

Southeast Michigan Current and Future Precipitation

Climate Resiliency and Flooding Mitigation Study

PRESENTED TO

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EXECUTIVE SUMMARY

The precipitation frequency estimates can be expressed as an equation to ease computational analysis. Nine common IDF equations were assessed for use in the southeast Michigan. The equation form that fit the present-day rainfall amounts the best and which includes the return period (T) in the equation is presented below. The table following summarizes county specific coefficients for the equation. The last row for SEMCOG represents an average for the seven counties.

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where i = intensity (inches per hour)
 t = duration (minutes)
 T = return period (years)

County	b	c	α	β
Livingston	7.0126	0.8334	37.0610	0.2240
Macomb	6.1276	0.8283	34.7452	0.2230
Monroe	5.7330	0.8299	35.8845	0.2136
Oakland	6.2760	0.8274	35.7367	0.2231
St. Clair	6.5744	0.8296	34.8230	0.2268
Washtenaw	5.7958	0.8301	35.9288	0.2172
Wayne	5.8249	0.8300	35.7204	0.2165
SEMCOG	6.1765	0.8295	35.6627	0.2208

Some hydrological computational methods require a temporal rainfall distribution. A temporal rainfall distribution describes how the rainfall intensity varies with time during a storm event. Traditionally within Michigan the NRCS (SCS) Type II distribution has been used. The Type II distribution was developed based on the National Weather Service *Technical Paper (TP-40) Rainfall Frequency Atlas of the United States*. The NRCS Type II distribution has been replaced with the NRCS Midwest-Southeast (MSE) Type 3 rainfall distribution based on updated rainfall precipitation frequency estimates. The MSE Type 3 distribution is recommended for sizing stormwater conveyance and storage infrastructure.

Less commonly used in Michigan is the Huff distribution which is based on actual rainfall events instead of nesting statistical intensities. The current version of the Precipitation-Frequency Atlas of the United States (NOAA Atlas 14) Volume 8: Midwestern States includes temporal distributions for 6-, 12-, 24-, and 96-hour durations. The methodology used to produce the temporal distributions is like the one developed by Huff. The Atlas 14 distribution should be used in place of the Huff distribution. This distribution results in lower intensity rainfall and is appropriate for use when design infrastructure that is reliant on commonly occurring events such as green infrastructure.

An analysis was conducted looking at the changes to precipitation frequency estimates due to climate change. The analysis evaluated data from eight NOAA weather stations in the region and used six dynamically downscaled climate projections created via a Regional Climate Model (RCM) as part of the Great Lakes Ensemble Project. The analysis was based on Representative Concentration Pathway (RCP) 8.5 which assumes greenhouse gas emissions continue to rise throughout the 1st century. Two future time periods were considered, mid-century (2040-2059) and end of the century (2080-2099). The table below summarizes the median predicted value from the six climate models and with the range of values. For example, the weather station in Ann Arbor

(20-0230) has mid-century projected median value of 5.08-inches for the 10-year 24-hour event and the data results for the six climate models ranged from 3.76- to 6.69-inches.

Stations	Flow Conveyance 10-year 24-hour			Flood Control 25-year 24-hour			Flood Control 100-year 24-hour		
	Base Atlas 14	Mid- Century	End-of- Century	Base Atlas 14	Mid- Century	End-of- Century	Base Atlas 14	Mid- Century	End-of- Century
Ann Arbor UM 20-0230	3.26 (2.93-3.65)	5.08 (3.76-6.69)	4.97 (3.74-7.38)	3.93 (3.46-4.58)	6.16 (3.90-9.00)	5.62 (4.50-11.07)	5.11 (4.23-6.13)	8.64 (4.02-15.06)	6.72 (5.14-20.77)
Detroit City Airport 20-2102	3.28 (2.83-3.84)	5.04 (4.61-6.04)	5.72 (3.71-8.03)	3.96 (3.32-4.80)	5.90 (4.88-8.10)	7.14 (3.83-11.92)	5.12 (4.02-6.38)	7.72 (4.97-13.28)	8.85 (3.92-21.22)
Detroit Metro Airport 20-2103	3.31 (2.91-3.78)	6.04 (3.31-6.94)	6.46 (2.79-8.05)	3.98 (3.42-4.71)	6.86 (3.35-10.20)	8.14 (2.81-10.22)	5.15 (4.17-6.24)	8.04 (3.38-18.65)	11.41 (2.82-14.90)
Howell WWTP 20-3947	3.33 (2.90-3.78)	5.42 (4.76-6.30)	5.05 (4.12-6.20)	4.05 (3.46-4.83)	6.49 (5.58-8.81)	6.98 (4.35-7.46)	5.36 (4.30-6.60)	8.60 (6.79-15.66)	8.57 (4.57-15.21)
Milford GM 20-5452	3.35 (2.92-3.82)	4.81 (3.95-5.86)	4.65 (3.63-5.30)	4.06 (3.46-4.83)	6.82 (5.34-8.56)	6.22 (4.51-7.50)	5.33 (4.28-6.51)	11.04 (7.66-15.01)	8.33 (6.12-17.16)
Pontiac WWTP 20-6658	3.39 (2.90-3.95)	5.07 (3.63-5.58)	5.96 (4.55-9.33)	4.11 (3.44-4.97)	6.56 (3.75-6.89)	8.17 (5.52-12.78)	5.36 (4.22-6.65)	8.87 (3.85-10.63)	11.12 (7.23-19.52)
Wayne – Canton 76-0065	3.30 (2.73-4.00)	5.64 (3.10-6.39)	6.02 (2.61-7.58)	3.98 (3.22-4.98)	6.51 (3.15-9.39)	7.61 (2.62-9.64)	5.15 (3.92-6.60)	7.66 (3.17-17.36)	10.82 (2.62-14.24)
Ypsilanti EMU 20-9218	3.26 (2.91-3.70)	4.40 (3.35-5.64)	4.12 (3.27-6.29)	3.93 (3.41-4.65)	5.27 (3.55-7.43)	4.55 (4.05-9.50)	5.11 (4.14-6.24)	7.35 (3.76-12.22)	5.71 (4.76-18.15)
Region Average	3.31 (2.77-3.95)	5.2 (3.8-6.2)	5.4 (3.6-7.3)	4.01 (3.28-4.97)	6.3 (4.2-8.5)	6.8 (4.0-10.0)	5.24 (4.05-6.66)	8.5 (4.7-14.7)	8.9 (4.6-17.6)

TABLE OF CONTENTS

1.0 PRECIPITATION FREQUENCY	1
1.1 Atlas 14	1
1.2 Intensity-Duration Frequency Equations.....	2
Livingston County.....	5
Macomb County	6
Monroe County.....	7
Oakland County	8
St. Clair County	9
Washtenaw County	10
Wayne County.....	11
SEMCOG Region.....	12
2.0 TEMPORAL RAINFALL DISTRIBUTIONS	13
2.1 NRCS (SCS) Type II	13
2.2 NRCS MSE	13
2.3 Huff.....	14
2.4 Atlas 14	15
2.5 Distribution Comparison.....	15
2.6 MSE 3 Distribution Details	16
3.0 FUTURE RAINFALL	19
4.0 REFERENCES	22

LIST OF TABLES

Table 1 IDF Functions	3
Table 2 Coefficients for Equation 5 Kimijima Equation	3
Table 3 Coefficients for Equation 9	4
Table 4 NRCS Distribution Coefficients.....	17
Table 5 MSE3 Tabular Data	18
Table 6 Future Rainfall Summary.....	19
Table 7 Mid-Century Average Regional Rainfall (in).....	20
Table 8 End of Century Average Regional Rainfall (in).....	21
Table 9 Coefficients for Equation 9	21

LIST OF FIGURES

Figure 1 10-year, 24-hour Isohytal Map for SEMCOG Region	1
Figure 2 Temporal Distribution Comparison.....	16
Figure 3 Comparison of Tabular Data and Equation.....	17

APPENDICES

APPENDIX A – PRECIPITATION IDF UNDER FUTURE CLIMATE	23
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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
EMU	Eastern Michigan University
GM	General Motors
IDF	Intensity Duration Frequency
MDOT	Michigan Department of Transportation
MSE	Midwest South-East
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PFDS	Precipitation Frequency Data Server
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SCS	Soil Conservation Service
SEMCOG	Southeast Michigan Council of Governments
UM	University of Michigan
WWTP	Wastewater Treatment Plan

1.0 PRECIPITATION FREQUENCY

The current state of the art rainfall information comes from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) and is published in *Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013)*, for Michigan. The website for the Hydrometeorological Design Studies Center's precipitation frequency data server information is <https://hdsc.nws.noaa.gov/hdsc/pfds/index.html>. The Precipitation Frequency Data Server (PFDS) is a point-and-click interface developed to deliver precipitation frequency estimate and associated information. Users identify a location where precipitation frequency estimates are desired and may view the site-specific information in a tabular or graphical format.

1.1 ATLAS 14

Rainfall statistics vary slightly across the counties and region. Figure 1 illustrates the variation across the region for the 10-year 24-hour storm in the form of an isohyetal map. An isohyet (or isohyetal) is a line on a map which connects points that have the same amounts of precipitation in each period or for a particular storm. Upon close inspection of the map data, the average 10-year 24-hour rainfall event total varies across the region from a low in St. Clair County of 3.245-inches and a low in Washtenaw County of 3.255-inches to a high in Oakland County of 3.412-inches, i.e. a maximum variation of 0.167-inches.

While the site-specific information is useful, it does not promote the use of consistent rainfall data across a political jurisdiction. Average rainfall depths for different frequencies were computed for each county and for the SEMCOG region (the seven counties together). Results are presented in subsequent sections for each county and the region beginning on page 6.

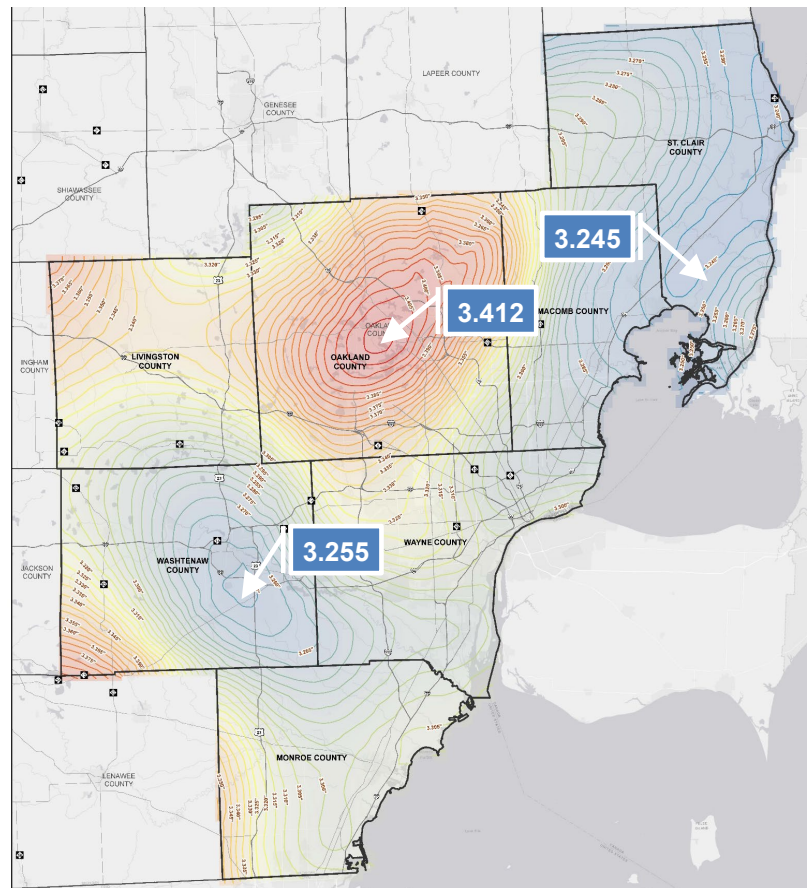


Figure 1 10-year, 24-hour Isohyetal Map for SEMCOG Region

1.2 INTENSITY-DURATION FREQUENCY EQUATIONS

The precipitation frequency estimates can be expressed as an equation to ease computational analysis and to avoid estimating the Intensity Duration Frequency (IDF) graphically. There are various IDF equations used around the world, and in a paper titled *Relative Performance of Intensity-Duration-Frequency Functions*, David Chin identifies the nine most common functions. The first 5 equations below, are functions for individual return periods where the rainfall intensities, i (inches per hour), correspond to the storm duration, t (minutes). These equations also have regional coefficients which include a , b , c , or n . The last four equations below are functions with the return period T (years) with regional coefficients that include α , β , b and c .

$$i = \frac{a}{(t + b)^c} \quad \text{Sherman Equation} \quad (\text{Equation 1})$$

$$i = \frac{a}{t + b} \quad \text{Talbot Equation} \quad (\text{Equation 2})$$

$$i = \frac{a}{t^n} \quad \text{Bernard Equation} \quad (\text{Equation 3})$$

$$i = \frac{a}{\sqrt{t} + b} \quad \text{Ishiguro Equation} \quad (\text{Equation 4})$$

$$i = \frac{a}{t^c + b} \quad \text{Kimijima Equation} \quad (\text{Equation 5})$$

$$i = \frac{\alpha + \beta \log T}{(t + b)^c} \quad (\text{Equation 6})$$

$$i = \frac{\alpha T^\beta}{(t + b)^c} \quad (\text{Equation 7})$$

$$i = \frac{\alpha + \beta \log T}{t^c + b} \quad (\text{Equation 8})$$

$$i = \frac{\alpha T^\beta}{t^c + b} \quad (\text{Equation 9})$$

For each county and equation, coefficients were developed. A logarithmic analysis was used to minimize the relative errors in the functions. The relative error for each equation is included in Table 1.

Table 1 IDF Functions

Equation No.	Livingston	Macomb	Monroe	Oakland	St. Clair	Washtenaw	Wayne	SEMCOG
<i>Functions for Individual Return Periods</i>								
1	3.0%	2.4%	1.9%	2.7%	2.8%	2.2%	2.1%	2.5%
2	9.6%	10.0%	10.0%	10.1%	9.8%	10.0%	10.0%	9.9%
3	11.8%	11.0%	10.5%	11.2%	11.4%	10.7%	10.7%	11.0%
4	30.5%	31.5%	32.9%	30.9%	30.6%	32.7%	32.7%	31.6%
5	2.4%	1.8%	1.3%	2.1%	2.1%	1.7%	1.5%	1.9%
<i>Functions with Return Periods</i>								
6	4.6%	3.8%	3.5%	4.2%	4.4%	4.0%	3.5%	4.0%
7	3.5%	3.0%	2.5%	3.2%	3.2%	2.9%	2.6%	3.0%
8	4.3%	3.5%	3.2%	3.8%	4.1%	3.6%	3.2%	3.7%
9	3.0%	2.6%	2.2%	2.8%	2.7%	2.5%	2.2%	2.6%

For the functions with individual return periods, the Kimijima Equation has the smallest relative error for the seven counties and overall region; thus, it most accurately models the region rainfall data. The coefficients for each return period were calculated for this equation and are included in Table 2.

Table 2 Coefficients for Equation 5 Kimijima Equation

County	Coeff	Recurrence Interval						
		1-year	2-year	5-year	10-year	25-year	50-year	100-year
Livingston	a	29.4903	38.6632	54.2372	67.2104	84.6905	97.7272	110.3618
	b	4.8931	5.8236	6.9476	7.5632	8.0632	8.2532	8.3274
	c	0.7967	0.8173	0.8370	0.8450	0.8485	0.8476	0.8447
Macomb	a	28.0478	36.7741	51.2136	62.9718	78.4697	89.7805	100.5188
	b	4.5050	5.2689	6.1295	6.5679	6.8875	6.9807	6.9845
	c	0.7941	0.8136	0.8317	0.8389	0.8419	0.8409	0.8380
Monroe	a	30.8499	38.7882	51.8013	62.4156	76.6386	87.2822	97.6749
	b	4.6751	5.1013	5.6158	5.9144	6.2032	6.3617	6.4851
	c	0.8055	0.8203	0.8337	0.8384	0.8396	0.8378	0.8347
Oakland	a	28.6338	37.6196	52.6111	64.8674	81.0622	92.9019	104.1957
	b	4.4799	5.2974	6.2514	6.7535	7.1393	7.2691	7.3039
	c	0.7920	0.8125	0.8315	0.8389	0.8417	0.8403	0.8370
St. Clair	a	28.2697	36.6215	50.8705	62.9200	79.5362	92.2758	104.9271
	b	4.8135	5.5674	6.4731	6.9785	7.4139	7.6051	7.7103
	c	0.7955	0.8137	0.8315	0.8391	0.8433	0.8435	0.8420

County	Coeff	Recurrence Interval						
		1-year	2-year	5-year	10-year	25-year	50-year	100-year
Washtenaw	a	28.8228	37.1863	51.4197	63.4425	80.0166	92.7301	105.3809
	b	4.0637	4.7286	5.5821	6.1111	6.6435	6.9427	7.1746
	c	0.7941	0.8131	0.8319	0.8401	0.8449	0.8453	0.8441
Wayne	a	30.2583	38.3272	51.6817	62.6665	77.4635	88.5568	99.3732
	b	4.6412	5.1798	5.7903	6.1069	6.3560	6.4470	6.4791
	c	0.8034	0.8181	0.8321	0.8378	0.8406	0.8402	0.8384
SEMCOG	a	29.1190	37.6377	51.9134	63.7329	79.6689	91.6084	103.2360
	b	4.5565	5.2575	6.0914	6.5514	6.9423	7.1112	7.2012
	c	0.7969	0.8151	0.8324	0.8395	0.8427	0.8421	0.8397

For the functions with return period T, Equation 9, has the smallest relative error for the seven counties and overall region. The coefficients for each county for this equation are shown in Table 3.

Table 3 Coefficients for Equation 9

County	b	c	α	β
Livingston	7.0126	0.8334	37.0610	0.2240
Macomb	6.1276	0.8283	34.7452	0.2230
Monroe	5.7330	0.8299	35.8845	0.2136
Oakland	6.2760	0.8274	35.7367	0.2231
St. Clair	6.5744	0.8296	34.8230	0.2268
Washtenaw	5.7958	0.8301	35.9288	0.2172
Wayne	5.8249	0.8300	35.7204	0.2165
SEMCOG	6.1765	0.8295	35.6627	0.2208

Equation 5 and Equation 9 both suitably predict the precipitation frequency information from NOAA Atlas 14. For ease of use and simplicity purposed, Equation 9 is recommended over Equation 5. This is because only a single set of coefficients are needed, which simplifies the calculations.

