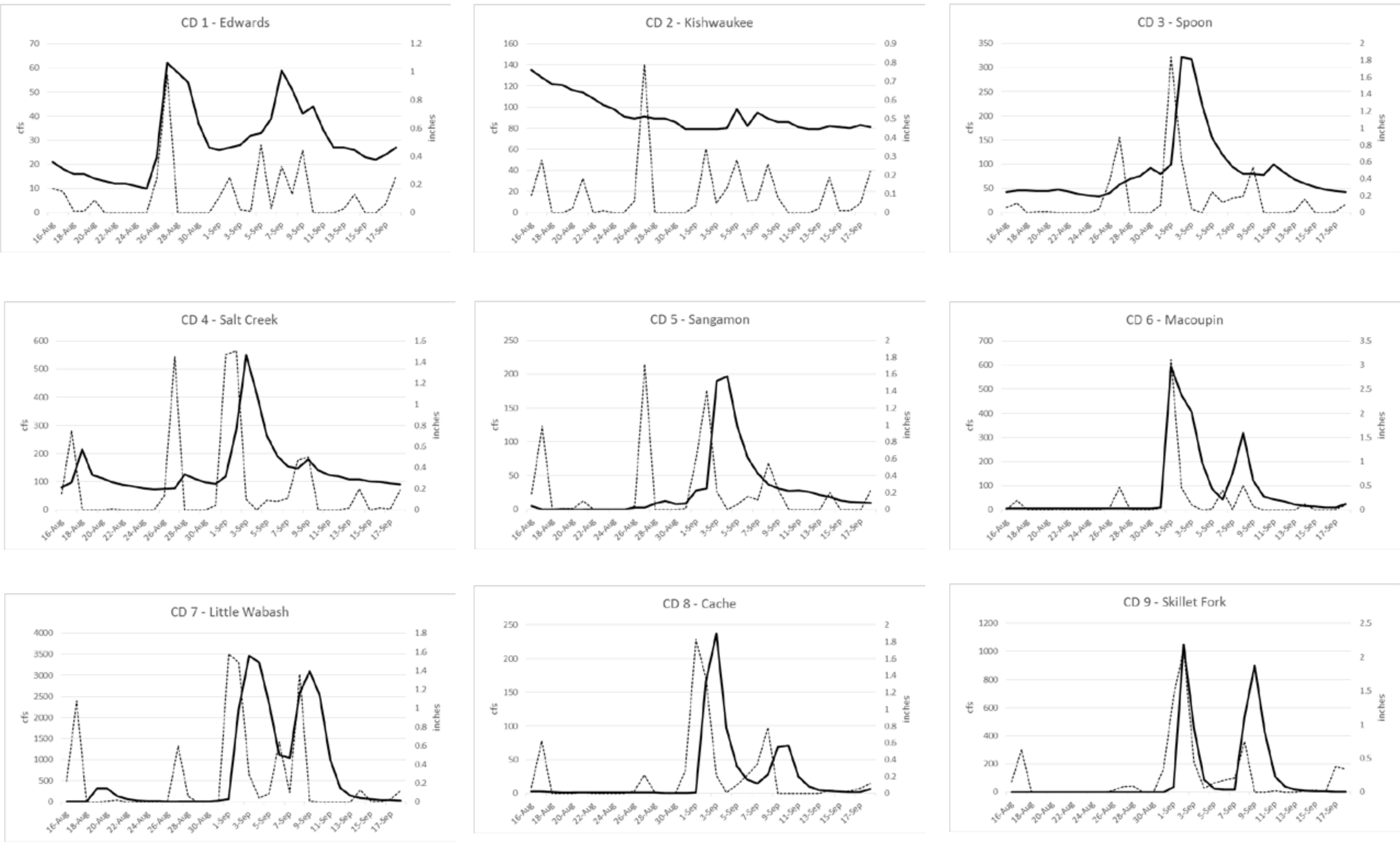

Figure 4. Streamflow (solid) and precipitation (dotted) for the two weeks before and after Hurricane Isaac traversed over Illinois in late August and early September of 2012. Second streamflow spike in CDs 6-9 was from synoptic frontal passage on 8 September 2012.