LIVINGSTON COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	7.0126	0.8334	37.0610	0.2240
90% Confidence Interval Lower	6.3474	0.8190	29.1879	0.2091
90% Confidence Interval Upper	7.8952	0.8471	45.9279	0.2453

Regression equation rainfall →

<i>Atlas 14 county-wide average rainfall</i> →	0.71	0.68
<i>Atlas 14 90% confidence interval</i> →	0.56 – 0.89	

Tabular Precipitation Frequency Estimates Rainfall Total (in)

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.30	0.28	0.35	0.33	0.44	0.41	0.51	0.48	0.62	0.59	0.71	0.68	0.80	0.80
	0.25 - 0.35		0.29 - 0.41		0.37 - 0.52		0.43 - 0.62		0.50 - 0.77		0.56 - 0.89		0.61 - 1.02	
10-min	0.43	0.45	0.51	0.52	0.64	0.64	0.75	0.75	0.91	0.92	1.04	1.07	1.17	1.25
	0.36 - 0.52		0.43 - 0.61		0.54 - 0.76		0.63 - 0.90		0.74 - 1.13		0.82 - 1.30		0.89 - 1.50	
15-min	0.53	0.56	0.62	0.65	0.78	0.80	0.92	0.94	1.11	1.15	1.27	1.34	1.43	1.57
	0.44 - 0.63		0.52 - 0.74		0.65 - 0.93		0.76 - 1.10		0.90 - 1.38		1.00 - 1.59		1.09 - 1.83	
30-min	0.75	0.77	0.88	0.90	1.11	1.11	1.31	1.29	1.59	1.59	1.81	1.85	2.04	2.16
	0.63 - 0.89		0.74 - 1.05		0.93 - 1.33		1.09 - 1.57		1.28 - 1.97		1.43 - 2.27		1.55 - 2.61	
60-min	0.97	0.99	1.14	1.16	1.45	1.42	1.72	1.66	2.11	2.04	2.42	2.38	2.75	2.78
	0.81 - 1.15		0.96 - 1.36		1.22 - 1.73		1.43 - 2.06		1.70 - 2.62		1.91 - 3.04		2.10 - 3.53	
2-hr	1.18	1.21	1.40	1.42	1.79	1.74	2.12	2.03	2.62	2.50	3.03	2.92	3.46	3.40
	1.00 - 1.39		1.19 - 1.66		1.51 - 2.11		1.78 - 2.53		2.14 - 3.24		2.41 - 3.78		2.66 - 4.41	
3-hr	1.31	1.34	1.55	1.57	1.98	1.93	2.36	2.25	2.93	2.76	3.40	3.23	3.90	3.77
	1.11 - 1.54		1.32 - 1.82		1.68 - 2.33		1.99 - 2.79		2.41 - 3.61		2.72 - 4.23		3.01 - 4.96	
6-hr	1.55	1.57	1.81	1.83	2.27	2.24	2.70	2.62	3.36	3.22	3.91	3.76	4.51	4.39
	1.33 - 1.81		1.55 - 2.11		1.94 - 2.66		2.30 - 3.17		2.79 - 4.13		3.16 - 4.85		3.52 - 5.71	
12-hr	1.83	1.80	2.08	2.10	2.54	2.58	2.98	3.01	3.66	3.69	4.25	4.31	4.90	5.04
	1.59 - 2.12		1.80 - 2.41		2.19 - 2.95		2.55 - 3.47		3.07 - 4.47		3.46 - 5.24		3.85 - 6.16	
24-hr	2.11	2.04	2.37	2.38	2.86	2.93	3.33	3.42	4.05	4.20	4.68	4.90	5.36	5.73
	1.84 - 2.42		2.06 - 2.73		2.48 - 3.30		2.87 - 3.85		3.42 - 4.91		3.84 - 5.71		4.25 - 6.68	

MACOMB COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	6.1276	0.8283	34.7452	0.2230
90% Confidence Interval Lower	5.2102	0.8060	24.5116	0.2064
90% Confidence Interval Upper	7.2903	0.8501	49.0269	0.2379

Tabular Precipitation Frequency Estimates Rainfall Total (in)

Regression equation rainfall → **0.72** 0.70
 Atlas 14 county-wide average rainfall → **0.72** 0.70
 Atlas 14 90% confidence interval → **0.53 – 0.96**

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.29	0.29	0.35	0.34	0.44	0.42	0.52	0.49	0.63	0.60	0.72	0.70	0.81	0.82
	0.23 - 0.38		0.27 - 0.45		0.34 - 0.57		0.40 - 0.68		0.47 - 0.84		0.53 - 0.96		0.57 - 1.09	
10-min	0.43	0.45	0.51	0.53	0.65	0.64	0.76	0.75	0.93	0.92	1.05	1.08	1.18	1.26
	0.33 - 0.55		0.40 - 0.66		0.50 - 0.84		0.59 - 0.99		0.69 - 1.22		0.77 - 1.4		0.84 - 1.60	
15-min	0.52	0.56	0.62	0.65	0.79	0.80	0.93	0.93	1.13	1.15	1.29	1.34	1.44	1.56
	0.41 - 0.68		0.49 - 0.81		0.61 - 1.02		0.72 - 1.21		0.85 - 1.49		0.94 - 1.71		1.03 - 1.95	
30-min	0.73	0.76	0.87	0.89	1.10	1.09	1.30	1.27	1.58	1.56	1.80	1.82	2.02	2.12
	0.57 - 0.94		0.68 - 1.12		0.86 - 1.43		1.00 - 1.69		1.18 - 2.08		1.31 - 2.39		1.43 - 2.71	
60-min	0.93	0.97	1.12	1.13	1.42	1.39	1.68	1.62	2.05	1.99	2.35	2.32	2.65	2.71
	0.73 - 1.20		0.87 - 1.44		1.10 - 1.84		1.30 - 2.18		1.54 - 2.72		1.72 - 3.13		1.88 - 3.58	
2-hr	1.14	1.18	1.36	1.38	1.74	1.69	2.06	1.97	2.53	2.42	2.90	2.82	3.29	3.30
	0.90 - 1.45		1.07 - 1.74		1.36 - 2.22		1.61 - 2.64		1.92 - 3.32		2.15 - 3.83		2.36 - 4.40	
3-hr	1.27	1.30	1.51	1.52	1.92	1.87	2.28	2.18	2.81	2.67	3.24	3.12	3.68	3.64
	1.01 - 1.61		1.19 - 1.91		1.52 - 2.44		1.79 - 2.90		2.15 - 3.67		2.42 - 4.25		2.66 - 4.90	
6-hr	1.51	1.52	1.77	1.77	2.22	2.18	2.63	2.54	3.23	3.12	3.73	3.64	4.27	4.25
	1.21 - 1.89		1.41 - 2.21		1.77 - 2.78		2.08 - 3.30		2.5 - 4.19		2.82 - 4.86		3.12 - 5.63	
12-hr	1.78	1.75	2.03	2.04	2.50	2.50	2.92	2.92	3.57	3.58	4.11	4.18	4.70	4.88
	1.44 - 2.2		1.64 - 2.52		2.01 - 3.09		2.34 - 3.63		2.80 - 4.59		3.15 - 5.31		3.48 - 6.16	
24-hr	2.04	1.99	2.32	2.32	2.82	2.85	3.28	3.32	3.97	4.08	4.55	4.76	5.18	5.56
	1.67 - 2.50		1.90 - 2.84		2.30 - 3.46		2.66 - 4.03		3.15 - 5.04		3.52 - 5.81		3.87 - 6.70	

MONROE COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	5.7330	0.8299	35.8845	0.2136
90% Confidence Interval Lower	4.7745	0.8062	25.7855	0.2012
90% Confidence Interval Upper	6.9818	0.8541	49.6601	0.2283

Tabular Precipitation Frequency Estimates Rainfall Total (in)

Regression equation rainfall →

<i>Atlas 14 county-wide average rainfall</i> →	0.74	0.72
<i>Atlas 14 90% confidence interval</i> →	0.56 – 0.95	

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.31	0.31	0.37	0.36	0.47	0.44	0.55	0.51	0.65	0.62	0.74	0.72	0.82	0.84
	0.25 - 0.39		0.30 - 0.47		0.37 - 0.59		0.43 - 0.69		0.51 - 0.84		0.56 - 0.95		0.61 - 1.07	
10-min	0.46	0.48	0.54	0.56	0.68	0.68	0.80	0.78	0.96	0.95	1.08	1.10	1.20	1.28
	0.37 - 0.58		0.44 - 0.68		0.55 - 0.86		0.63 - 1.01		0.74 - 1.23		0.82 - 1.39		0.89 - 1.57	
15-min	0.56	0.59	0.66	0.68	0.83	0.83	0.97	0.97	1.17	1.17	1.32	1.36	1.47	1.58
	0.45 - 0.70		0.53 - 0.83		0.67 - 1.05		0.77 - 1.23		0.90 - 1.49		1.00 - 1.7		1.08 - 1.91	
30-min	0.77	0.80	0.91	0.92	1.15	1.12	1.35	1.30	1.61	1.58	1.82	1.83	2.02	2.13
	0.61 - 0.96		0.73 - 1.15		0.92 - 1.45		1.07 - 1.70		1.25 - 2.06		1.38 - 2.34		1.50 - 2.63	
60-min	0.98	1.01	1.16	1.17	1.45	1.42	1.70	1.65	2.06	2.00	2.35	2.32	2.64	2.69
	0.78 - 1.23		0.92 - 1.45		1.16 - 1.83		1.35 - 2.15		1.60 - 2.65		1.79 - 3.03		1.96 - 3.45	
2-hr	1.19	1.22	1.40	1.41	1.75	1.72	2.06	1.99	2.51	2.42	2.88	2.81	3.26	3.26
	0.97 - 1.48		1.13 - 1.74		1.41 - 2.18		1.66 - 2.57		1.98 - 3.21		2.22 - 3.69		2.44 - 4.22	
3-hr	1.32	1.34	1.54	1.56	1.92	1.89	2.26	2.20	2.77	2.67	3.19	3.10	3.64	3.59
	1.08 - 1.63		1.25 - 1.90		1.56 - 2.37		1.83 - 2.80		2.20 - 3.53		2.48 - 4.08		2.75 - 4.71	
6-hr	1.56	1.56	1.78	1.81	2.20	2.20	2.59	2.55	3.18	3.10	3.69	3.60	4.23	4.17
	1.28 - 1.89		1.47 - 2.17		1.81 - 2.69		2.12 - 3.16		2.56 - 4.02		2.90 - 4.67		3.24 - 5.43	
12-hr	1.81	1.79	2.05	2.07	2.50	2.52	2.92	2.92	3.56	3.56	4.11	4.12	4.70	4.78
	1.51 - 2.17		1.71 - 2.47		2.08 - 3.02		2.42 - 3.53		2.90 - 4.45		3.27 - 5.15		3.64 - 5.96	
24-hr	2.07	2.03	2.35	2.36	2.85	2.87	3.30	3.32	3.98	4.04	4.55	4.69	5.16	5.44
	1.75 - 2.46		1.99 - 2.80		2.40 - 3.39		2.77 - 3.94		3.27 - 4.90		3.66 - 5.62		4.03 - 6.45	

OAKLAND COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	6.2760	0.8274	35.7367	0.2231
90% Confidence Interval Lower	5.7259	0.8157	27.8552	0.2066
90% Confidence Interval Upper	7.0577	0.8418	46.3038	0.2417

Tabular Precipitation Frequency Estimates Rainfall Total (in)

Regression equation rainfall → **0.73** 0.71
 Atlas 14 county-wide average rainfall
 Atlas 14 90% confidence interval → 0.56 – 0.94

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.30	0.30	0.36	0.35	0.45	0.42	0.53	0.49	0.64	0.61	0.73	0.71	0.82	0.83
	0.25 - 0.37		0.29 - 0.44		0.37 - 0.56		0.43 - 0.66		0.50 - 0.82		0.56 - 0.94		0.61 - 1.07	
10-min	0.44	0.46	0.52	0.53	0.66	0.66	0.78	0.77	0.94	0.94	1.07	1.10	1.20	1.28
	0.36 - 0.55		0.43 - 0.65		0.54 - 0.82		0.63 - 0.97		0.74 - 1.20		0.82 - 1.38		0.89 - 1.57	
15-min	0.54	0.57	0.64	0.67	0.81	0.82	0.95	0.95	1.15	1.17	1.30	1.36	1.47	1.59
	0.44 - 0.67		0.52 - 0.79		0.65 - 1.00		0.77 - 1.18		0.90 - 1.46		1.00 - 1.68		1.08 - 1.92	
30-min	0.75	0.78	0.89	0.91	1.12	1.11	1.32	1.30	1.60	1.60	1.82	1.86	2.05	2.17
	0.61 - 0.92		0.72 - 1.10		0.91 - 1.39		1.07 - 1.64		1.25 - 2.04		1.39 - 2.35		1.51 - 2.68	
60-min	0.96	1.00	1.14	1.16	1.45	1.43	1.72	1.66	2.11	2.04	2.41	2.38	2.73	2.78
	0.78 - 1.19		0.93 - 1.42		1.18 - 1.8		1.39 - 2.14		1.65 - 2.7		1.85 - 3.11		2.02 - 3.58	
2-hr	1.17	1.22	1.40	1.42	1.79	1.74	2.12	2.03	2.61	2.49	3.00	2.91	3.42	3.40
	0.97 - 1.44		1.15 - 1.72		1.46 - 2.20		1.73 - 2.62		2.06 - 3.32		2.32 - 3.85		2.55 - 4.45	
3-hr	1.31	1.34	1.56	1.57	1.99	1.93	2.36	2.25	2.92	2.76	3.37	3.22	3.85	3.76
	1.08 - 1.60		1.29 - 1.90		1.63 - 2.43		1.93 - 2.90		2.32 - 3.71		2.62 - 4.31		2.89 - 5.01	
6-hr	1.57	1.57	1.83	1.83	2.29	2.25	2.72	2.62	3.36	3.22	3.90	3.76	4.47	4.38
	1.30 - 1.9		1.52 - 2.21		1.90 - 2.79		2.24 - 3.31		2.70 - 4.25		3.05 - 4.96		3.39 - 5.79	
12-hr	1.84	1.80	2.09	2.11	2.56	2.58	3.00	3.02	3.68	3.70	4.25	4.32	4.88	5.04
	1.54 - 2.21		1.75 - 2.52		2.14 - 3.09		2.49 - 3.62		2.99 - 4.63		3.37 - 5.38		3.73 - 6.29	
24-hr	2.11	2.06	2.39	2.40	2.89	2.95	3.36	3.44	4.09	4.22	4.70	4.92	5.37	5.75
	1.78 - 2.51		2.01 - 2.84		2.43 - 3.45		2.81 - 4.03		3.34 - 5.09		3.75 - 5.90		4.14 - 6.86	

ST. CLAIR COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: *Midwestern States (2013)*, for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

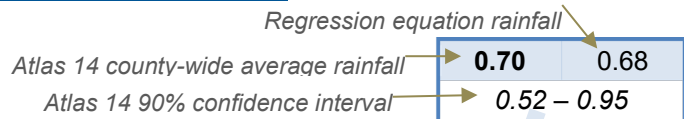
Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	6.5744	0.8296	34.8230	0.2268
90% Confidence Interval Lower	5.5520	0.8078	24.9100	0.2092
90% Confidence Interval Upper	7.8482	0.8516	48.5373	0.2486

Tabular Precipitation Frequency Estimates Rainfall Total (in)



Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.29	0.28	0.34	0.33	0.43	0.40	0.51	0.47	0.62	0.58	0.70	0.68	0.80	0.79
	0.23 - 0.37		0.27 - 0.44		0.33 - 0.55		0.39 - 0.65		0.46 - 0.82		0.52 - 0.95		0.57 - 1.1	
10-min	0.42	0.44	0.50	0.51	0.63	0.63	0.74	0.73	0.90	0.90	1.03	1.06	1.17	1.24
	0.33 - 0.54		0.39 - 0.64		0.49 - 0.81		0.58 - 0.96		0.68 - 1.21		0.76 - 1.39		0.83 - 1.61	
15-min	0.51	0.54	0.61	0.64	0.76	0.78	0.90	0.92	1.10	1.13	1.26	1.32	1.42	1.54
	0.40 - 0.66		0.48 - 0.78		0.60 - 0.99		0.70 - 1.17		0.83 - 1.47		0.93 - 1.7		1.01 - 1.96	
30-min	0.72	0.74	0.85	0.87	1.08	1.07	1.27	1.26	1.56	1.55	1.78	1.81	2.02	2.12
	0.57 - 0.93		0.67 - 1.10		0.84 - 1.39		0.99 - 1.65		1.17 - 2.08		1.31 - 2.41		1.43 - 2.77	
60-min	0.93	0.96	1.10	1.12	1.40	1.38	1.66	1.61	2.05	1.98	2.36	2.32	2.68	2.72
	0.73 - 1.20		0.87 - 1.42		1.10 - 1.81		1.29 - 2.16		1.54 - 2.74		1.73 - 3.19		1.90 - 3.7	
2-hr	1.14	1.17	1.35	1.37	1.72	1.68	2.05	1.97	2.54	2.42	2.93	2.84	3.35	3.32
	0.91 - 1.45		1.07 - 1.72		1.36 - 2.20		1.62 - 2.63		1.94 - 3.36		2.18 - 3.92		2.41 - 4.57	
3-hr	1.27	1.29	1.50	1.51	1.91	1.86	2.28	2.18	2.83	2.68	3.28	3.14	3.76	3.67
	1.01 - 1.60		1.20 - 1.89		1.52 - 2.42		1.80 - 2.89		2.18 - 3.73		2.46 - 4.36		2.72 - 5.10	
6-hr	1.51	1.51	1.76	1.76	2.21	2.17	2.62	2.54	3.25	3.13	3.78	3.66	4.35	4.28
	1.22 - 1.88		1.42 - 2.19		1.78 - 2.75		2.10 - 3.28		2.54 - 4.25		2.88 - 4.97		3.19 - 5.84	
12-hr	1.77	1.73	2.02	2.03	2.48	2.50	2.90	2.92	3.57	3.59	4.14	4.21	4.76	4.92
	1.45 - 2.18		1.65 - 2.48		2.02 - 3.05		2.36 - 3.59		2.83 - 4.61		3.19 - 5.38		3.54 - 6.31	
24-hr	2.03	1.97	2.30	2.31	2.80	2.84	3.26	3.33	3.97	4.09	4.57	4.79	5.22	5.61
	1.69 - 2.46		1.91 - 2.79		2.31 - 3.40		2.68 - 3.98		3.18 - 5.04		3.56 - 5.85		3.92 - 6.82	

WASHTENAW COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: *Midwestern States (2013)*, for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

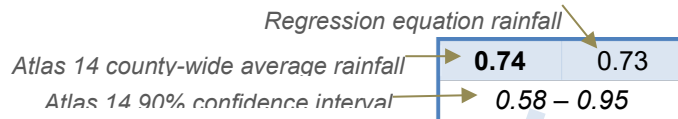
Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	5.7958	0.8301	35.9288	0.2172
90% Confidence Interval Lower	5.2349	0.8157	27.9950	0.2034
90% Confidence Interval Upper	6.7143	0.8480	47.0572	0.2356

Tabular Precipitation Frequency Estimates Rainfall Total (in)



Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.32	0.31	0.37	0.36	0.47	0.44	0.55	0.51	0.66	0.63	0.74	0.73	0.83	0.85
	0.26 - 0.39		0.31 - 0.46		0.38 - 0.57		0.45 - 0.67		0.52 - 0.83		0.58 - 0.95		0.63 - 1.08	
10-min	0.46	0.48	0.55	0.55	0.68	0.68	0.80	0.79	0.96	0.96	1.09	1.12	1.22	1.30
	0.38 - 0.57		0.45 - 0.67		0.56 - 0.84		0.65 - 0.99		0.76 - 1.22		0.85 - 1.39		0.92 - 1.58	
15-min	0.56	0.59	0.67	0.68	0.83	0.83	0.97	0.97	1.17	1.18	1.33	1.38	1.49	1.60
	0.47 - 0.69		0.55 - 0.82		0.68 - 1.03		0.80 - 1.20		0.93 - 1.48		1.03 - 1.70		1.12 - 1.93	
30-min	0.77	0.79	0.91	0.92	1.14	1.13	1.33	1.31	1.61	1.60	1.82	1.86	2.04	2.16
	0.63 - 0.94		0.75 - 1.11		0.93 - 1.4		1.09 - 1.65		1.27 - 2.04		1.42 - 2.33		1.54 - 2.66	
60-min	0.97	1.01	1.15	1.17	1.45	1.43	1.71	1.66	2.08	2.02	2.38	2.35	2.70	2.73
	0.80 - 1.19		0.94 - 1.41		1.19 - 1.78		1.39 - 2.11		1.66 - 2.65		1.86 - 3.06		2.04 - 3.52	
2-hr	1.18	1.22	1.39	1.42	1.76	1.73	2.08	2.01	2.56	2.45	2.95	2.85	3.36	3.31
	0.98 - 1.43		1.15 - 1.69		1.45 - 2.14		1.71 - 2.55		2.06 - 3.23		2.31 - 3.75		2.56 - 4.34	
3-hr	1.31	1.34	1.53	1.56	1.94	1.90	2.30	2.21	2.84	2.70	3.29	3.14	3.78	3.65
	1.09 - 1.58		1.28 - 1.86		1.61 - 2.35		1.90 - 2.8		2.30 - 3.59		2.61 - 4.18		2.90 - 4.87	
6-hr	1.55	1.56	1.79	1.81	2.23	2.21	2.63	2.57	3.26	3.14	3.79	3.65	4.36	4.24
	1.31 - 1.87		1.51 - 2.15		1.87 - 2.68		2.2 - 3.18		2.67 - 4.09		3.03 - 4.78		3.38 - 5.59	
12-hr	1.83	1.79	2.07	2.08	2.51	2.53	2.92	2.95	3.57	3.60	4.12	4.18	4.73	4.86
	1.56 - 2.18		1.76 - 2.46		2.12 - 2.99		2.46 - 3.49		2.96 - 4.44		3.33 - 5.16		3.70 - 6.01	
24-hr	2.11	2.03	2.37	2.36	2.85	2.88	3.29	3.35	3.97	4.09	4.54	4.75	5.16	5.52
	1.81 - 2.49		2.03 - 2.8		2.43 - 3.36		2.8 - 3.89		3.31 - 4.87		3.70 - 5.60		4.07 - 6.48	

WAYNE COUNTY

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

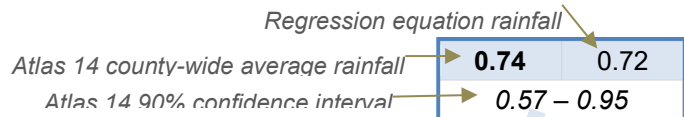
Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	5.8249	0.8300	35.7204	0.2165
90% Confidence Interval Lower	5.0132	0.8118	26.9999	0.2005
90% Confidence Interval Upper	6.3819	0.8424	45.7588	0.2323

Tabular Precipitation Frequency Estimates Rainfall Total (in)



Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.31	0.31	0.37	0.36	0.46	0.44	0.54	0.51	0.65	0.62	0.74	0.72	0.83	0.84
	0.25 - 0.38		0.30 - 0.45		0.38 - 0.57		0.44 - 0.67		0.51 - 0.83		0.57 - 0.95		0.62 - 1.08	
10-min	0.45	0.47	0.54	0.55	0.67	0.67	0.79	0.78	0.96	0.95	1.09	1.10	1.22	1.28
	0.37 - 0.56		0.44 - 0.66		0.55 - 0.83		0.64 - 0.98		0.75 - 1.21		0.83 - 1.39		0.91 - 1.59	
15-min	0.55	0.58	0.65	0.68	0.82	0.83	0.96	0.96	1.17	1.17	1.32	1.36	1.48	1.58
	0.45 - 0.68		0.54 - 0.81		0.67 - 1.02		0.78 - 1.20		0.92 - 1.48		1.02 - 1.7		1.10 - 1.93	
30-min	0.76	0.79	0.90	0.92	1.13	1.12	1.33	1.30	1.61	1.58	1.83	1.84	2.05	2.14
	0.62 - 0.94		0.74 - 1.11		0.92 - 1.40		1.08 - 1.65		1.26 - 2.04		1.40 - 2.34		1.52 - 2.67	
60-min	0.97	1.00	1.15	1.16	1.44	1.42	1.70	1.65	2.07	2.01	2.36	2.33	2.66	2.71
	0.80 - 1.20		0.94 - 1.41		1.18 - 1.79		1.38 - 2.11		1.63 - 2.63		1.81 - 3.02		1.98 - 3.47	
2-hr	1.18	1.21	1.39	1.41	1.76	1.72	2.07	1.99	2.52	2.43	2.89	2.82	3.26	3.28
	0.98 - 1.44		1.15 - 1.71		1.45 - 2.16		1.70 - 2.55		2.01 - 3.19		2.24 - 3.68		2.45 - 4.23	
3-hr	1.31	1.33	1.54	1.55	1.94	1.89	2.29	2.20	2.79	2.68	3.20	3.11	3.63	3.62
	1.09 - 1.59		1.28 - 1.88		1.60 - 2.37		1.88 - 2.8		2.23 - 3.52		2.50 - 4.07		2.74 - 4.69	
6-hr	1.54	1.55	1.80	1.80	2.24	2.20	2.63	2.55	3.21	3.11	3.69	3.62	4.19	4.20
	1.29 - 1.86		1.50 - 2.17		1.86 - 2.71		2.18 - 3.19		2.59 - 4.02		2.90 - 4.65		3.19 - 5.38	
12-hr	1.80	1.78	2.06	2.07	2.52	2.52	2.94	2.93	3.57	3.57	4.09	4.15	4.65	4.82
	1.52 - 2.15		1.73 - 2.46		2.12 - 3.02		2.45 - 3.53		2.91 - 4.44		3.25 - 5.13		3.57 - 5.93	
24-hr	2.06	2.02	2.35	2.35	2.85	2.86	3.30	3.33	3.98	4.06	4.54	4.72	5.15	5.48
	1.75 - 2.45		1.99 - 2.78		2.41 - 3.38		2.78 - 3.93		3.27 - 4.91		3.64 - 5.64		3.99 - 6.50	

SEMCOG REGION

Countywide average precipitation frequency estimates are provided below based on NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2: Midwestern States (2013), for Michigan. An intensity-duration-frequency (IDF) equation is provided based on a best fit regression analysis. The IDF equation is provided to simplify computational analysis. Tabular data is provided along with the results of using the IDF equation for comparison purposes. Ninetieth percentile (90%) confidence intervals are provided to illustrate the plausible range of values based on the statistics of the observed data.

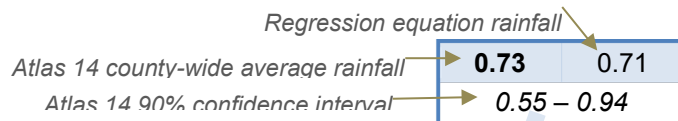
Regression Equation

$$i = \frac{\alpha T^\beta}{t^c + b}$$

where, i = rainfall intensity (inches per hour)
 T = recurrence interval (years)
 t = duration (minutes)

Coefficients	b	c	α	β
Mean	6.1765	0.8295	35.6627	0.2208
90% Confidence Interval Lower	5.3073	0.8110	26.5765	0.2053
90% Confidence Interval Upper	7.1146	0.8472	47.2394	0.2393

Tabular Precipitation Frequency Estimates Rainfall Total (in)



Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.30	0.30	0.36	0.35	0.45	0.42	0.53	0.50	0.64	0.61	0.73	0.71	0.82	0.82
	0.25 - 0.38		0.29 - 0.45		0.36 - 0.56		0.42 - 0.66		0.50 - 0.82		0.55 - 0.94		0.60 - 1.07	
10-min	0.44	0.46	0.52	0.54	0.66	0.66	0.77	0.76	0.94	0.94	1.06	1.09	1.20	1.27
	0.36 - 0.55		0.42 - 0.65		0.53 - 0.82		0.62 - 0.97		0.73 - 1.20		0.81 - 1.38		0.88 - 1.57	
15-min	0.54	0.57	0.64	0.66	0.80	0.81	0.94	0.95	1.14	1.16	1.30	1.35	1.46	1.58
	0.44 - 0.67		0.52 - 0.80		0.65 - 1.00		0.76 - 1.18		0.89 - 1.47		0.99 - 1.68		1.07 - 1.92	
30-min	0.75	0.78	0.89	0.90	1.12	1.11	1.32	1.29	1.59	1.58	1.81	1.84	2.04	2.15
	0.61 - 0.93		0.72 - 1.11		0.90 - 1.40		1.06 - 1.65		1.24 - 2.04		1.38 - 2.35		1.50 - 2.68	
60-min	0.96	0.99	1.14	1.15	1.44	1.41	1.70	1.65	2.08	2.01	2.38	2.35	2.69	2.74
	0.78 - 1.19		0.92 - 1.42		1.16 - 1.80		1.37 - 2.13		1.62 - 2.67		1.81 - 3.09		1.99 - 3.55	
2-hr	1.17	1.20	1.39	1.40	1.76	1.72	2.08	2.00	2.56	2.45	2.94	2.86	3.35	3.33
	0.96 - 1.44		1.13 - 1.71		1.43 - 2.17		1.69 - 2.58		2.02 - 3.27		2.27 - 3.79		2.49 - 4.38	
3-hr	1.30	1.33	1.53	1.55	1.94	1.90	2.31	2.21	2.85	2.71	3.29	3.15	3.76	3.68
	1.07 - 1.59		1.26 - 1.88		1.59 - 2.39		1.88 - 2.84		2.26 - 3.63		2.55 - 4.22		2.82 - 4.91	
6-hr	1.54	1.55	1.79	1.80	2.24	2.21	2.65	2.57	3.27	3.15	3.79	3.67	4.35	4.28
	1.28 - 1.87		1.49 - 2.18		1.85 - 2.72		2.18 - 3.23		2.63 - 4.14		2.97 - 4.83		3.30 - 5.64	
12-hr	1.81	1.78	2.06	2.07	2.52	2.54	2.94	2.96	3.60	3.62	4.16	4.22	4.77	4.91
	1.52 - 2.17		1.72 - 2.48		2.10 - 3.03		2.44 - 3.56		2.93 - 4.52		3.30 - 5.26		3.65 - 6.13	
24-hr	2.08	2.02	2.35	2.36	2.85	2.89	3.31	3.36	4.00	4.12	4.60	4.80	5.24	5.59
	1.76 - 2.47		1.99 - 2.80		2.40 - 3.40		2.77 - 3.95		3.28 - 4.97		3.67 - 5.74		4.05 - 6.66	

2.0 TEMPORAL RAINFALL DISTRIBUTIONS

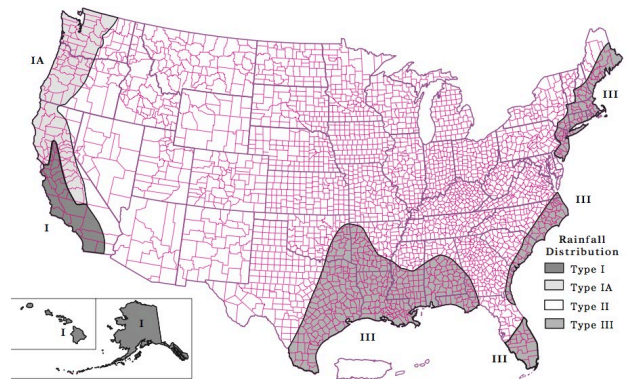
Some hydrological computational methods require a temporal rainfall distribution. A temporal rainfall distribution describes how the rainfall intensity varies with time during a storm event. Four rainfall distributions are discussed here including: NRCS (SCS) Type II, NRCS Midwest and South-East (MSE), Huff, and NOAA Atlas14. Historically a NRCS Type II rainfall distribution has been used. The NRCS Type II distribution has been replaced with the NRCS Midwest-Southeast (MSE) Type 3 rainfall distribution for sizing grey infrastructure and detention systems as this distribution is more conservative. The Atlas 14 distribution, which is based on actual rainfall distributions, is recommended for green stormwater infrastructure (GSI) design.

2.1 NRCS (SCS) TYPE II

Traditionally within Michigan the NRCS (SCS) Type II distribution has been used. The Type II distribution was developed based on the National Weather Service *Technical Paper (TP-40) Rainfall Frequency Atlas of the United States*.

The distribution is based on nesting the high intensity short durations within the longer lower intensity durations. For example, the maximum 5-minute rainfall is nested within the maximum 10-minute rainfall which is nested inside the maximum 15-minute rainfall. The process continues until the 24-hour duration is reached. The primary assumption made in the development of the rainfall distribution is that the rainfall values for all durations for a single return period occur within one 24-hour period.

The Type II distribution is being replaced by NRCS with rainfall distributions developed from the newer Atlas 14 dataset.

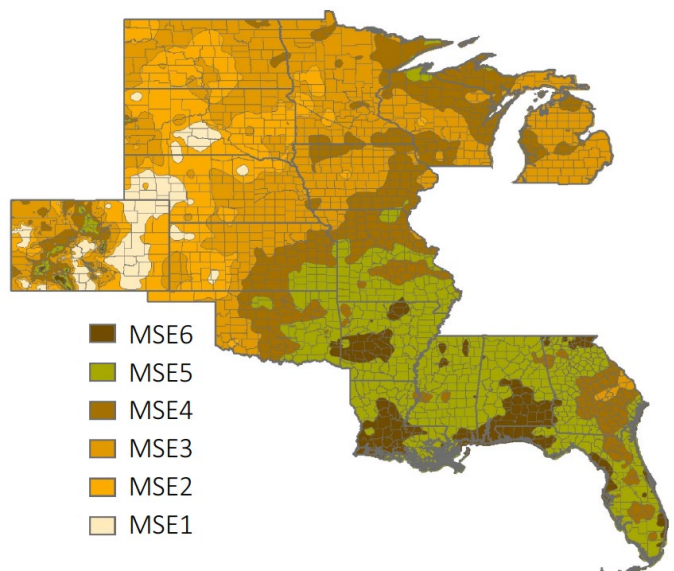


2.2 NRCS MSE

NRCS has developed a procedure to take point data from Atlas 14 and develop a distribution. NRCS has also developed regional distributions referred to as MSE. MSE is an abbreviation for Midwest Southeast states.

MSE (1-6) are based on the most recent rainfall data from NOAA Atlas 14 volumes 8 and 9. Each county in the Midwest is sorted into MSE 1 through MSE 6 based on 25-year recurrence storm relationships. Michigan falls into MSE 3 and 4 with a fraction of Alger County classified as MSE 5. The counties in the SEMCOG region are all classified as MSE 3. The MSE distributions, like SCS Type II, produce high peak intensities and flow rates.

Like the Type II distribution, the high intensity short duration rainfalls are nested inside the longer lower intensity rainfalls.



The intensity of the MSE distributions range from MSE 6 being the least intense to MSE 1 as the most intense. For comparison purposes, the intensity generated from a Type II distribution falls between MSEs 4 and 5. Since SEMCOG counties fall into the MSE 3 area, the distribution is more intense compared to a Type II and will result in higher peak flow rates. Peak flow rates increase by approximately 12% using an MSE 3 distribution compared to a Type II distribution.

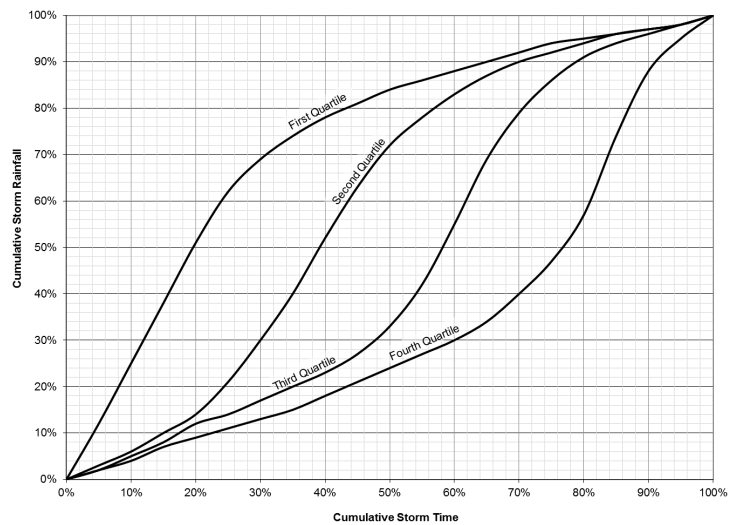
These MSE rainfall distributions are meant for design purposes and are not meant to recreate actual rainfall events.

2.3 HUFF

A time distribution of heavy rainstorms was developed by Floyd A. Huff in the State of Illinois Circular 173, 1990. The analysis was based strictly on real rainfall data in Illinois. In 1992, with the release of the *Rainfall Frequency Atlas of the Midwest, Bulletin 71*, the temporal rainfall distribution was applied to Midwestern states including Michigan.

The rainfall distributions are presented in the form of families of curves derived for groups of storms categorized as first-, second-, third-, or fourth-quartile storms, depending on whether the greatest percentage of total storm rainfall occurred in the first, second, third, or fourth quarter of the storm period.

The individual curves for each storm type (quartile group) provide estimates of the time-distribution characteristics at probability levels ranging from 10% to 90% of the total storm occurrences. For most purposes, the median curves are probably most applicable to design. These curves are more firmly established than the more extreme curves, such as those for the 10% and 90% probability levels, which are determined from a relatively small portion of each quartile's sample.



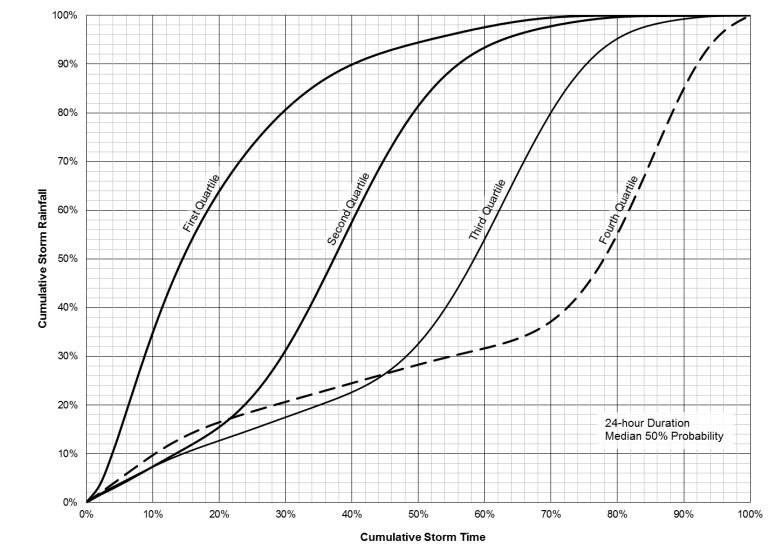
Storms with durations of 6 hours or less showed a tendency to be associated more often with first-quartile distributions, and those lasting from 6.1 to 12 hours were most commonly the second-quartile type. Rainstorms having durations of 12.1 to 24 hours occurred most often with the third-quartile type of distribution. Those having durations greater than 24 hours were most frequently associated with the fourth-quartile distribution. However, it should be noted that all durations may be associated with any of the four quartile types.

Time distributions are also provided based on the drainage area as a point, areas 10 to 50 square miles, and areas 50 to 400 square miles.

2.4 ATLAS 14

The NOAA Atlas 14 temporal distribution is like the one developed by Huff. The difference is in the definition of precipitation cases. The precipitation case, or event, was computed as the total accumulation over a specific duration (6, 12, 24 or 96 hours). As a result, a precipitation case may contain parts of one or more storms. This methodology was used to be consistent with the way a precipitation case was defined for the precipitation frequency analysis.

As with the approach used by Huff, the distributions are presented as a family of curves categorized into quartiles and includes probability levels ranging from 10% to 90%. The derivation of the distributions grouped climate stations into climate regions. Michigan is contained within the North Plains climate region, region number 1 in NOAA Atlas 14 Volume 8 Version 2.



2.5 DISTRIBUTION COMPARISON

Figure 2 illustrates a comparison of the temporal distributions discussed. Type II and MSE 3 are both based on a 24-hour distribution. Rainstorms having durations of 12.1 to 24 hours occurred most often with the third-quartile type of distribution (Huff 1970), hence the 3rd quartile distributions are included in Figure 2. The Huff and Atlas 14 distributions are also plotted for the median 50% probability. The intensity of a storm is related to the slope of the cumulative distribution line. The steeper the slope, the more intense the rainfall. MSE 3 has the most intense rainfall followed by the Type II with the Huff and Atlas 14 both having the least intense rainfall.

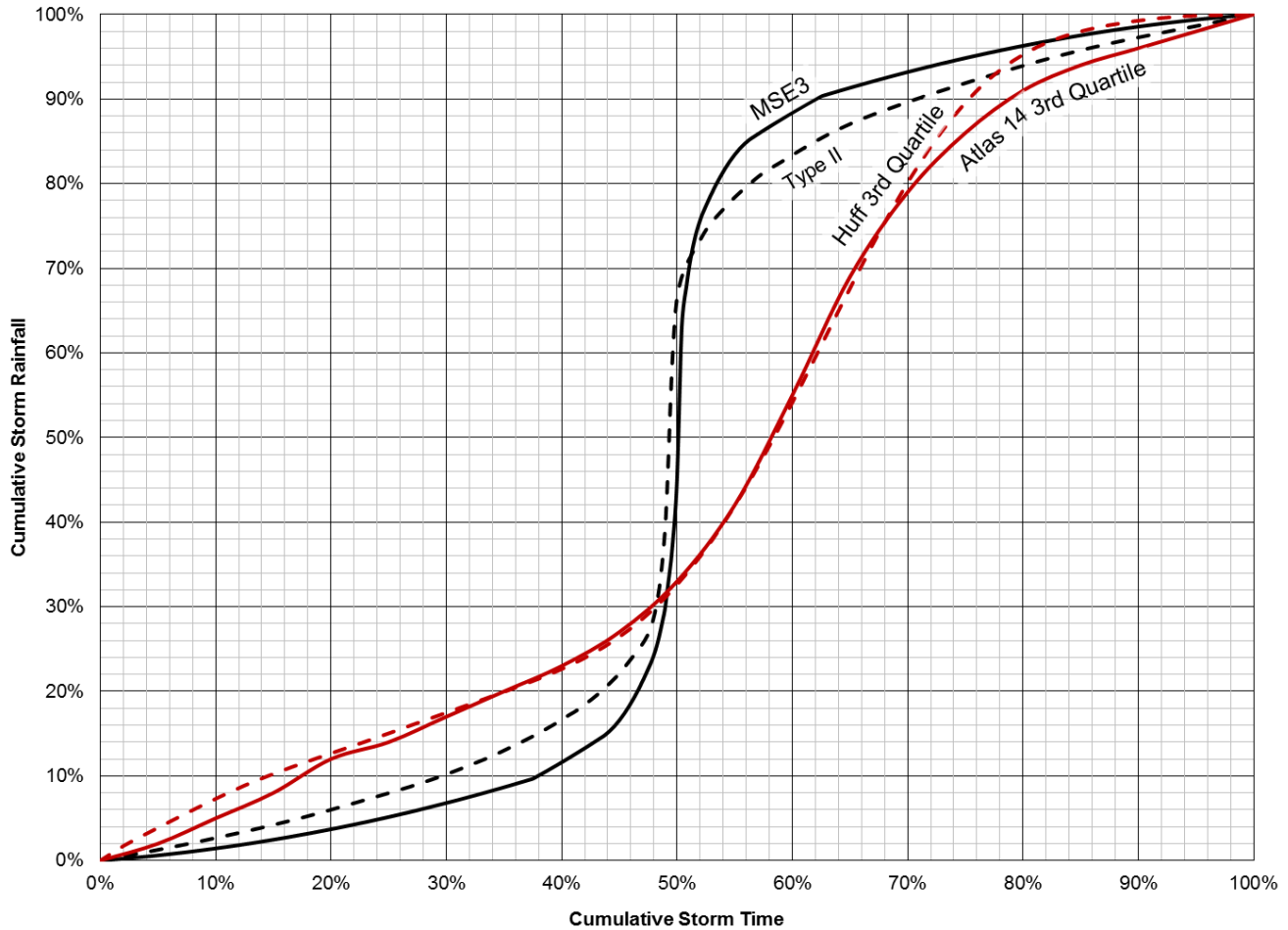


Figure 2 Temporal Distribution Comparison

In general terms, the Type II distribution is being replaced with the MSE 3. Similarly, the Huff distribution is being replaced with the Atlas 14. Based on the way in which the Type II and MSE distributions are developed they result in high peak flows compared to the Huff and Atlas 14 distributions. The Type II/MSE 3 distribution has a long history of use and is a widely accepted method; however, it is generally recognized as predicting relatively high peak flow rates.