When examined at the watershed scale, the percent change in ST (post tropical system ST minus pre tropical system ST) depended greatly on whether the watershed was impacted by a tropical system event (>2.54 cm per day in that CD). For example, the Sangamon (CD5) experienced an average 38% increase in ST for non-events (i.e., CD did not experience >2.54 cm per day) with five cases when the ST actually decreased and nine cases with an increase (maximum increase in non-event was 164%), while during events the average ST increased 866% with increases ranging from 24% (1949 #10 event) to 2305% for Isaac.

The relationship of CD storm total rainfall to percent change in ST in each of the nine CDs for the 26 tropical storms was examined (Table 3). R-squared values ranged from 0.26 to 0.85 and were statistically significant (p-value <0.0051) for eight of nine watersheds (only the Macoupin River in CD 6 did not exhibit a statistically significant r-squared value). The relationships were higher in the northern half of the state.

Table 3. R-squared and p-values between CD storm total rainfall to percent change in streamflow for the nine Illinois CDs/Watersheds.

CD/Watershed	R-squared Value	p-value
1/Edwards	0.83	<0.0001
2/Kishwaukee	0.70	<0.0006
3/Spoon	0.70	<0.0001
4/Salt Cr.	0.85	<0.0001
5/Sangamon	0.72	<0.0001
6/Macoupin	0.26	0.244
7/Little Wabash	0.53	0.0051
8/Cache	0.64	0.001
9/Skillet Fork	0.63	0.0011

Hydro-climatic variables for each of the 26 tropical systems were examined (Table 4). Isaac's storm rainfall total (i.e., statewide average of 2.69 inches) was the highest and occurred during the most extreme drought conditions (i.e., statewide average PDSI value of -3.69), thus produced the most dramatic statewide change in streamflow (i.e., 50,483%) despite an actual increase of only 597 cfs (ninth highest value). Hurricane Carla produced the greatest estimated statewide rainfall rate of .13 in hr $^{-1}$ (Table 4). Since tropical systems typically spend at least a day over the Midwest, the statewide rainfall rates noted in Table 4 indicate that these systems produce large amounts of precipitation (>2.54 cm per day) over many hours. The average rainfall duration associated with tropical systems is longer than that for MCS events and contributes to very different hydrologic characteristics.

Table 4. State averages for each storm. *Hours in region based on 6 hour resolution of HURDAT database.

Storm	Preceding PDSI	Storm Total (in)	Hours in Corn Belt*	Inches Per Hour*	Percent Event CDs	CFS change	Percent CFS Change
Isaac	-3.69	2.69	24	0.11	78%	597	50483
1941-2	-2.86	1.05	24	0.04	38%	243	7661
1932-3	0.47	1.23	36	0.03	17%	530	6002
Betsy	1.14	0.82	30	0.03	22%	188	3167
1948-5	-0.41	0.66	30	0.02	22%	119	2635
Candy	0.31	2.41	24	0.10	89%	1531	2078
Carla	1.04	2.41	18	0.13	67%	1419	1944
1926-1	-0.20	1.01	42	0.02	20%	487	1844
Audrey	1.42	1.32	18	0.07	33%	2848	1794
1923-9	0.59	1.06	30	0.04	80%	1140	1342
1947-2	-0.82	0.75	6	0.12	11%	195	1096
1949-10	-0.38	0.98	18	0.05	44%	681	916
Gustav	2.02	1.95	30	0.07	56%	350	571
1915-2	2.34	1.71	54	0.03	75%	11899	523
Ike	2.02	2.43	24	0.10	67%	4235	496
Baker	2.14	0.45	12	0.04	22%	295	314
Dennis	-2.28	1.22	144	0.01	22%	18	291
Claudette	0.33	0.94	30	0.03	22%	1125	288
Arlene	-1.57	0.55	42	0.01	11%	93	266
1923-8	0.69	0.99	12	0.08	67%	106	171
Rita	-2.05	0.59	12	0.05	11%	18	116
1916-14	-0.94	0.59	12	0.05	0%	4.2	68
Ethel	0.35	0.24	12	0.02	11%	9	12
Bob	0.33	1.97	42	0.05	11%	-5	9
1955-5	-1.65	0.58	12	0.05	11%	2	-2.94
Katrina	-2.23	0.32	18	0.02	11%	-7	-5.8

Predictive Model

The relationships between hydro-climatic variables that were considered to influence ST (e.g., basin size, time of year of occurrence, soil moisture conditions as measured with PDSI, etc.) and the average pre-/post- change in ST for the 26 events were examined. The strongest relationship revealed by the statewide averages was between preceding PDSI and ST change, but only when preceding PDSI was positive (Figure 5; $r^2 = .31$, $p = .03$). This suggests that as statewide soil moisture increases, the average change in ST (associated with a tropical system) will linearly increase, but only in moist (positive PDSI) soil moisture conditions, regardless of rainfall amount.