2.6 MSE 3 DISTRIBUTION DETAILS

The MSE 3 rainfall distribution can be describe in tabular form or in an equation. Provided in Table 5 is a tabular form of the distribution. A journal paper titled *Mathematical Formulations of NRCS 24-Hour Design Storms* (2009) by David Froehlich provides an equation form for the NRCS Type I, IA, II and III rainfall distributions. The same formula approach may be used with the MSE distribution after deriving new coefficients. The basic equation is shown below with the coefficients provided in Table 4. Figure 3 illustrates a comparison between the NRCS tabular data and the Froehlich equation. Even though the rainfall equation appears complex, entering the equation into a spreadsheet allows the user to quickly develop the rainfall distribution in whatever time increments are required.

$$\hat{P}_*(t) = r(i_{p*} - i_{o*}) \left[\eta \frac{e^{-m_1(rt_d-t)/r} - e^{-m_1t_d}}{m_1t_d} + \eta' \frac{e^{-m_2(rt_d-t)/r} - e^{-m_2t_d}}{m_2t_d} \right] + i_{o*} \left(\frac{t}{t_d} \right) \text{ for } 0 \leq t \leq rt_d$$

$$\hat{P}_*(t) = (1-r)(i_{p*} - i_{o*}) \left[\eta \frac{1 - e^{-m_1(t-rt_d)/(1-r)}}{m_1t_d} + \eta' \frac{1 - e^{-m_2(t-rt_d)/(1-r)}}{m_2t_d} \right] + i_{o*} \left(\frac{t}{t_d} - r \right) + r \text{ for } rt_d \leq t \leq t_d$$

Where $\hat{P}_*(t)$ is the accumulated rainfall depth (inches), t is time (hours), t_d is the design storm duration (hours, typically 24-hours), and $\eta' = 1 - \eta$.

Table 4 NRCS Distribution Coefficients

Variables	Units	NRCS Type II	NRCS MSE 3
i_{p*}	-	39.261	23.141
i_{o*}	-	0.311	0.100
η	-	0.0522	0.0679
m_1	h^{-1}	0.264	0.165
m_2	h^{-1}	4.098	1.822
r	-	0.493	0.502

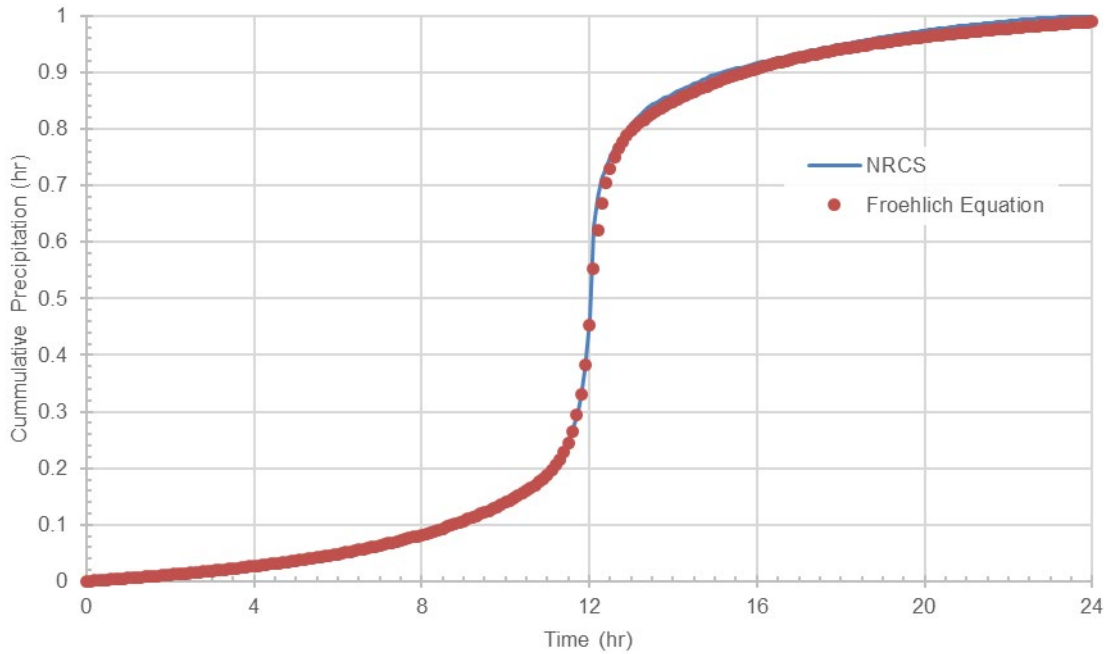


Figure 3 Comparison of Tabular Data and Equation

Table 5 MSE3 Tabular Data

Time (hr)	Cum. Rainfall (in)	Increm. Rainfall (in)	Time (hr)	Cum. Rainfall (in)	Increm. Rainfall (in)	Time (hr)	Cum. Rainfall (in)	Increm. Rainfall (in)	Time (hr)	Cum. Rainfall (in)	Increm. Rainfall (in)
0.1	0.000 267	0.000 267	6.1	0.052 400	0.001 450	12.1	0.627 550	0.164 660	18.1	0.950 480	0.001 430
0.2	0.000 555	0.000 288	6.2	0.053 870	0.001 470	12.2	0.675 550	0.048 000	18.2	0.951 890	0.001 410
0.3	0.000 861	0.000 306	6.3	0.055 360	0.001 490	12.3	0.709 380	0.033 830	18.3	0.953 280	0.001 390
0.4	0.001 190	0.000 329	6.4	0.056 870	0.001 510	12.4	0.733 700	0.024 320	18.4	0.954 650	0.001 370
0.5	0.001 530	0.000 340	6.5	0.058 400	0.001 530	12.5	0.752 000	0.018 300	18.5	0.956 010	0.001 360
0.6	0.001 900	0.000 370	6.6	0.059 950	0.001 550	12.6	0.764 570	0.012 570	18.6	0.957 340	0.001 330
0.7	0.002 290	0.000 390	6.7	0.061 520	0.001 570	12.7	0.776 380	0.011 810	18.7	0.958 650	0.001 310
0.8	0.002 690	0.000 400	6.8	0.063 110	0.001 590	12.8	0.787 440	0.011 060	18.8	0.959 940	0.001 290
0.9	0.003 120	0.000 430	6.9	0.064 720	0.001 610	12.9	0.797 740	0.010 300	18.9	0.961 220	0.001 280
1.0	0.003 560	0.000 440	7.0	0.066 350	0.001 630	13.0	0.807 280	0.009 540	19.0	0.962 470	0.001 250
1.1	0.004 030	0.000 470	7.1	0.067 990	0.001 640	13.1	0.816 060	0.008 780	19.1	0.963 700	0.001 230
1.2	0.004 510	0.000 480	7.2	0.069 660	0.001 670	13.2	0.824 090	0.008 030	19.2	0.964 920	0.001 220
1.3	0.005 010	0.000 500	7.3	0.071 350	0.001 690	13.3	0.831 370	0.007 280	19.3	0.966 110	0.001 190
1.4	0.005 540	0.000 530	7.4	0.073 060	0.001 710	13.4	0.837 880	0.006 510	19.4	0.967 290	0.001 180
1.5	0.006 080	0.000 540	7.5	0.074 780	0.001 720	13.5	0.843 640	0.005 760	19.5	0.968 440	0.001 150
1.6	0.006 650	0.000 570	7.6	0.076 530	0.001 750	13.6	0.847 520	0.003 880	19.6	0.969 580	0.001 140
1.7	0.007 230	0.000 580	7.7	0.078 300	0.001 770	13.7	0.851 340	0.003 820	19.7	0.970 690	0.001 110
1.8	0.007 830	0.000 600	7.8	0.080 080	0.001 780	13.8	0.855 130	0.003 790	19.8	0.971 790	0.001 100
1.9	0.008 450	0.000 620	7.9	0.081 890	0.001 810	13.9	0.858 870	0.003 740	19.9	0.972 860	0.001 070
2.0	0.009 100	0.000 650	8.0	0.083 710	0.001 820	14.0	0.862 560	0.003 690	20.0	0.973 920	0.001 060
2.1	0.009 760	0.000 660	8.1	0.085 560	0.001 850	14.1	0.866 200	0.003 640	20.1	0.974 960	0.001 040
2.2	0.010 440	0.000 680	8.2	0.087 420	0.001 860	14.2	0.869 800	0.003 600	20.2	0.975 970	0.001 010
2.3	0.011 140	0.000 700	8.3	0.089 310	0.001 890	14.3	0.873 360	0.003 560	20.3	0.976 970	0.001 000
2.4	0.011 860	0.000 720	8.4	0.091 210	0.001 900	14.4	0.876 860	0.003 500	20.4	0.977 950	0.000 980
2.5	0.012 600	0.000 740	8.5	0.093 140	0.001 930	14.5	0.880 330	0.003 470	20.5	0.978 910	0.000 960
2.6	0.013 360	0.000 760	8.6	0.095 080	0.001 940	14.6	0.883 740	0.003 410	20.6	0.979 840	0.000 930
2.7	0.014 140	0.000 780	8.7	0.097 040	0.001 960	14.7	0.887 110	0.003 370	20.7	0.980 760	0.000 920
2.8	0.014 940	0.000 800	8.8	0.099 030	0.001 990	14.8	0.890 440	0.003 330	20.8	0.981 660	0.000 900
2.9	0.015 760	0.000 820	8.9	0.101 030	0.002 000	14.9	0.893 720	0.003 280	20.9	0.982 540	0.000 880
3.0	0.016 600	0.000 840	9.0	0.103 050	0.002 020	15.0	0.896 950	0.003 230	21.0	0.983 400	0.000 860
3.1	0.017 460	0.000 860	9.1	0.106 280	0.003 230	15.1	0.898 970	0.002 020	21.1	0.984 240	0.000 840
3.2	0.018 340	0.000 880	9.2	0.109 560	0.003 280	15.2	0.900 970	0.002 000	21.2	0.985 060	0.000 820
3.3	0.019 240	0.000 900	9.3	0.112 890	0.003 330	15.3	0.902 960	0.001 990	21.3	0.985 860	0.000 800
3.4	0.020 160	0.000 920	9.4	0.116 260	0.003 370	15.4	0.904 920	0.001 960	21.4	0.986 640	0.000 780
3.5	0.021 090	0.000 930	9.5	0.119 670	0.003 410	15.5	0.906 860	0.001 940	21.5	0.987 400	0.000 760
3.6	0.022 050	0.000 960	9.6	0.123 140	0.003 470	15.6	0.908 790	0.001 930	21.6	0.988 140	0.000 740
3.7	0.023 030	0.000 980	9.7	0.126 640	0.003 500	15.7	0.910 690	0.001 900	21.7	0.988 860	0.000 720
3.8	0.024 030	0.001 000	9.8	0.130 200	0.003 560	15.8	0.912 580	0.001 890	21.8	0.989 560	0.000 700
3.9	0.025 040	0.001 010	9.9	0.133 800	0.003 600	15.9	0.914 440	0.001 860	21.9	0.990 240	0.000 680
4.0	0.026 080	0.001 040	10.0	0.137 440	0.003 640	16.0	0.916 290	0.001 850	22.0	0.990 900	0.000 660
4.1	0.027 140	0.001 060	10.1	0.141 130	0.003 690	16.1	0.918 110	0.001 820	22.1	0.991 550	0.000 650
4.2	0.028 210	0.001 070	10.2	0.144 870	0.003 740	16.2	0.919 920	0.001 810	22.2	0.992 170	0.000 620
4.3	0.029 310	0.001 100	10.3	0.148 660	0.003 790	16.3	0.921 700	0.001 780	22.3	0.992 770	0.000 600
4.4	0.030 420	0.001 110	10.4	0.152 480	0.003 820	16.4	0.923 470	0.001 770	22.4	0.993 350	0.000 580
4.5	0.031 560	0.001 140	10.5	0.156 360	0.003 880	16.5	0.925 220	0.001 750	22.5	0.993 920	0.000 570
4.6	0.032 710	0.001 150	10.6	0.162 120	0.005 760	16.6	0.926 940	0.001 720	22.6	0.994 460	0.000 540
4.7	0.033 890	0.001 180	10.7	0.168 630	0.006 510	16.7	0.928 650	0.001 710	22.7	0.994 990	0.000 530
4.8	0.035 080	0.001 190	10.8	0.175 910	0.007 280	16.8	0.930 340	0.001 690	22.8	0.995 490	0.000 500
4.9	0.036 300	0.001 220	10.9	0.183 940	0.008 030	16.9	0.932 010	0.001 670	22.9	0.995 970	0.000 480
5.0	0.037 530	0.001 230	11.0	0.192 720	0.008 780	17.0	0.933 650	0.001 640	23.0	0.996 440	0.000 470
5.1	0.038 780	0.001 250	11.1	0.202 260	0.009 540	17.1	0.935 280	0.001 630	23.1	0.996 880	0.000 440
5.2	0.040 060	0.001 280	11.2	0.212 560	0.010 300	17.2	0.936 890	0.001 610	23.2	0.997 310	0.000 430
5.3	0.041 350	0.001 290	11.3	0.223 620	0.011 060	17.3	0.938 480	0.001 590	23.3	0.997 710	0.000 400
5.4	0.042 660	0.001 310	11.4	0.235 430	0.011 810	17.4	0.940 050	0.001 570	23.4	0.998 100	0.000 390
5.5	0.043 990	0.001 330	11.5	0.248 000	0.012 570	17.5	0.941 600	0.001 550	23.5	0.998 470	0.000 370
5.6	0.045 350	0.001 360	11.6	0.266 300	0.018 300	17.6	0.943 130	0.001 530	23.6	0.998 810	0.000 340
5.7	0.046 720	0.001 370	11.7	0.290 620	0.024 320	17.7	0.944 640	0.001 510	23.7	0.999 139	0.000 329
5.8	0.048 110	0.001 390	11.8	0.324 450	0.033 830	17.8	0.946 130	0.001 490	23.8	0.999 445	0.000 306
5.9	0.049 520	0.001 410	11.9	0.372 450	0.048 000	17.9	0.947 600	0.001 470	23.9	0.999 733	0.000 288
6.0	0.050 950	0.001 430	12.0	0.462 890	0.090 440	18.0	0.949 050	0.001 450	24.0	1.000 000	0.000 267

3.0 FUTURE RAINFALL

An analysis was conducted looking at the changes to precipitation frequency estimates due to climate change. The analysis evaluated data from eight NOAA weather stations in the region and used six dynamically downscaled climate projections created via a Regional Climate Model (RCM) as part of the Great Lakes Ensemble Project. The analysis was based on Representative Concentration Pathway (RCP) 8.5 which assumes greenhouse gas emissions continue to rise throughout the 1st century. Two future time periods were considered, mid-century (2040-2059) and end of the century (2080-2099) and used 1980 to 1999 as a baseline. A technical report of the analysis is provided in Appendix A.

Table 6 provides a summary of the results for several recurrence intervals and the eight weather stations. The results in Table 6 are shown for the median value from the six climate models and with the range of values. For example, the weather station in Ann Arbor (20-0230) has mid-century projected median value of 5.08-inches for the 10-year 24-hour event and the data results for the six climate models ranged from 3.76- to 6.69-inches.

Table 6 Future Rainfall Summary

Stations	Flow Conveyance 10-year 24-hour			Flood Control 25-year 24-hour			Flood Control 100-year 24-hour		
	Base Atlas 14	Mid- Century	End-of- Century	Base Atlas 14	Mid- Century	End-of- Century	Base Atlas 14	Mid- Century	End-of- Century
Ann Arbor UM 20-0230	3.26 (2.93-3.65)	5.08 (3.76-6.69)	4.97 (3.74-7.38)	3.93 (3.46-4.58)	6.16 (3.90-9.00)	5.62 (4.50-11.07)	5.11 (4.23-6.13)	8.64 (4.02-15.06)	6.72 (5.14-20.77)
Detroit City Airport 20-2102	3.28 (2.83-3.84)	5.04 (4.61-6.04)	5.72 (3.71-8.03)	3.96 (3.32-4.80)	5.90 (4.88-8.10)	7.14 (3.83-11.92)	5.12 (4.02-6.38)	7.72 (4.97-13.28)	8.85 (3.92-21.22)
Detroit Metro Airport 20-2103	3.31 (2.91-3.78)	6.04 (3.31-6.94)	6.46 (2.79-8.05)	3.98 (3.42-4.71)	6.86 (3.35-10.20)	8.14 (2.81-10.22)	5.15 (4.17-6.24)	8.04 (3.38-18.65)	11.41 (2.82-14.90)
Howell WWTP 20-3947	3.33 (2.90-3.78)	5.42 (4.76-6.30)	5.05 (4.12-6.20)	4.05 (3.46-4.83)	6.49 (5.58-8.81)	6.98 (4.35-7.46)	5.36 (4.30-6.60)	8.60 (6.79-15.66)	8.57 (4.57-15.21)
Milford GM 20-5452	3.35 (2.92-3.82)	4.81 (3.95-5.86)	4.65 (3.63-5.30)	4.06 (3.46-4.83)	6.82 (5.34-8.56)	6.22 (4.51-7.50)	5.33 (4.28-6.51)	11.04 (7.66-15.01)	8.33 (6.12-17.16)
Pontiac WWTP 20-6658	3.39 (2.90-3.95)	5.07 (3.63-5.58)	5.96 (4.55-9.33)	4.11 (3.44-4.97)	6.56 (3.75-6.89)	8.17 (5.52-12.78)	5.36 (4.22-6.65)	8.87 (3.85-10.63)	11.12 (7.23-19.52)
Wayne – Canton 76-0065	3.30 (2.73-4.00)	5.64 (3.10-6.39)	6.02 (2.61-7.58)	3.98 (3.22-4.98)	6.51 (3.15-9.39)	7.61 (2.62-9.64)	5.15 (3.92-6.60)	7.66 (3.17-17.36)	10.82 (2.62-14.24)
Ypsilanti EMU 20-9218	3.26 (2.91-3.70)	4.40 (3.35-5.64)	4.12 (3.27-6.29)	3.93 (3.41-4.65)	5.27 (3.55-7.43)	4.55 (4.05-9.50)	5.11 (4.14-6.24)	7.35 (3.76-12.22)	5.71 (4.76-18.15)
Region Average	3.31 (2.77-3.95)	5.2 (3.8-6.2)	5.4 (3.6-7.3)	4.01 (3.28-4.97)	6.3 (4.2-8.5)	6.8 (4.0-10.0)	5.24 (4.05-6.66)	8.5 (4.7-14.7)	8.9 (4.6-17.6)

The last row of Table 6 provides an average projection for the region. Table 7 and Table 8 provide more detailed information for the mid-century and end of century projections based on the average for the region. The average for the region is computed based on the median value from the six-climate models at each station. The numbers in parenthesis represent the predicted range from the climate models.