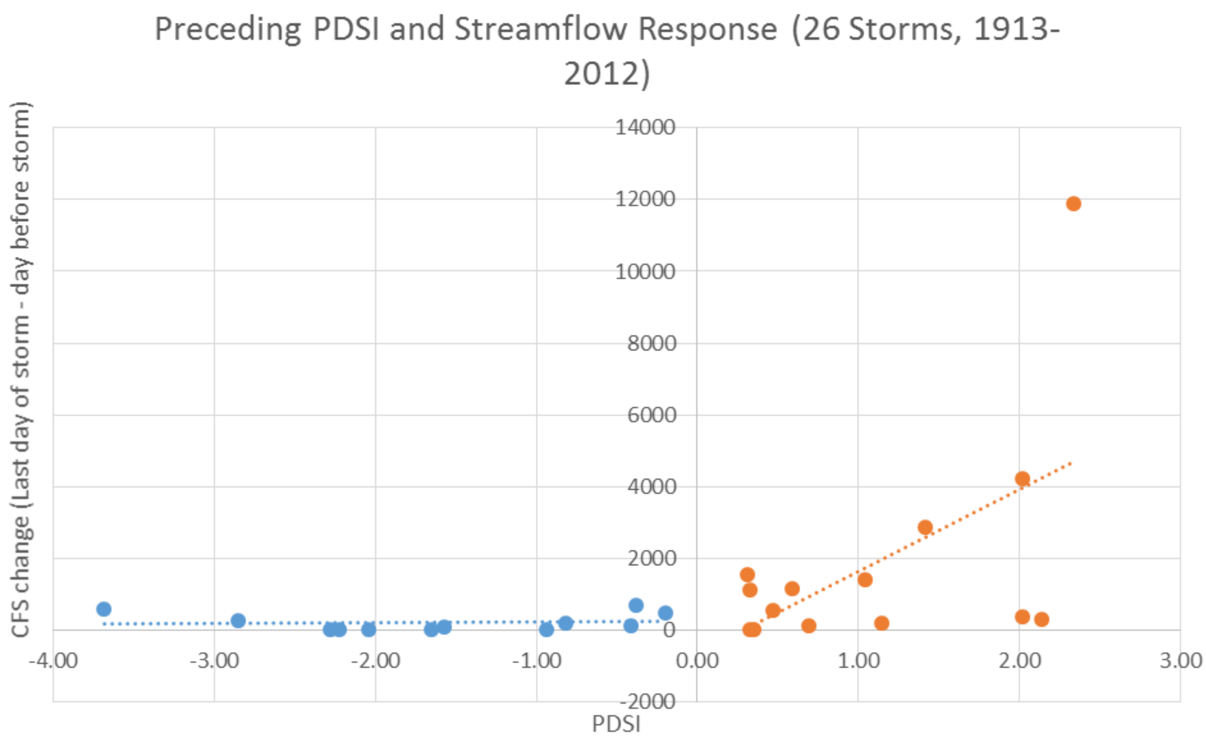

Figure 5. Preceding PDSI value to change in statewide change in streamflow for 26 tropical cyclones (1913-2012).

In developing a generalized model that could predict ST response to tropical system rainfall, we examined CD specific data for each storm. An unexpected result was the extreme responses to tropical system rainfall. Of specific interest was the data for CD 9 when Isaac traversed the state.

On August 31st, the daily average ST on the Skillet Fork at Wayne City (CD9) was at 0.12 cfs. Just two days later, rainfall from Isaac caused the Skillet Fork to swell to a daily average ST of 1050 cfs—a near-record daily ST value and a positive percentage change of 374,000% (USGS 2012). Isaac was associated with the largest statewide percent change in ST among the 26 tropical systems (Table 4) and when examining the largest percent changes in daily average ST by CD four of the top 20 changes were associated with Isaac (Table 5). Upon further inspection of Table 5, other tropical systems are noted more than once suggesting that these extreme precipitation events impact broad areas of Illinois, not generally one CD. Furthermore, these results indicate that extreme, multi-day, heavy rainfall events associated with tropical systems can increase average daily ST significantly. This may be especially true in late summer when daily average ST in Illinois rivers can be at its lowest levels in the warm-season.