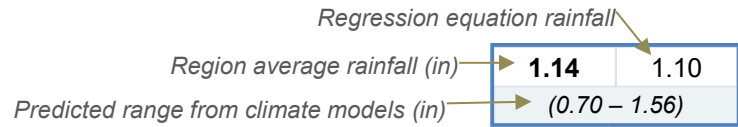


Table 7 Mid-Century Average Regional Rainfall (in)

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.42	0.41	0.53	0.49	0.69	0.62	0.83	0.73	1.00	0.92	1.14	1.10	1.30	1.30
	(0.33 - 0.57)		(0.43 - 0.69)		(0.54 - 0.81)		(0.60 - 0.94)		(0.67 - 1.25)		(0.70 - 1.56)		(0.74 - 2.04)	
10-min	0.60	0.64	0.75	0.77	1.00	0.96	1.19	1.15	1.43	1.44	1.64	1.71	1.87	2.04
	(0.48 - 0.82)		(0.61 - 0.99)		(0.78 - 1.16)		(0.87 - 1.35)		(0.96 - 1.80)		(1.01 - 2.25)		(1.06 - 2.93)	
15-min	0.73	0.80	0.92	0.96	1.22	1.20	1.45	1.43	1.75	1.80	1.99	2.14	2.29	2.54
	(0.58 - 1.00)		(0.74 - 1.21)		(0.95 - 1.42)		(1.06 - 1.64)		(1.17 - 2.19)		(1.23 - 2.74)		(1.29 - 3.57)	
30-min	1.00	1.11	1.27	1.31	1.68	1.65	2.00	1.96	2.42	2.47	2.76	2.94	3.17	3.49
	(0.80 - 1.37)		(1.02 - 1.65)		(1.31 - 1.95)		(1.47 - 2.27)		(1.63 - 3.02)		(1.71 - 3.78)		(1.80 - 4.93)	
60-min	1.27	1.42	1.61	1.69	2.15	2.12	2.58	2.52	3.13	3.17	3.61	3.77	4.17	4.48
	(1.02 - 1.74)		(1.30 - 2.11)		(1.68 - 2.50)		(1.88 - 2.92)		(2.11 - 3.92)		(2.24 - 4.94)		(2.37 - 6.48)	
2-hr	1.69	1.73	2.15	2.06	2.89	2.59	3.42	3.08	4.19	3.87	4.84	4.61	5.57	5.48
	(1.44 - 2.13)		(1.79 - 2.59)		(2.13 - 3.34)		(2.37 - 4.15)		(2.64 - 5.60)		(2.83 - 7.12)		(3.01 - 9.34)	
3-hr	1.90	1.92	2.43	2.28	3.23	2.87	3.79	3.41	4.66	4.28	5.37	5.09	6.18	6.06
	(1.58 - 2.39)		(1.93 - 2.92)		(2.33 - 3.81)		(2.58 - 4.76)		(2.88 - 6.39)		(3.08 - 8.18)		(3.26 - 10.7)	
6-hr	2.12	2.23	2.71	2.66	3.60	3.34	4.20	3.97	5.19	4.99	6.02	5.94	6.99	7.06
	(1.74 - 2.68)		(2.10 - 3.26)		(2.53 - 4.23)		(2.80 - 5.30)		(3.15 - 7.23)		(3.35 - 9.26)		(3.55 - 12.1)	
12-hr	2.38	2.56	3.05	3.05	3.99	3.83	4.67	4.56	5.75	5.73	6.70	6.81	7.77	8.10
	(2.00 - 2.91)		(2.42 - 3.51)		(2.92 - 4.61)		(3.22 - 5.85)		(3.58 - 8.10)		(3.80 - 10.5)		(4.03 - 13.8)	
24-hr	2.55	2.92	3.26	3.47	4.38	4.36	5.19	5.18	6.32	6.52	7.32	7.75	8.49	9.21
	(2.21 - 3.25)		(2.72 - 3.93)		(3.45 - 4.98)		(3.81 - 6.18)		(4.19 - 8.55)		(4.45 - 11.2)		(4.70 - 14.7)	

Table 8 End of Century Average Regional Rainfall (in)

Duration	1-year		2-year		5-year		10-year		25-year		50-year		100-year	
5-min	0.47	0.44	0.58	0.53	0.73	0.66	0.86	0.79	1.07	0.99	1.22	1.18	1.40	1.40
	(0.35 - 0.57)		(0.44 - 0.69)		(0.55 - 0.87)		(0.63 - 1.03)		(0.72 - 1.38)		(0.76 - 1.78)		(0.80 - 2.35)	
10-min	0.68	0.69	0.83	0.82	1.06	1.03	1.24	1.23	1.54	1.54	1.75	1.83	2.01	2.17
	(0.50 - 0.81)		(0.63 - 0.99)		(0.79 - 1.25)		(0.90 - 1.48)		(1.04 - 1.99)		(1.09 - 2.55)		(1.15 - 3.39)	
15-min	0.83	0.86	1.02	1.03	1.29	1.29	1.52	1.53	1.87	1.92	2.14	2.28	2.45	2.71
	(0.61 - 0.99)		(0.77 - 1.21)		(0.97 - 1.52)		(1.10 - 1.80)		(1.27 - 2.43)		(1.34 - 3.11)		(1.40 - 4.13)	
30-min	1.14	1.18	1.40	1.40	1.77	1.76	2.09	2.09	2.59	2.63	2.96	3.12	3.39	3.71
	(0.84 - 1.37)		(1.06 - 1.66)		(1.33 - 2.10)		(1.52 - 2.48)		(1.75 - 3.36)		(1.85 - 4.3)		(1.94 - 5.71)	
60-min	1.45	1.51	1.78	1.80	2.27	2.25	2.69	2.68	3.36	3.36	3.86	3.99	4.45	4.74
	(1.07 - 1.74)		(1.35 - 2.13)		(1.71 - 2.69)		(1.96 - 3.19)		(2.27 - 4.34)		(2.42 - 5.61)		(2.56 - 7.50)	
2-hr	1.84	1.84	2.29	2.19	3.03	2.74	3.64	3.26	4.48	4.09	5.17	4.86	5.88	5.78
	(1.46 - 2.34)		(1.81 - 2.90)		(2.15 - 3.68)		(2.44 - 4.55)		(2.80 - 6.33)		(2.99 - 8.29)		(3.16 - 11.1)	
3-hr	2.03	2.03	2.54	2.41	3.35	3.03	4.00	3.60	4.93	4.52	5.71	5.37	6.53	6.38
	(1.70 - 2.60)		(1.98 - 3.23)		(2.31 - 4.30)		(2.60 - 5.31)		(2.97 - 7.45)		(3.25 - 9.82)		(3.46 - 13.1)	
6-hr	2.31	2.36	2.91	2.81	3.77	3.52	4.51	4.18	5.54	5.25	6.44	6.24	7.41	7.41
	(1.86 - 2.99)		(2.18 - 3.82)		(2.52 - 5.17)		(2.83 - 6.30)		(3.21 - 8.58)		(3.50 - 11.2)		(3.75 - 15.0)	
12-hr	2.55	2.70	3.21	3.21	4.13	4.03	4.94	4.79	6.14	6.01	7.15	7.14	8.20	8.48
	(2.07 - 3.25)		(2.42 - 4.14)		(2.84 - 5.56)		(3.14 - 6.77)		(3.56 - 9.26)		(3.89 - 12.2)		(4.16 - 16.3)	
24-hr	2.79	3.07	3.51	3.64	4.53	4.57	5.37	5.43	6.80	6.82	7.81	8.10	8.94	9.63
	(2.30 - 3.49)		(2.70 - 4.53)		(3.20 - 5.99)		(3.55 - 7.27)		(4.02 - 10.0)		(4.34 - 13.2)		(4.65 - 17.7)	

An IDF curve may be fit to the predicted rainfall data as discussed in Section 1.2. Equation 9 (as previously presented) was selected. This form of an IDF equation has the return period included. The derived coefficients for the mid-century and end of century projections are provided in Table 9. Coefficients presented for the minimum and maximum values shown in Table 9 represent the predicted range based on the different climate models.

$$i = \frac{\alpha T^\beta}{t^c + b} \quad \text{(Equation 9)}$$

where i = rainfall intensity (inches per hour)
 t = storm duration (minutes)
 T = return period (years)

Table 9 Coefficients for Equation 9

County		b	c	α	β
Mid Century	Median	6.7713	0.8321	52.4348	0.2498
	Min	5.8802	0.8306	43.5470	0.1567
	Max	8.2969	0.8522	71.0401	0.2868
End of Century	Median	6.7164	0.8351	56.3097	0.2484
	Min	7.3336	0.8615	53.8482	0.1564
	Max	6.2462	0.8092	58.9531	0.3161

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APPENDIX A – PRECIPITATION IDF UNDER FUTURE CLIMATE

Precipitation Intensity-Duration-Frequency under Future Climate, SEMCOG Region, Michigan

**Prepared for
Southeast Michigan Council of Governments**

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Contents

1	Introduction.....	1
2	Methods	3
2.1	NOAA Atlas 14 IDF Curves	3
2.2	Theoretical Basis for Updating IDF Curves.....	3
2.3	Atlas 14 IDF Curves Update Approach using Generalized Extreme Value Distribution.....	5
3	Future Climate Scenarios.....	7
3.1	Selection of Future Climate Scenarios	7
3.2	Historic Climate Data.....	9
4	Results	11
4.1	IDF Curves for 10-year Recurrence for Mid-century.....	12
4.2	IDF Curves for 10-year Recurrence for End-of-the-century	16
4.3	IDF Curves for 25-year Recurrence for Mid-century.....	20
4.4	IDF Curves for 25-year Recurrence for End-of-the-century	24
4.5	IDF Curves for 100-year Recurrence for Mid-century.....	28
4.6	IDF Curves for 100-year Recurrence for End of the century	32
5	Discussion	37
6	References	39

List of Tables

Table 1. Dynamically Downscaled Climate Scenarios Provided by the Center for Climatic Research (Notaro et al., 2015).....	8
Table 2. Selected NOAA Atlas 14 Weather Stations	10

List of Figures

Figure 1. Historical Precipitation in Lower Southeast Michigan through 2017 (from GLISA, http://glisa.umich.edu/division/mi10).....	1
Figure 2. Predicted Change in Days per Decade with Precipitation Greater than 3” for Mid-century Conditions in the MIROC5-RegCM4 and IPSL-RegCM4 Model Outputs (https://www.nelson.wisc.edu/ccr/resources/dynamical-downscaling/index.php).....	9
Figure 3. Location of Selected Weather Stations in Southeast Michigan.....	10
Figure 4. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-0230.....	12
Figure 5. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-2102.....	12
Figure 6. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-2103.....	13
Figure 7. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-3947.....	13
Figure 8. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-5452.....	14
Figure 9. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-6658.....	14
Figure 10. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-9218.....	15
Figure 11. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 76-0065.....	15
Figure 12. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-0230.....	16
Figure 13. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-2102.....	16
Figure 14. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-2103.....	17
Figure 15. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-3947.....	17
Figure 16. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-5452.....	18
Figure 17. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-6658.....	18
Figure 18. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-9218.....	19
Figure 19. End-century IDF Curves for 10-year Recurrence Precipitation of site 76-0065.....	19
Figure 20. Mid-century IDF Curves for 25-year Recurrence Precipitation of site 20-0230.....	20
Figure 21. Mid-century IDF Curves for 25-year Recurrence Precipitation of site 20-2102.....	20
Figure 22. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2103.....	21
Figure 23. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-3947.....	21

Figure 24. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-5452.....	22
Figure 25. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-6658.....	22
Figure 26. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-9218.....	23
Figure 27. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 76-0065.....	23
Figure 28. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-0230.....	24
Figure 29. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2102.....	24
Figure 30. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2103.....	25
Figure 31. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-3947.....	25
Figure 32. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-5452.....	26
Figure 33. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-6658.....	26
Figure 34. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-9218.....	27
Figure 35. End-century IDF Curves for 25-year Recurrence Precipitation for Site 76-0065.....	27
Figure 36. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-0230....	28
Figure 37. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2102....	28
Figure 38. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2103....	29
Figure 39. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-3947....	29
Figure 40. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-5452....	30
Figure 41. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-6658....	30
Figure 42. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-9218....	31
Figure 43. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 76-0065....	31
Figure 44. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-0230....	32
Figure 45. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2102....	32
Figure 46. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2103....	33
Figure 47. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-3947....	33
Figure 48. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-5452....	34
Figure 49. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-6658....	34
Figure 50. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-9218....	35
Figure 51. End-century IDF Curves for 100-year Recurrence Precipitation for Site 76-0065....	35

Acronyms

AEP	Annual Exceedance Probability
AMP	Annual Maximum Precipitation
AMS	Annual Maximum Series
ARI	Average Recurrence Interval
CCR	Center for Climatic Research, University of Wisconsin - Madison
CDF	Cumulative Distribution Function
CMIP5	Coupled Model Intercomparison Project Round 5
EQM	Equidistant Quantile Mapping
GCM	Global Climate Model (General Circulation Model)
GEV	Generalized Extreme Value Distribution
GLISA	Great Lakes Integrated Sciences + Assessments
IDF	Intensity Duration Frequency
IPCC	Intergovernmental Panel on Climate Change
MDOT	Michigan Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
PDS	Partial Duration Series
QM	Quantile Mapping
RCPs	Representative Concentration Pathways
SEMCOG	Southeast Michigan Council of Governments

1 Introduction

Recent flood events in the southeast Michigan area have caused significant impacts to transportation infrastructure and have demonstrated that the system, and particularly the depressed freeways, are not resilient as desired. For example, 6 inches of rainfall in an 8-hour period resulted in over \$1.8 billion in damages and a federal disaster declaration in August 2014 (SEMCOG, 2018). Unfortunately, these types of flood events are projected to occur more frequently and potentially be even more severe over time due to climate change. To stay ahead of this mounting risk, the Southeast Michigan Council of Governments (SEMCOG) and Michigan Department of Transportation (MDOT) are seeking to develop a better understanding of where they are vulnerable. This information can then be used to strategically guide planning and investments in the continued safe and efficient operation of the region's transportation network.

The SEMCOG region has a humid continental climate. Most of the annual precipitation falls during the summer months in the form of afternoon thunderstorms. Analysis of precipitation records since 1950 suggests a 16% increase as a linear fit through 2017 relative to a 1951-1980 historical reference period, with possible acceleration since 2000 (Figure 1).

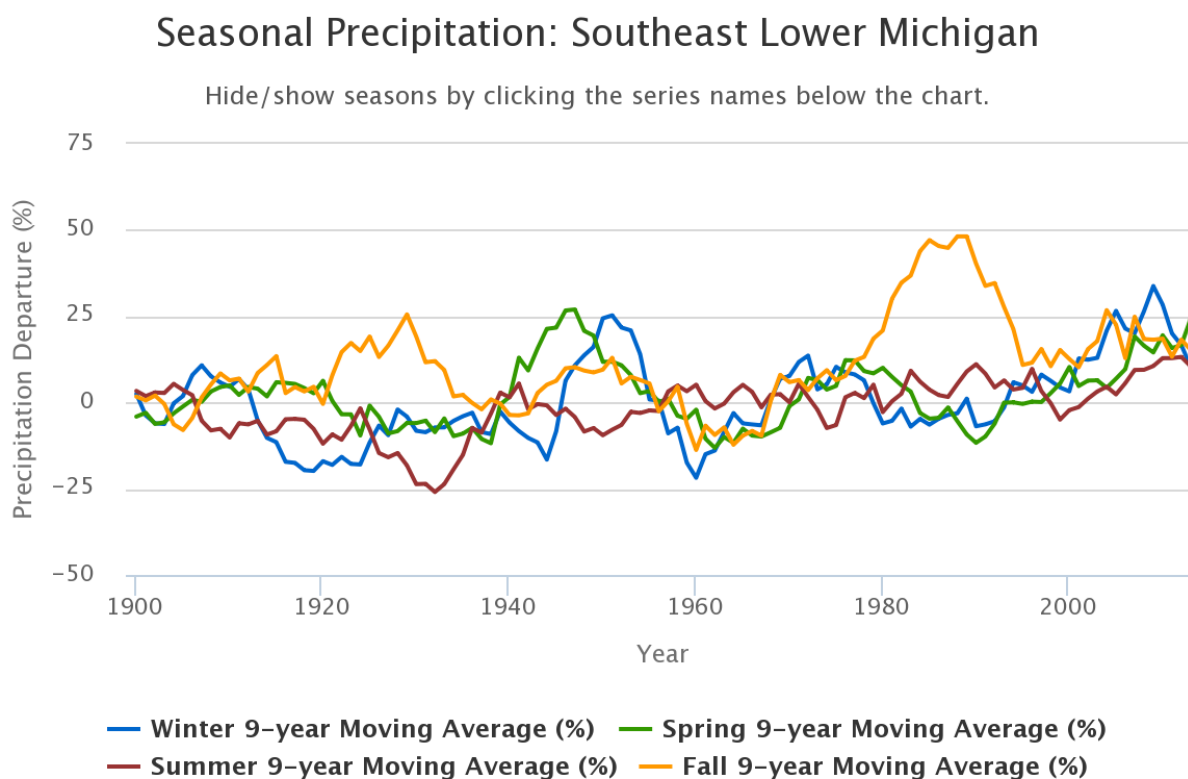


Figure 1. Historical Precipitation in Lower Southeast Michigan through 2017 (from GLISA, <http://glisa.umich.edu/division/mi10>).

Climate change is expected to increase the severity and frequency of extreme high temperature and intense precipitation events in Southeast Michigan. Global Climate or General Circulation Models (GCMs) have a high skill level for predicting changes in average air temperature as a function of global greenhouse gas concentrations, but are less clear as to changes in precipitation, especially for extreme

events and local scales, which are not well-resolved in global models. Rather than relying on direct output of GCMs to evaluate the range of potential future extreme precipitation events, it is necessary to apply downscaling and bias-correction techniques to evaluate risk.

Highway flood risk is evaluated from precipitation intensity-duration-frequency (IDF) relationships. Rainfall data in MDOT's Drainage Manual (2003) was developed by Michigan Technological University and is based on fitting statistical extreme value distributions to the series of annual maximum precipitation depths (AMPs). IDF curves graphically and tabularly summarize the relationship between precipitation intensity and the duration of precipitation events for a given frequency or recurrence interval.

For this study, we worked with a suite of climate model projections that have been downscaled using a regional climate model (RCM) to produce results that capture some of the complex interactions between the Great Lakes and nearby land areas. We use the relative change between extreme value statistics for model output for historic and future climate conditions to map expected changes in the IDF curves developed for Southeast Michigan by NOAA.

Southeast Michigan faces a range of significant transportation impacts from climate change, creating risks and resiliency challenges now and into the future. Understanding those risks and options for improving resiliency is an important step toward developing and prioritizing effective adaptation strategies. This work aims to develop a flooding risk assessment for major Interstates, US highways, and state routes in the project area, with the goal of providing alternative recommendations for climate resiliency goals for MDOT's Long Range Transportation Plan. In addition, this understanding of future climate conditions in the area is informative to general storm water management planning in Southeast Michigan, consistent with objectives outlined in SEMCOG's mission.

2 Methods

2.1 NOAA ATLAS 14 IDF CURVES

Intensity-Duration-Frequency (IDF) curves graphically summarize the relationship between precipitation intensity and the duration of precipitation events for a given frequency or recurrence interval. IDF curves provide important information for engineering design and planning purposes. In the U.S., estimates of precipitation frequency for specific geographic locations are provided as IDF curves and tables in NOAA's Atlas 14 (Perica et al., 2013). The specific objective of this task is to update the NOAA Atlas 14 IDF curves for the SEMCOG region to reflect potential future changes in local climate. To satisfy this objective it is important to understand the way in which the Atlas 14 estimates were created. Specifically, frequency estimates in the Atlas are based on fitting a generalized extreme value (GEV) distribution to the time series of annual maximum precipitation (AMP) amounts at a station for seventeen durations ranging from 15 minutes to 60 days. The AMP series consists of one measurement per year, and does not account for the possibility of more than one event in a year exceeding a threshold of interest. The true probability of occurrence of events of a given intensity and duration should be derived from the partial duration series, which includes all events of a specified duration and above a pre-defined volume threshold. Frequency estimates for partial duration series were developed by NOAA from the series of AMPs using Langbein's conversion formula, which transforms a partial duration series-based average recurrence interval (ARI) to an annual exceedance probability (AEP):

$$AEP = 1 - \exp\left(-\frac{1}{ARI}\right) \quad (2-1)$$

Selected partial duration ARIs were first converted to AEPs using this formula, and frequency estimates were then calculated for the AEP using the GEV fit to annual maxima. This means that only the annual maximum series is needed for future climate conditions and not the complete or partial duration series.

NOAA fit the GEV for each station using the method of L-moments (Hosking and Wallis, 1997), incorporating regionalization across approximately the 10 nearest stations for higher order L-moments. NOAA intentionally does not release the fitted coefficients of the GEV distribution, although the annual maximum series are provided (see item 1.7 at <http://www.nws.noaa.gov/oh/hdsc/FAQ.html>).

The NOAA method is ultimately based only on annual maxima (the AMP series), and not analysis of continuous weather time series. This has important implications for the mathematical approach to updating the IDF curves, as described below.

2.2 THEORETICAL BASIS FOR UPDATING IDF CURVES

As noted above, the primary objective of this work is to evaluate potential changes to IDF curves in NOAA Atlas 14 under future climate, which requires understanding how the extreme value distribution fit to annual maximum precipitation series may change. Over the past decade researchers have proposed a variety of methods for updating IDF curves. These have generally been characterized by a high level of complexity and computational intensity, a lack of consensus, and concerns regarding whether non-stationarity is properly accounted for. Typically, the proposed methods have worked with complete future downscaled precipitation series, even though the Atlas 14 IDF curves depend only on the AMP series.

A simple, more direct, and computationally efficient approach to updating IDF curves was recently proposed by Srivastav et al. (2014a, 2014b). Their insight was that the essence of the problem was the need to update extreme value distributions for future conditions, and that this could be done through a

direct analysis of the distributions. The general concept of the approach of Srivastav et al. (2014a) is described as follows: "...quantile-mapping functions can be directly applied to establish the statistical relationship between the AMPs of a GCM and sub-daily observed data rather than using complete records. Further, the IDF is a distributional function; therefore, it would be easy to derive the functional relationships between the distributions of the GCM AMPs and sub-daily observed data. One way of deriving such relationship is by using quantile-mapping functions."

Quantile mapping (QM) methods, otherwise known as cumulative distribution function (CDF) matching methods, have long been used as a method to correct for local biases in GCM output. The method first establishes a statistical relationship or transfer function between model outputs and historical observations, then applies the transfer function to future model projections (Panofsky and Brier, 1968) and has been successfully used as a downscaling method in various climate impact studies (e.g., Hayhoe et al., 2004).

Using the notation of Li et al. (2010), for a climate variable x , the QM method for finding the bias-adjusted future value of a climate variable can be written as:

$$\hat{x}_{m-p.adjst.} = F_{o-c}^{-1} \left(F_{m-c} (x_{m-p}) \right) \quad (2-2)$$

where F is the CDF of either the observations (o) or model (m) for observed current climate (c) or future projected climate (p), and F^{-1} is the inverse of the cumulative distribution function. The bias correction for a future period is thus done by finding the corresponding percentile values for these future projection points in the CDF of the model for current observations, then locating the observed values for the same CDF values of the observations.

A significant weakness of the QM method is that it assumes that the climate CDF does not change much over time, and that, as the mean changes, the variance and skew do not change, which is likely not true (e.g., Milly et al., 2008). To address these issues, Li et al. (2010) proposed the equidistant quantile mapping (EQM) method, which incorporates additional information from the CDF of the model projection. The method assumes that the difference between the model and observed value during the current calibration period also applies to the future period; however, the difference between the shape of the CDFs for the future and historic periods is also taken into account. This is written as:

$$\hat{x}_{m-p.adjst.} = x_{m-p} + F_{o-c}^{-1} \left(F_{m-p} (x_{m-p}) \right) - F_{m-c}^{-1} \left(F_{m-p} (x_{m-p}) \right), \quad (2-3)$$

where the form and parameters of the CDF are not yet specified. Srivastav et al. (2014a) argue for using EQM to update IDF curves; however, the specific method of Srivastav et al. (2014b) is not directly applicable to updating Atlas 14 IDF curves in the US for several reasons:

- Canada assumes that the AMP series follows a Gumbel, rather than a GEV distribution.
- Bias-corrected statistically downscaled climate model output is not widely available for Canada, therefore the Srivastav method must also incorporate a spatial downscaling step from the coarse scale of GCMs, whereas output that is already spatially downscaled to a fine resolution grid is readily available for the US.
- The method of Srivastav et al. justifies use of EQM, but largely consists of a multi-step QM procedure, without the additional EQM corrections.

To address these issues Tetra Tech developed an EQM method that is consistent with U.S. design guidelines and that can make use of either statistically or dynamically downscaled climate data derived from GCM output.

2.3 ATLAS 14 IDF CURVES UPDATE APPROACH USING GENERALIZED EXTREME VALUE DISTRIBUTION

The EQM approach can be used to update IDF curves for any location conditional on downscaled output of GCMs for future climate conditions. This is implemented in Python code. The process begins with GCM output that has already been subject to spatial bias correction and downscaling to a finer (e.g., 25x25 km) spatial scale and hourly time step. The calculation step consists of additional spatial downscaling from the climate output grid to the specific point location of the first-order weather station used by Atlas 14 along with bias correction for the AMP series (as distinct from the general bias correction of the complete precipitation series) using the EQM method for different time durations from hourly to daily.

The historical data are the historical AMP series used by Atlas 14 (X_{amp}^{STN}). Model data include the predicted AMP series from 1980 to 1999 as historical period (X_{amp}^{GCM}) and two future periods (2040-2059 and 2080-2099) of interest ($X_{amp}^{GCM_{FUT}}$). A GEV distribution is fit to each of these series, using the L-moments method (Hosking and Wallis, 1997; implemented in Python in *lmoments3* v1.0.4 at <https://pypi.org/project/lmoments3/>), consistent with Atlas 14 methods:

$$\mathbf{Prob}(STN) = f(\boldsymbol{\theta}^{STN}, X_{amp}^{STN}) \quad (2-4)$$

$$\mathbf{Prob}(GCM) = f(\boldsymbol{\theta}^{GCM}, X_{amp}^{GCM}) \quad (2-5)$$

$$\mathbf{Prob}(GCM_{FUT}) = f(\boldsymbol{\theta}^{GCM_{FUT}}, X_{amp}^{GCM_{FUT}}) \quad (2-6)$$

where $f()$ is the probability density function, and $\boldsymbol{\theta}$ represents the vector of parameters of the fitted distribution (GEV for this case).

To apply the EQM method, quantiles of modeled future AMP series are matched to the distribution for historical AMPs. For a given percentile, it is assumed that the difference between the model and observed value also applies to the future period. There are two EQM factors. The first is:

$$Y_{amp}^{adj1} = F_{o-c}^{-1}(F_{m-p}(x_{m-p})) = F^{-1}((F(X_{amp}^{GCM_{FUT}} | \boldsymbol{\theta}^{GCM_{FUT}})) | \boldsymbol{\theta}^{STN}), \quad (2-7)$$

where the vertical bar “|” indicates conditional dependence, i.e., $F(X_{max}^{GCM_{FUT}} | \boldsymbol{\theta}^{GCM_{FUT}})$ indicates the cumulative distribution function of the future GCM AMP series calculated at the cumulative probability corresponding to $X_{max}^{GCM_{FUT}}$ using the parameter set $\boldsymbol{\theta}^{GCM_{FUT}}$ calculated for that future series. To account for the difference between the CDFs for the model outputs of future and current periods, a second adjustment factor is calculated:

$$Y_{amp}^{adj2} = F_{m-c}^{-1}(F_{m-p}(x_{m-p})) = F^{-1}((F(X_{amp}^{GCM_{FUT}} | \boldsymbol{\theta}^{GCM_{FUT}})) | \boldsymbol{\theta}^{GCM}) \quad (2-8)$$

The projected AMP series is then calculated as:

$$Y_{amp}^{STN_{FUT}} = X_{amp}^{GCM_{FUT}} + Y_{amp}^{adj1} - Y_{amp}^{adj2} \quad (2-9)$$

Once this series is calculated, a GEV fit is applied to estimate the full distribution of the future extreme events for the local station. This EQM step is applied to six different durations (hourly, 2 hours, 3 hours, 6 hours, 12 hours, and 24 hours) respectively to update the IDF curves at different durations. We include corrections for constrained data (i.e., results for a given duration that are artificially truncated by crossing over the midnight boundary) using the Atlas 14 factors at this step.

As noted in Atlas 14 (Perica et al., 2013), estimates for shorter durations can be noisy due to limited data availability and are improved by smoothing. To account for the short modeling simulation period, the

modeled extreme values with less than 24 hours' duration are thus smoothed by fitting them to a linear regression relative to the daily maximum series before fitting them to the GEV distribution:

$$Y_{amp}^{GCM_sub24} = a_1 * Y_{amp}^{GCM_24h} + b_1 \quad (2-10)$$

$$Y_{amp}^{GCM_FUT_sub24} = a_2 * Y_{amp}^{GCM_FUT_24h} + b_2 \quad (2-11)$$

The adjusted model predictions ($Y_{amp}^{GCM_FUT}$) are then used to fit the GEV distribution with the L-moments method, and the model predicted partial duration series (PDS) series were retrieved from the derived GEV distribution at given annual exceedance probability (AEP).

$$Y_{pds}^{GCM_FUT} = F^{-1}((F(Y_{amp}^{GCM_FUT} | \theta_Y^{GCM_FUT})) | AEP) \quad (2-12)$$

The derived IDF values at less than 24-hour durations are also smoothed by a zero-intercept linear regression relative to IDF values of 24 hours. The coefficient is constrained to be 0.99 or less to prevent any crossing in which depths for shorter durations become greater than depths for longer durations at high recurrence intervals from occurring.

$$Y_{pds}^{GCM_FUT_sub24} = a_3 * Y_{pds}^{GCM_FUT_24h} \quad (2-13)$$

The final future 24-hour IDF ordinates are estimated by multiplying the Atlas 14 published values by the ratio of fitted GEV PDS results for climate-adjusted future conditions to the fitted GEV PDS results obtained for the Atlas 14 observed data:

$$IDF_{FUT}^{24h} = IDF_{Atlas}^{24h} * \frac{Y_{STN}^{GCM_FUT}}{Y_{STN}}, \quad (2-14)$$

This last step adjusts for the regional representation of higher L moments that is incorporated in the original Atlas 14 calculations but not explicitly documented.

For durations less than one hour, Atlas 14 (Perica et al., 2013) relates 15 and 30-minute durations to the 60-minute duration using local scaling factors:

$$S = \frac{X_k^{Atlas_14}}{X_{60-minute}^{Atlas_14}}, \quad k=15 \text{ minutes or } 30 \text{ minutes.} \quad (2-15)$$

The same scaling factors are applied for the future IDF estimates. Fixed scaling factors are used in Atlas 14 for deriving 10-minute and 5-minute annual maxima. The ratio of the 10-minute annual maximum to the 15-minute annual maximum is assumed to be 0.82 in Atlas 14 and the ratio for the 5-minute annual maxima is 0.57. These assumptions are also applied to future climate conditions.

3 Future Climate Scenarios

3.1 SELECTION OF FUTURE CLIMATE SCENARIOS

GCMs are not weather predictions; they present possible future climates conditional on ongoing policy and energy choices, filtered by model assumptions. It is therefore necessary to look at multiple GCM predictions to establish the range of likely futures.

The IPCC (2013) has released the 5th Reassessment Report, incorporating results from a new round of GCM runs (CMIP5). CMIP5 incorporates many refinements to the GCMs. It also uses a different set of greenhouse gas concentration scenarios than the emissions-based scenarios that were used in CMIP3. These greenhouse gas scenarios are now referred to as Representative Concentration Pathways (RCPs) and are based on a future target radiative forcing rather than inferring the radiative forcing (e.g., RCP 4.5 represents radiative forcing of 4.5 W/m² in year 2100) from uncertain projections of future population growth, energy use patterns, and associated greenhouse gas emissions.

Future climate projections are uncertain and are best used to describe a probability envelope of potential future conditions (an “ensemble of opportunity”; Mote et al., 2011) to which adaptation may be needed. The original scope for this work called for analysis of three statistically downscaled climate scenarios that would approximate the low, medium, and high ranges of future precipitation intensity. However, this plan was modified based on input from climatologists at the Great Lakes Integrated Sciences + Assessments (GLISA) team (<http://glisa.umich.edu/>).

The opinion of the GLISA team, as stated on a conference call on March 4, 2019 between SEMCOG, ICF, and Tetra Tech, was that statistically downscaled climate products are not ideal for the southeastern Michigan area as the underlying GCMs do not fully resolve the spatial influence of the Great Lakes on local climate. While statistical downscaling relying on constructed analogs extracted from historic data can resolve spatial patterns of lake influence under historic climate, the statistical approach cannot account for systematic changes in weather patterns that may occur under future climate. It was therefore recommended that the approach be modified to use dynamically downscaled climate projections created via a Regional Climate Model (RCM) as part of the Great Lakes Ensemble Project. These projections were created using a finer-scale regional climate model to complete the downscaling, with the express intention of incorporating a process-based representation of Great Lakes climate processes.

The recommended dynamically downscaled climate products (Notaro et al., 2015) are supported by the Center for Climatic Research (CCR), Nelson Institute, University of Wisconsin-Madison (<https://www.nelson.wisc.edu/ccr/resources/dynamical-downscaling/index.php>). The associated data archive on Sciencebase (<https://www.sciencebase.gov/catalog/item/5b2d6121e4b040769c124c0c>) provides the following summary of the product:

Six global climate models (GCMs) from the Coupled Model Intercomparison Project Phase Five (CMIP5) were dynamically downscaled to 25-km grid spacing according to the representative concentration pathway 8.5 (RCP8.5) scenario using the International Centre for Theoretical Physics (ICTP) Regional Climate Model Version Four (RegCM4), interactively coupled to a 1D lake model to represent the Great Lakes. These GCMs include the Centre National de Recherches Meteorologiques Coupled Global Climate Model Version Five (CNRM-CM5), the Model for Interdisciplinary Research on Climate Version Five (MIROC5), the Institut Pierre Simon Laplace Coupled Model Version Five-Medium Resolution (IPSL-CM5-MR), the Meteorological Research Institute Coupled Global Climate Model Version Three (MRI-CGCM3), the Centre for Australian Weather and Climate Research, Australia GCM (ACCESS1-0), and the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory model (GFDL-ESM2M). The complete downscaling dataset is roughly 30 TB in size, stored on University of Wisconsin-Madison

servers. Here, we extracted a sub-region over the Northeast Climate Science Center domain for select surface variables alone. Only 20-year time chunks for 1980-1999, 2040-2059, and 2080-2099 are provided here.

Tetra Tech was requested to analyze all six model output sets in this archive. In contrast to the original plan, these six models do not necessarily represent the full range of CMIP5 GCM model outputs for the region, and only include results for RCP 8.5 (a relatively pessimistic scenario under which atmospheric CO₂ equivalent exceeds 1,370 ppm in 2100 with radiative forcing of 8.5 W/m² that is continuing to rise; see Meinshausen et al., 2011). Therefore, we cannot state that the available scenarios bound the range of potential future conditions; however, they are likely to approximate the upper bounds of end-of-century conditions.

Use of the CCR dynamically downscaled climate products introduces some other challenges as well. First, the data are provided in 20-year time chunks, which is sub-optimal for attempting to fit extreme value distributions and much shorter than the 30-year time chunks that we typically use for this sort of work. Second, the RCM output is not constrained to follow weather patterns that are similar to observed historical events. While this may be an advantage in terms of evaluating the possible future climate, it can also lead to unexpected results. For instance, some of the models predict future conditions in which short-duration sub-daily events increase greatly in intensity, but daily events do not, leading to a flattening of the IDF curves. The additional uncertainty associated with 20-year time chunks plus predicting flattening of the IDF curves created situations in which rank order was not always maintained; for instance, end-of-century predicted 3-hr duration 100-year event might be greater than the predicted 6-hr 100-yr event – an issue that we have not experienced with analysis of 30-year statistically downscaled climate output. This required the addition of some additional checks and smoothing protocols in the analysis as described in Section 2.3.

In sum, we analyzed all six CCR RCM-downscaled, RCP 8.5 climate scenarios with a spatial scale of (25 km x 25 km). For future time periods, we examined the mid-21st century (2040-2059) and the end of the century (2080-2099), taking year 1980-1999 as baseline. The hourly RCM outputs were downloaded from the Center for Integrated Data Analytics(CIDA) USGS portal (<https://cida.usgs.gov/thredds/catalog.html>).

Table 1. Dynamically Downscaled Climate Scenarios Provided by the Center for Climatic Research (Notaro et al., 2015)

Models (GCM-RCM)	CNRM-RegCM4, Miroc5-RegCM4, IPSL-RegCM4, MRI-RegCM4, ACCESS-RegCM4, GFDL-RegCM4
Scenario	RCP8.5
Time Frame	Baseline (1980-1999), Mid-century (2040-2059), End-of-century (2080-2099)

While the original proposed approach of selecting three climate scenarios to represent the potential range of future conditions was abandoned in favor of the analysis of the full set of CCR dynamically downscaled scenarios, those scenarios can still be sorted in terms of their relative change in conditions. Data visualization tools supplied by CCR include a tabulation of the change in days with precipitation greater than 3 inches, which provides a useful index to high-risk flood events. For the mid-21st century, these results suggest that the highest increases in extreme precipitation events in the SEMCOG region for the mid-21st century are provided by the MIROC5 model, with the smallest increase associated with the IPSL model (Figure 2). Note that the difference between the two is largely due to a slight southward shift in the high precipitation band from Southeast Michigan into northern Ohio in the IPSL model. However,

as will be seen below, there are significant spatial differences in which model produces the greatest future precipitation.

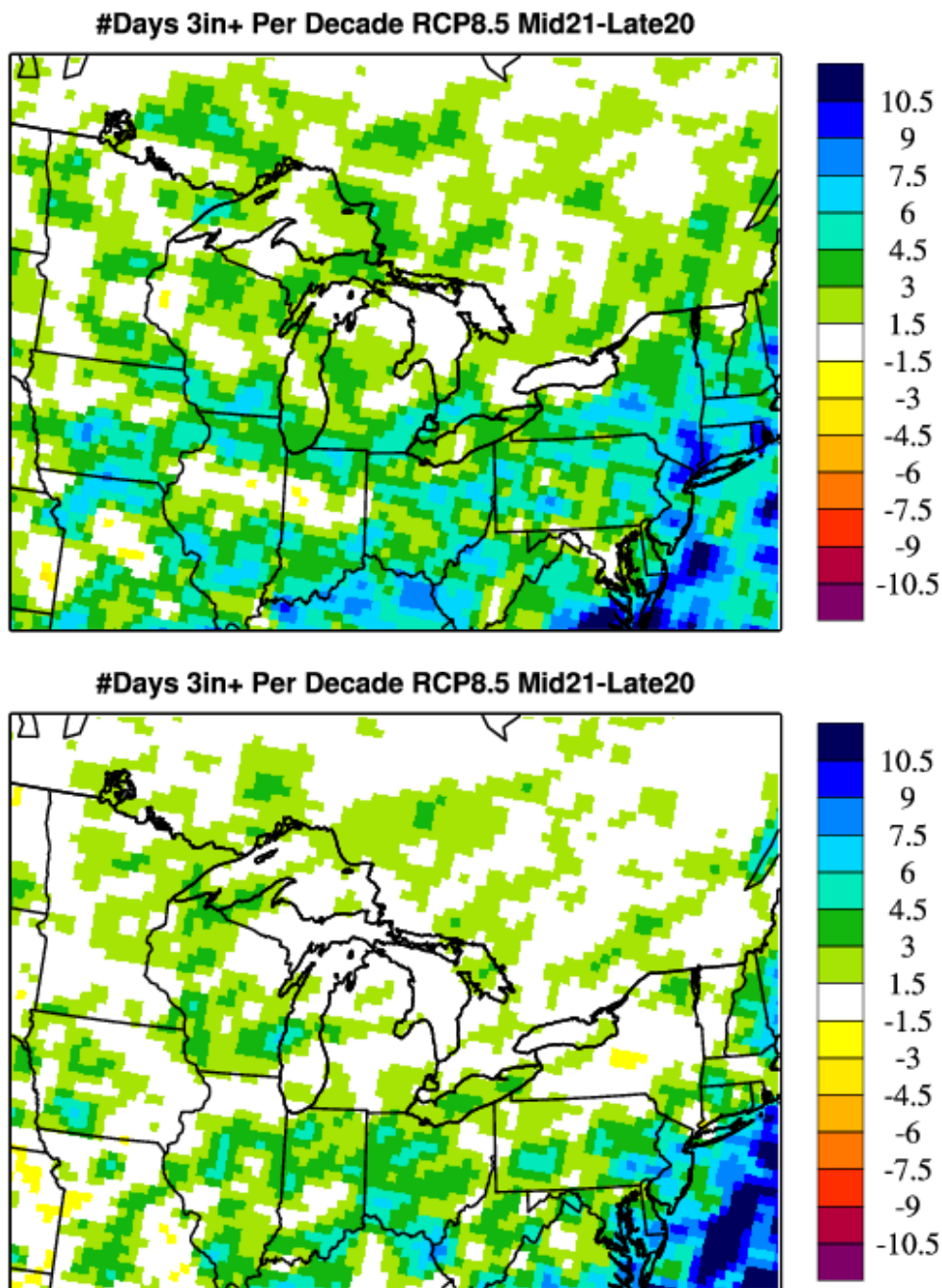


Figure 2. Predicted Change in Days per Decade with Precipitation Greater than 3” for Mid-century Conditions in the MIROC5-RegCM4 and IPSL-RegCM4 Model Outputs (<https://www.nelson.wisc.edu/ccr/resources/dynamical-downscaling/index.php>)

3.2 HISTORIC CLIMATE DATA

The annual maximum series (AMS) and partial duration series (PDS) of each weather stations used in Atlas 14 within the SEMCOG region were downloaded from NOAA Atlas 14 webpage and ftp

(ftp://hdsc.nws.noaa.gov/pub/hdsc/data/). For all the sites, only sites with both AMS and PDS data available and with longer than 25 years AMS records were selected. Table 2 and Figure 3 show the selected weather stations for this task.