Table 5. Top 20 percent change magnitude increases in daily average streamflow associated with tropical systems.

Storm	CD	Basin Size	StormTotal	Max Day	Event	PriorPDSI	Day of Year	Days	Per Day	ChangeCFS	PercentChange
"Isaac"	9	464	4.44	2.11	1	-3.66	245	4	1.11	448.88	374066.67
"1941-2"	6	868	1.85	1.05	1	-2.77	267	2	0.93	1008.30	59311.76
"Isaac"	7	1131	3.41	1.58	1	-3.81	245	4	0.85	3451.20	39218.18
"Isaac"	8	244	3.72	1.83	1	-3.93	245	4	0.93	236.21	29900.00
"Betsy"	8	244	2.34	1.25	1	0.59	254	2	1.17	1474.00	24566.67
"1932-3"	9	464	2.95	1.52	1	0.55	247	3	0.98	288.70	22207.69
"1948-5"	8	244	1.76	1.14	1	0.70	249	2	0.88	572.50	16357.14
"1932-3"	7	1131	1.95	0.96	0	0.44	247	3	0.65	1767.00	13592.31
"Carla"	1	445	5.07	3.28	1	-0.39	256	2	2.54	2268.00	10309.09
"Candy"	8	244	1.06	1.05	1	0.67	177	2	0.53	438.60	9968.18
"Isaac"	6	868	3.73	3.11	1	-4.01	245	4	0.93	401.10	8185.71
"Audrey"	9	464	0.99	0.93	0	2.03	179	2	0.50	2024.00	7784.62
"1948-5"	9	464	2.15	1.30	1	0.78	249	2	1.08	564.40	7426.32
"1926-1"	7	1131	1.05	0.47	0	-0.58	213	3	0.35	373.00	6216.67
"Audrey"	6	868	2.66	2.65	1	1.96	179	2	1.33	16790.00	5416.13
"1947-2"	1	445	1.12	1.12	1	-0.89	264	1	1.12	949.00	4745.00
"Candy"	9	464	1.32	1.22	1	0.53	177	2	0.66	391.50	4121.05
"1947-2"	6	868	0.71	0.71	0	-1.77	264	1	0.71	277.20	4076.47
"1923-9"	7	1131	1.54	1.48	1	0.50	291	2	0.77	666.00	3700.00
"Betsy"	9	464	3.40	1.77	1	0.32	254	2	1.70	835.00	3630.43

Table 6 shows the correlation between values from every climate division. Per Day, Storm Total, and Max Day are all strongly correlated. Thus, the final regression variables, chosen for their non-collinearity, are Storm Total (total rainfall per event per CD), prior PDSI (PDSI monthly value before the event), Day of Year (Days since January 1st), and Days (Count of days tropical system was in the region).

Table 6. Correlation matrix comparing possible regression variables.

	PercentChange	StormTotal	Max Day	PriorPDSI	Day of Year	Days	Per Day
PercentChange	1.0000	0.2849	0.1685	-0.1398	0.0267	0.1139	0.0867
StormTotal	0.2849	1.0000	0.9368	0.1343	-0.0321	0.1873	0.8359
Max Day	0.1685	0.9368	1.0000	0.2124	-0.0265	0.0460	0.8844
PriorPDSI	-0.1398	0.1343	0.2124	1.0000	-0.0030	-0.2867	0.2979
Day of Year	0.0267	-0.0321	-0.0265	-0.0030	1.0000	-0.4628	0.1602
Days	0.1139	0.1873	0.0460	-0.2867	-0.4628	1.0000	-0.2173
Per Day	0.0867	0.8359	0.8844	0.2979	0.1602	-0.2173	1.0000

The generalized statewide regression model performed poorly ($r^2 = 0.11$) when predicting percent change in ST. This is likely caused by a heterogeneous response to tropical system rainfall in Illinois due to differences in soil types, geomorphology, site to site base flow, and year to year base flow and the fact that no one tropical system impacted all 9 CDs. We then addressed these issues by examining ST response in each basin separately (Table 7).