Table 2. Selected NOAA Atlas 14 Weather Stations

State	Station name	Station ID	Latitude	Longitude	Elevation (ft)	Period of record
MI	ANN ARBOR U OF MICH	20-0230	42.2947	-83.7108	900	1/1880-10/2011
MI	DETROIT CITY AP	20-2102	42.4072	-83.0083	625	1/1840-12/2005
MI	DETROIT METRO AP	20-2103	42.2314	-83.3308	631	3/1897-10/2010
MI	HOWELL WWTP	20-3947	42.5939	-83.9325	917	9/1891-10/2011
MI	MILFORD GM PROVING GRD	20-5452	42.5794	-83.6844	990	1/1893-10/2011
MI	PONTIAC WWTP	20-6658	42.6389	-83.2556	890	6/1894-10/2011
MI	WAYNE - CANTON	76-0065	42.2706	-83.4753	679	3/1950-12/2001
MI	YPSILANTI E MICH U	20-9218	42.2475	-83.6253	780	1/1948-12/2010

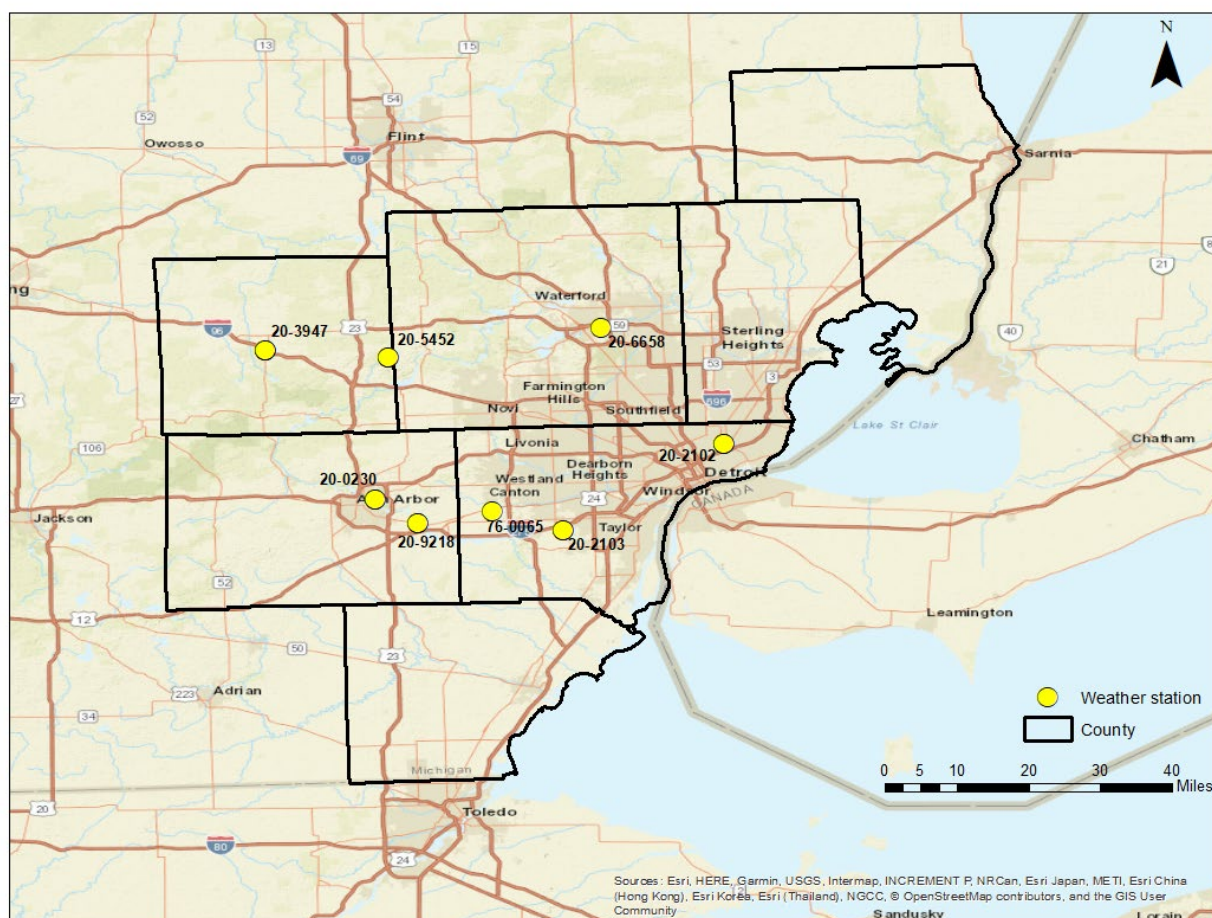


Figure 3. Location of Selected Weather Stations in Southeast Michigan

4 Results

IDF curves were calculated for 1, 2, 5, 10, 25, 50, 100, 200, 500, and 1000-year recurrence events at variety of durations ranging from 5 minutes up to 24 hours. 10, 25 and 100-year events results are presented in graphical and tabular format in Sections 4.1 through 4.6. Results for other recurrence intervals are provided electronically in the accompanying Excel files.