Table 7. Regression and coefficient results for each climate division.

	Storm Total		Prior PDSI		Day of Year		Days		Overall	
CD	p-value	parameter	p-value	parameter	p-value	parameter	p-value	parameter	p-value	r2
1	< 0.001	411.43	0.4	-29.1375	0.56	1.24	0.73	-19.4	< 0.001	0.79
2	0.002	494.4	0.11	129.45	0.56	2.81	0.56	72.49	0.007	0.58
3	< 0.001	1667.19	0.24	217.83	0.24	-13.25	0.51	-215.02	< 0.001	0.62
4	0.06	994.18	0.27	359.57	0.83	3.86	0.93	44.36	0.09	0.41
5	0.007	690.58	0.21	154.74	0.9	-0.72	0.78	-51.96	0.003	0.52
6	0.003	1969.85	0.19	417.76	0.11	-33.61	0.18	-806.03	0.007	0.53
7	0.07	3127.73	0.49	448.52	0.73	13.76	0.83	258.56	0.21	0.24
8	0.1	192.77	0.08	84.54	0.18	4.12	0.92	-10.59	0.1	0.34
9	0.62	348	0.12	532.6	0.85	4.25	0.64	327.53	0.57	0.14

Regression for individual CDs/watersheds explained more variability than the statewide model with the prediction model explaining 50 percent or more of the variance in five of the 9 CDs (Table 7). However, performance decreased with the southernmost CDs. Only Storm Total significantly explained percent change in ST, with values ranging from a 411% to 1970% increase in ST per inch or rain associated with the tropical systems.

Chapter 4. Conclusions, Implications, and Recommendations

Summary of Motivation and Exploratory Results

This research project examined the influence of tropical system precipitation on ST response in nine watersheds located within Illinois' nine climate divisions (CDs). A statistically significant percent change in streamflow was found for those watersheds experiencing a tropical system event (i.e., CD experiencing >2.54 cm per 24-hour period) versus those that don't. When the monthly PDSI value prior to the tropical system was average or above (i.e., generally wet soil moisture conditions), there was a linear relationship between pre-event PDSI and actual change in ST. In other words, the wetter the soil moisture conditions were prior to the event the larger the ST response. When soil moisture conditions were dry (negative PDSI values) the actual change in streamflow levels was small. This descriptive information may be useful to those faced with preparing for a relatively infrequent tropical system heavy precipitation event.

Summary or Implications for Forecasters and Decision Makers

Statewide average ST response to tropical systems is poorly predicted by surface-based observations alone. The best predictor of percent change in ST in each CD was storm total precipitation amount. This relationship had R-squared values that exceeded 0.52 in all but CD6 (Table 3). Furthermore, when all the variables were evaluated in a multi-regression model more than 50 percent of the variance was explained in CD 1-3 and 5 and 6. Although regression analysis did not find a clear predictive tool for hydro-meteorologists tasked with forecasting post storm ST, four factors enhance the opportunity to improve short-term forecasts in Illinois including 1) greater forecast warning time (i.e., typically one to three days for tropical systems versus two to six hours for MCSs), 2) heavy precipitation and related high ST values will impact a larger region (i.e., tropical systems impact 3.8 CDs on average where MCSs impact less area), 3) under wet soil moisture conditions, the actual increase in ST is much greater, and 4) the more total precipitation expected from the tropical system, the larger the percent change in ST.

Limitations of Results

The lack of stronger predictive relationships is attributed to a number of factors. Importantly, these watersheds exist in parts of Illinois with very different surface soils and geomorphologies. Differences in basin characteristics such as basin size and shape impact the ST results. Finally, a small sample size (i.e., only 26 tropical storms in 100 years), changes in land cover (e.g., urbanization, farming in floodplains, etc.) and changing agricultural practices (e.g., types of row crops planted, post-harvest tilling of the surface, frequent updates to underground tiling systems, etc.) limit the ability to find commonality among these watersheds. Despite these limitations it appears that results from this study can provide additional information to those involved with predicting hydro-meteorological responses from tropical systems.

Recommendations for Future Studies

A more detailed study of these watersheds, their changing characteristics and man’s influence on ST response to precipitation events such as tropical systems would potentially yield a better predictive model. A comparison of ST response to MCSs (i.e., shorter duration heavy precipitation events) versus tropical system events might shed further light on differences in hydrographs associated with the two types of events. This knowledge could then be integrated more fully into National Weather Service hydrologist forecasts, especially when tropical system events are expected one to three days in advance. Finally, we suggest that other watersheds in the eastern Midwest be assessed to expand the tropical system event sample size.

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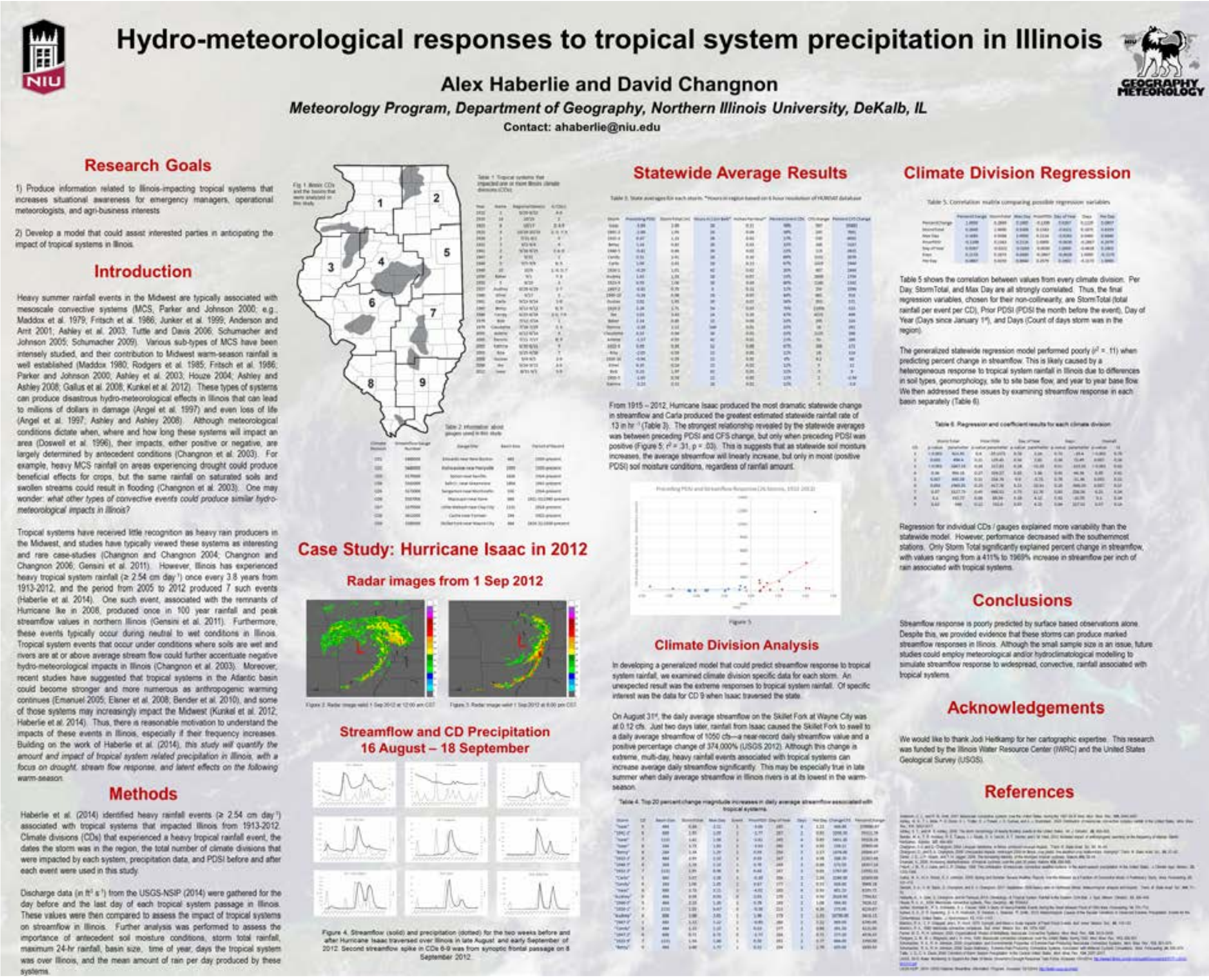
Appendices


Hydro-meteorological responses to tropical system precipitation in Illinois
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