4.1 IDF CURVES FOR 10-YEAR RECURRENCE FOR MID-CENTURY

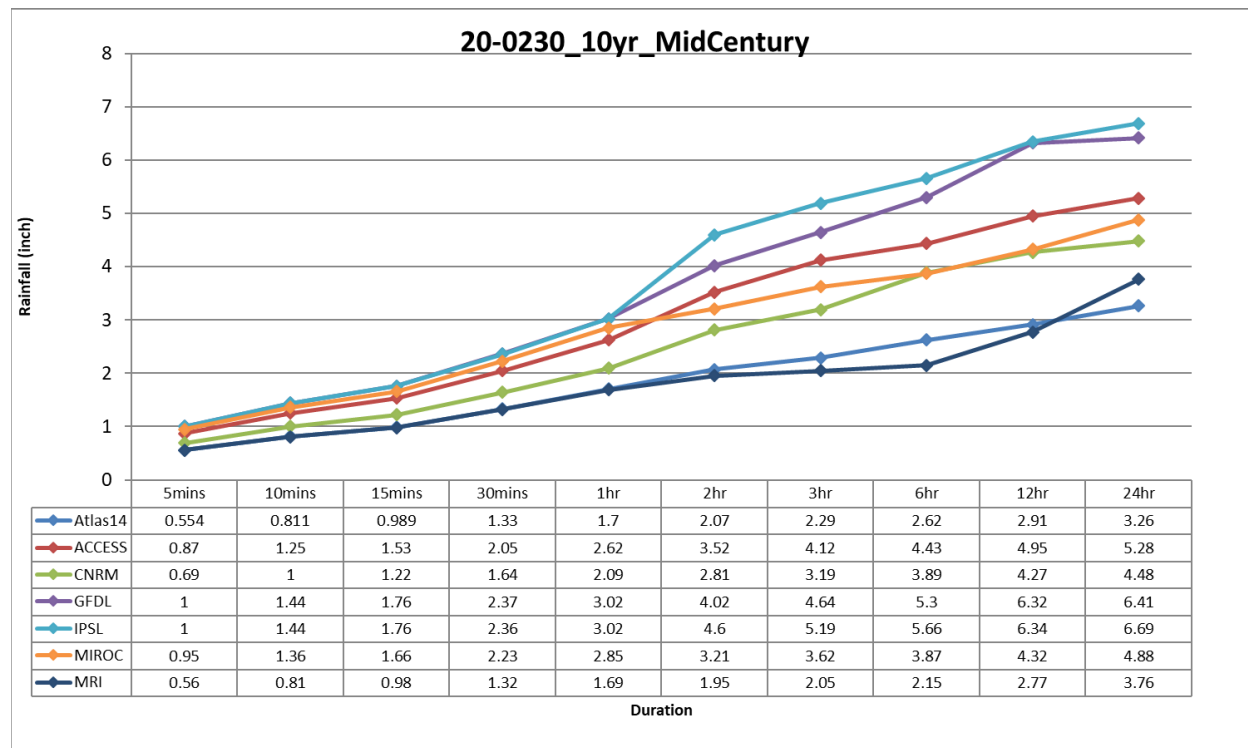


Figure 4. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-0230

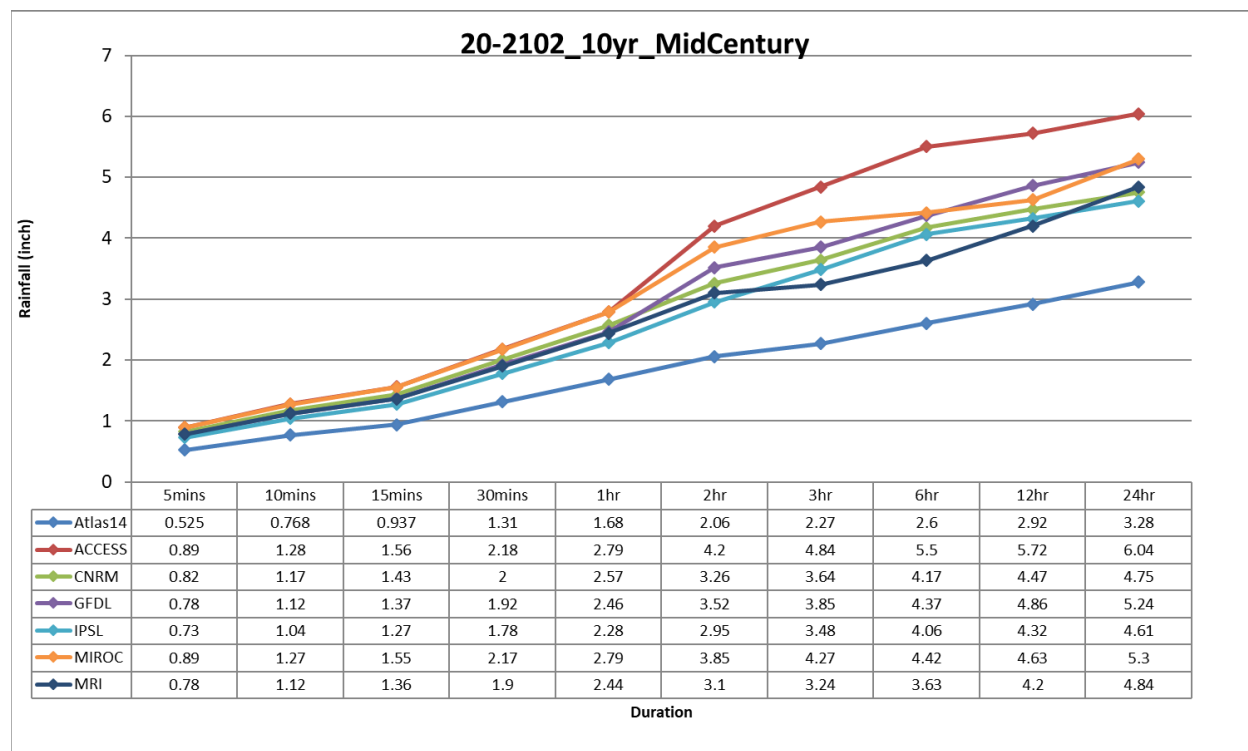


Figure 5. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-2102

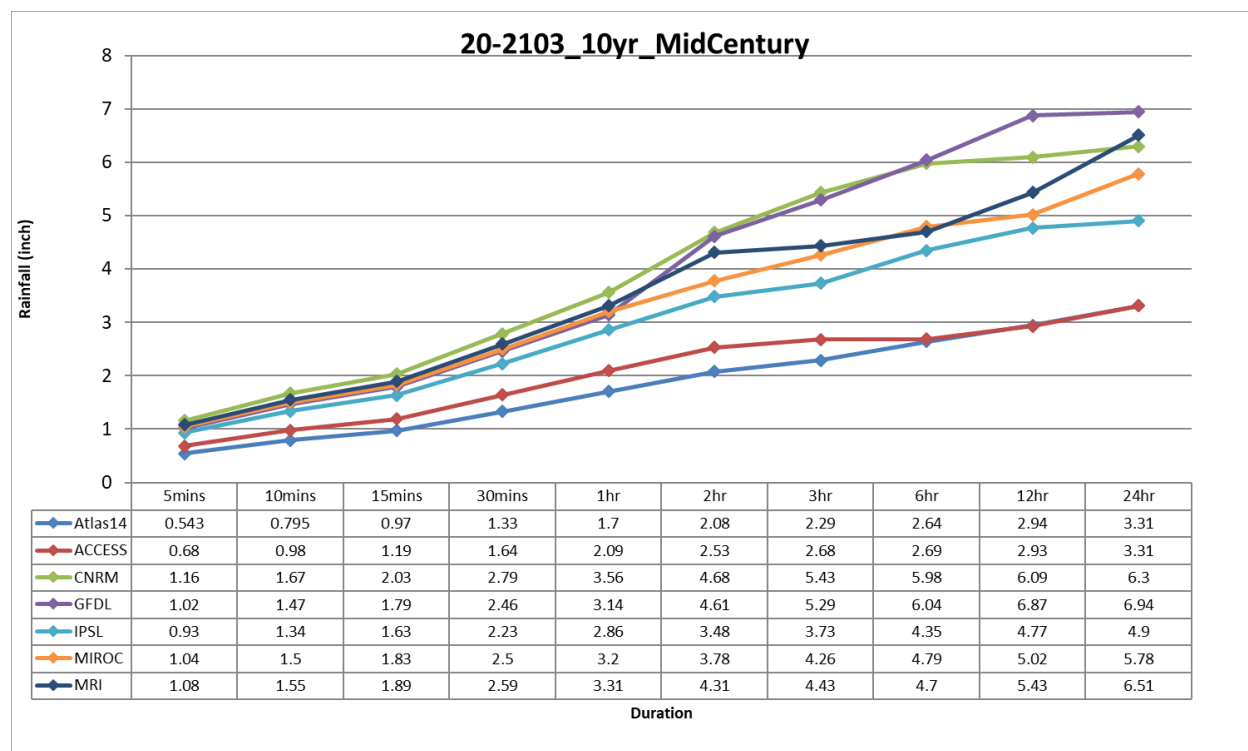


Figure 6. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-2103

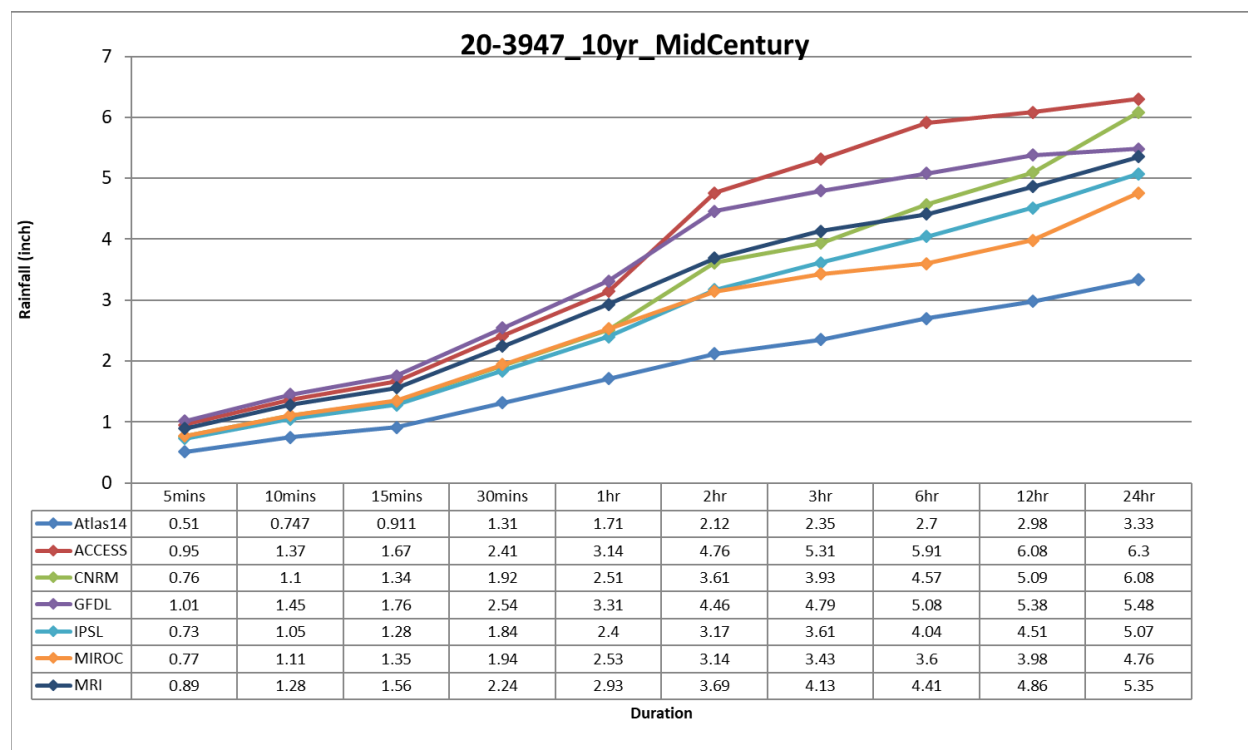


Figure 7. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-3947

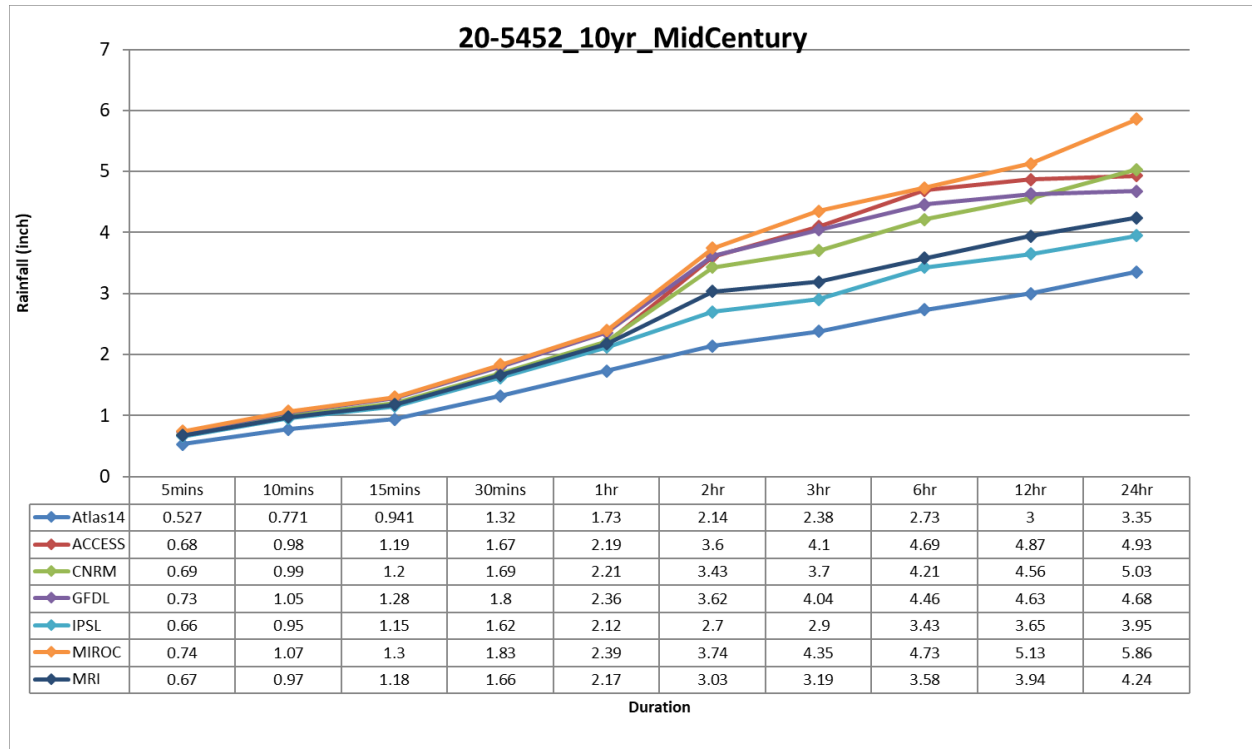


Figure 8. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-5452

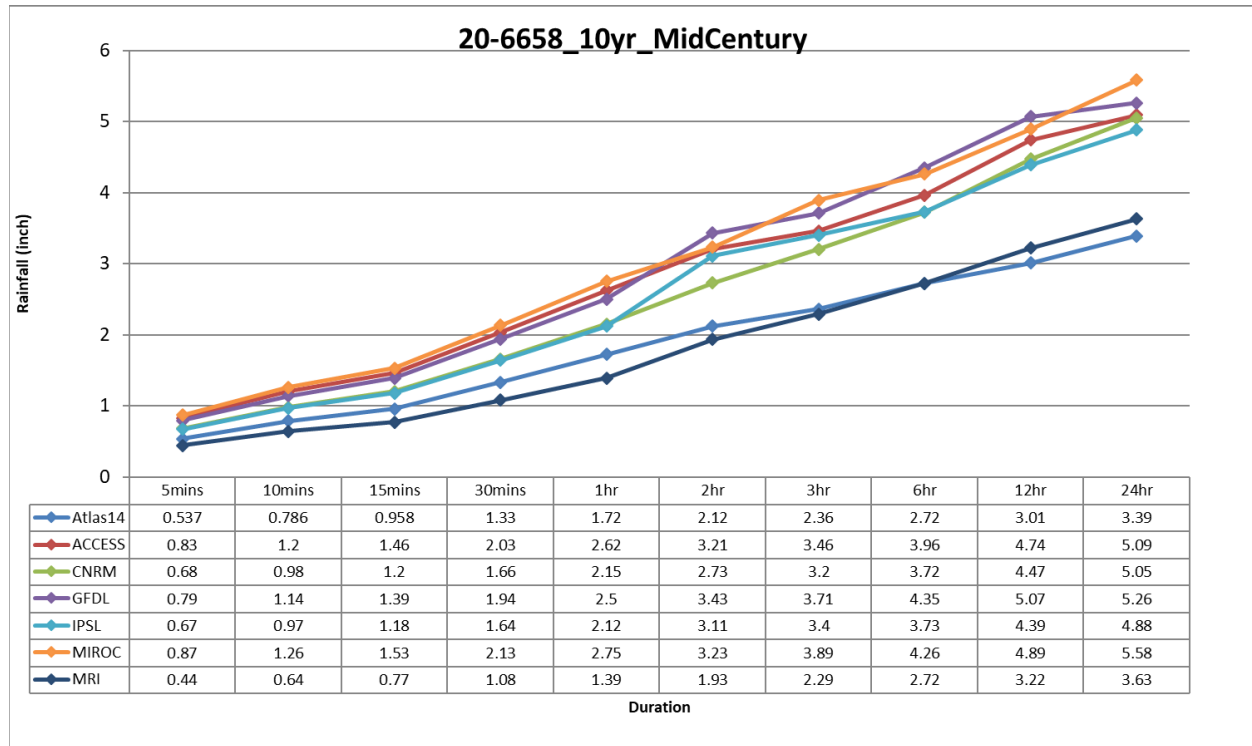


Figure 9. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-6658

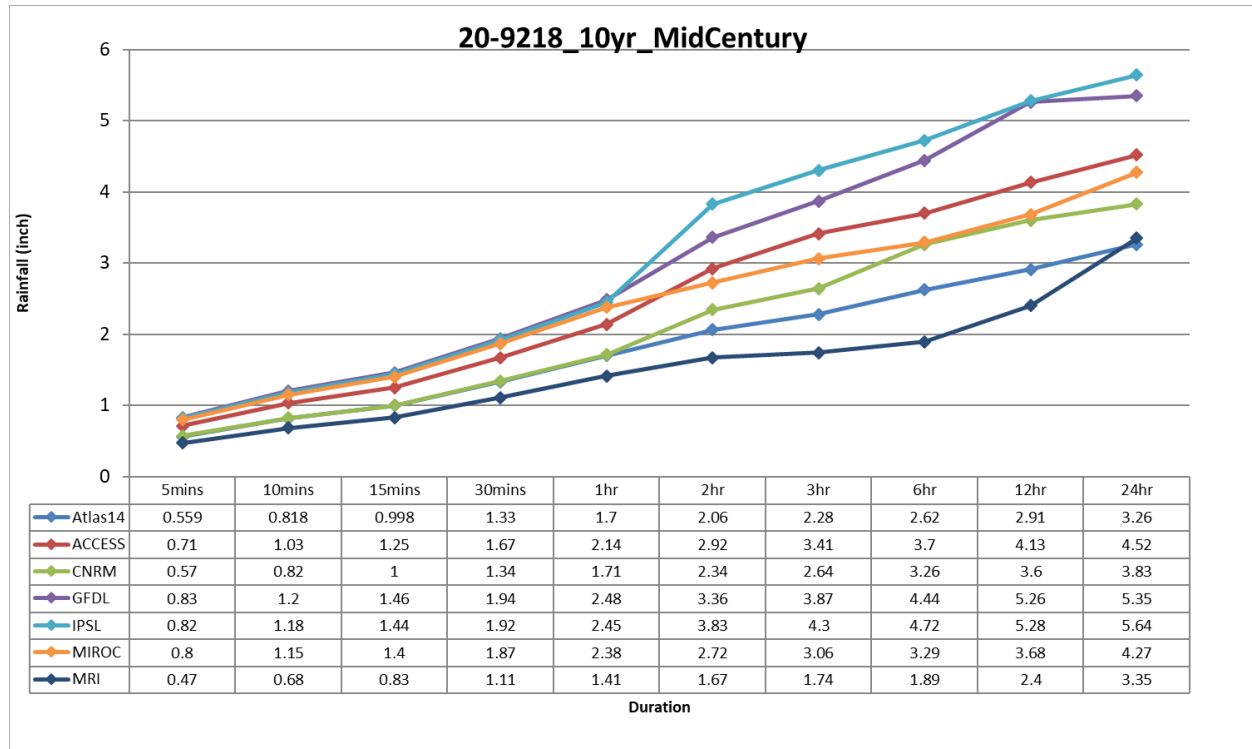


Figure 10. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 20-9218

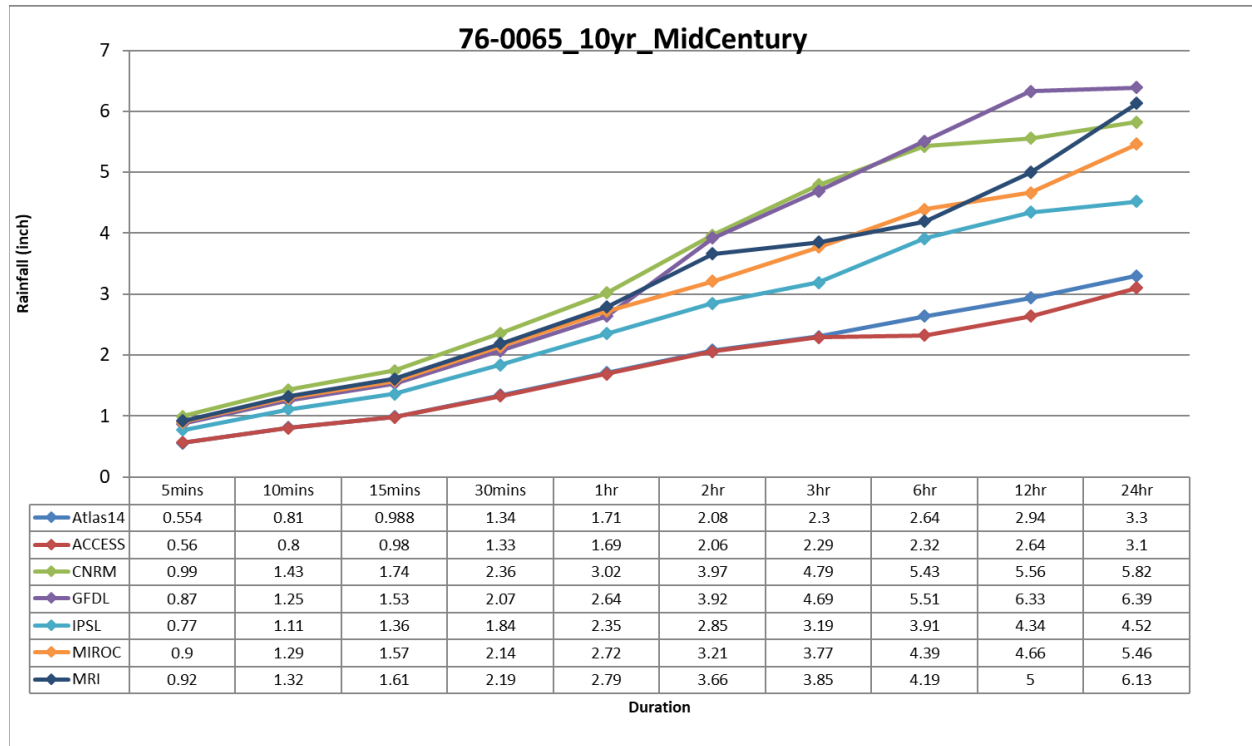


Figure 11. Mid-century IDF Curves for 10-year Recurrence Precipitation of site 76-0065

4.2 IDF CURVES FOR 10-YEAR RECURRENCE FOR END-OF-THE-CENTURY

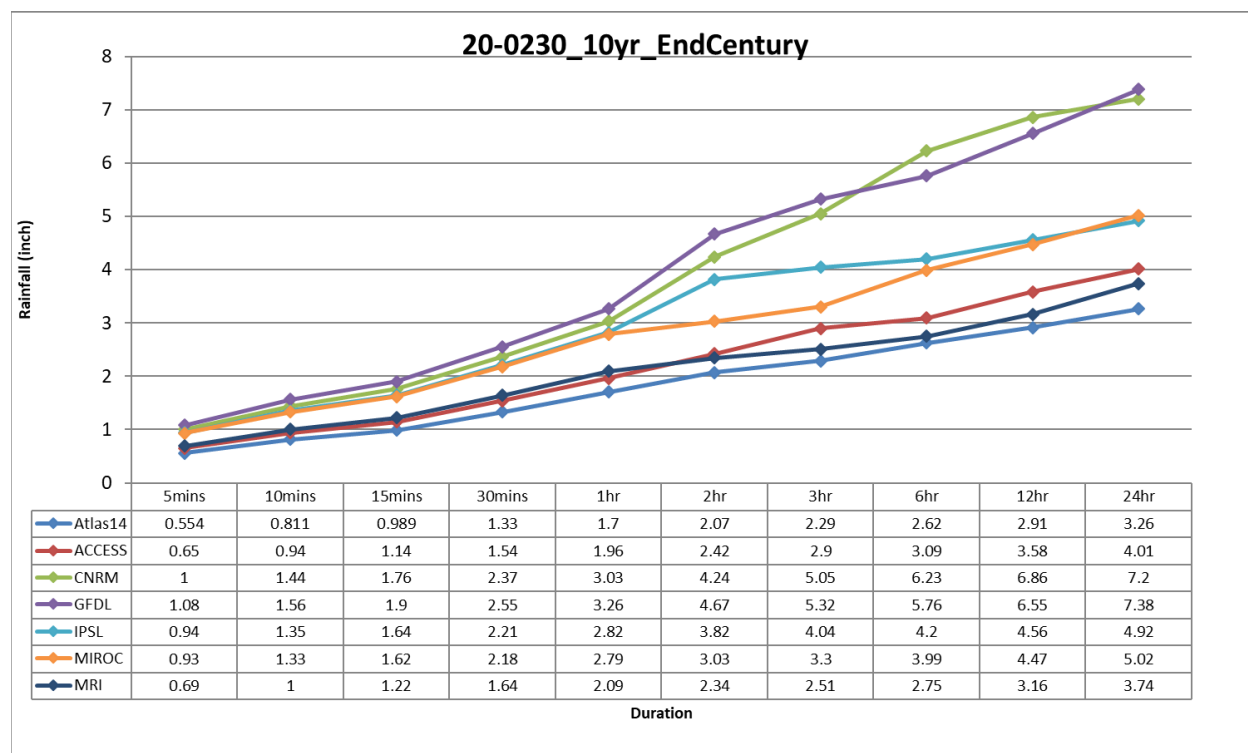


Figure 12. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-0230

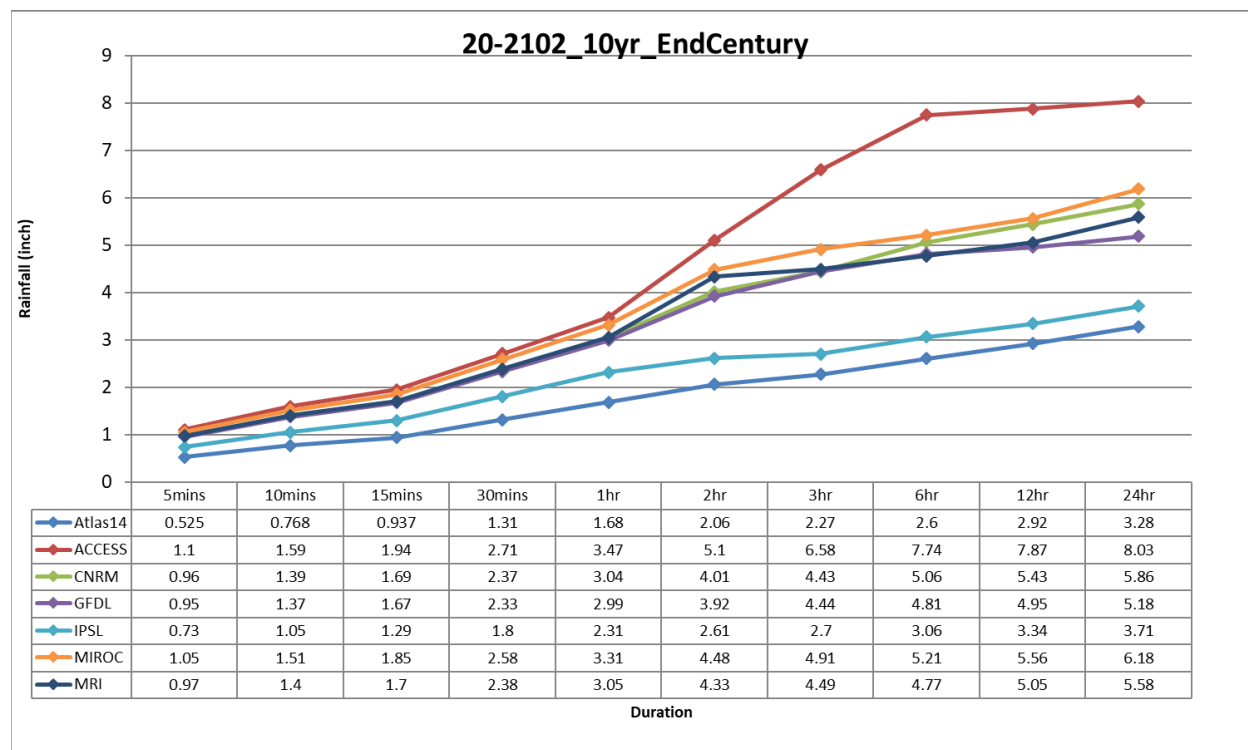


Figure 13. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-2102

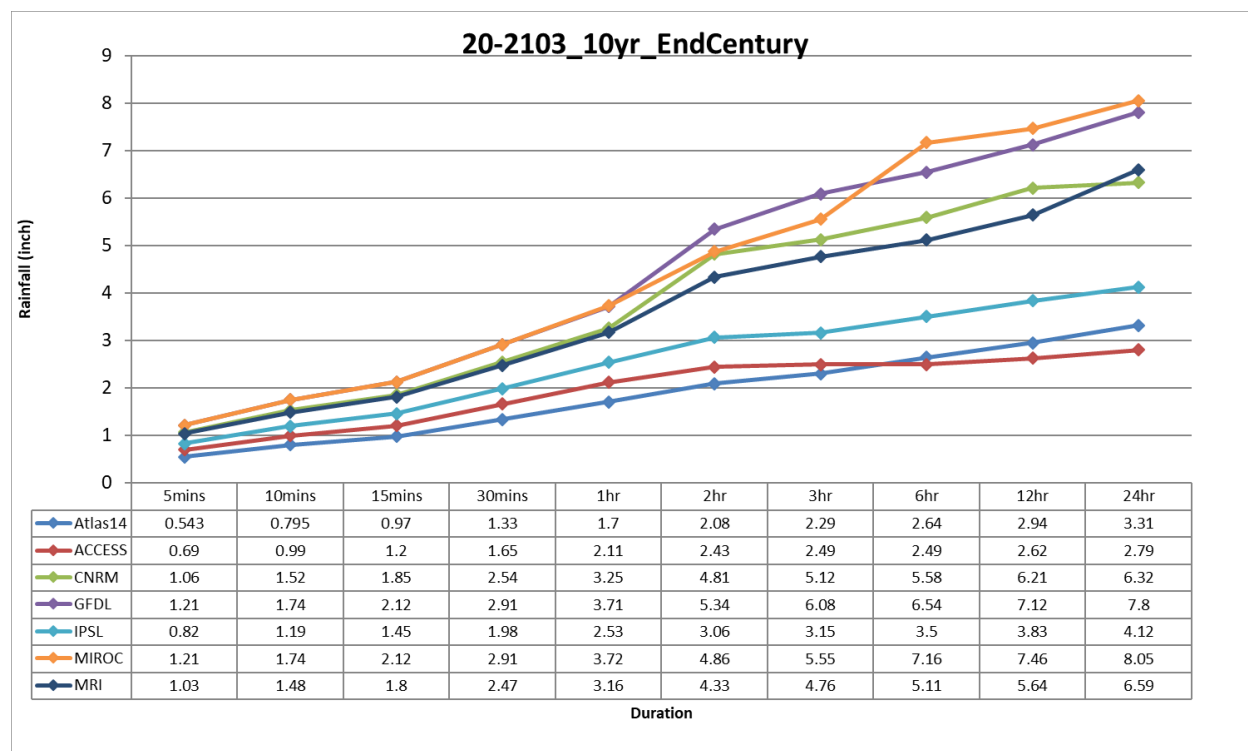


Figure 14. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-2103

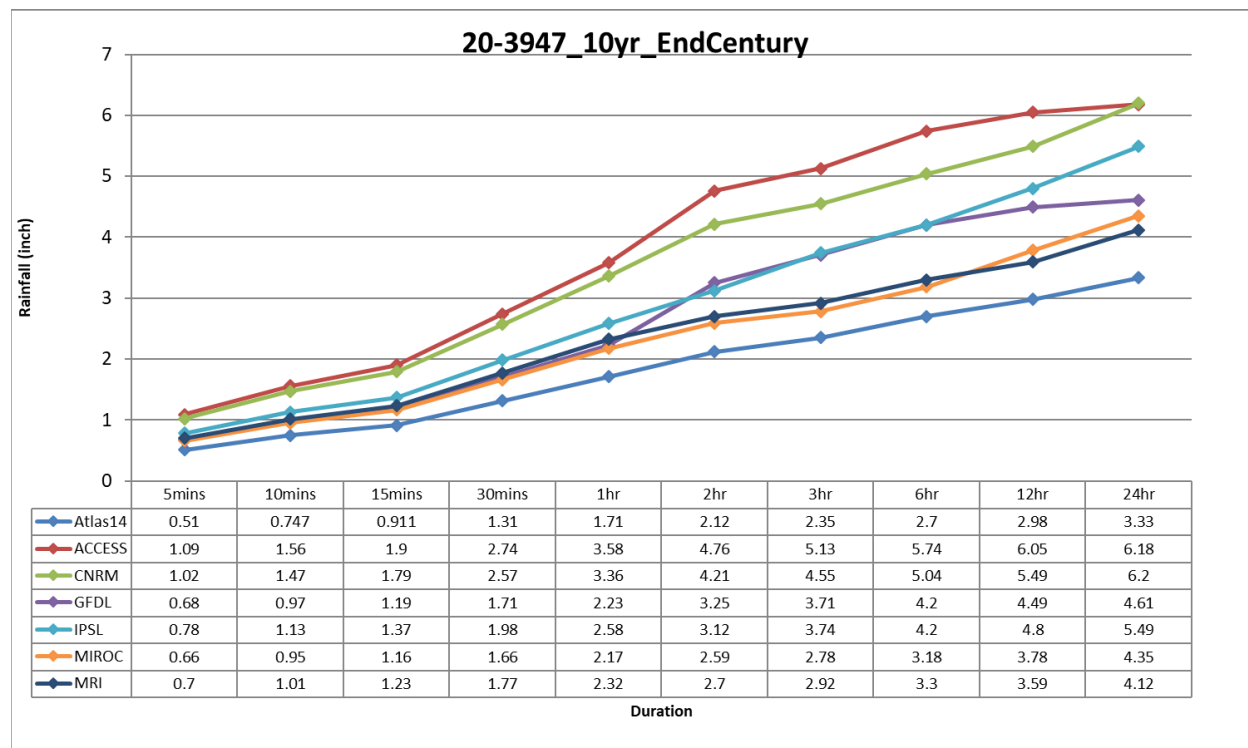


Figure 15. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-3947

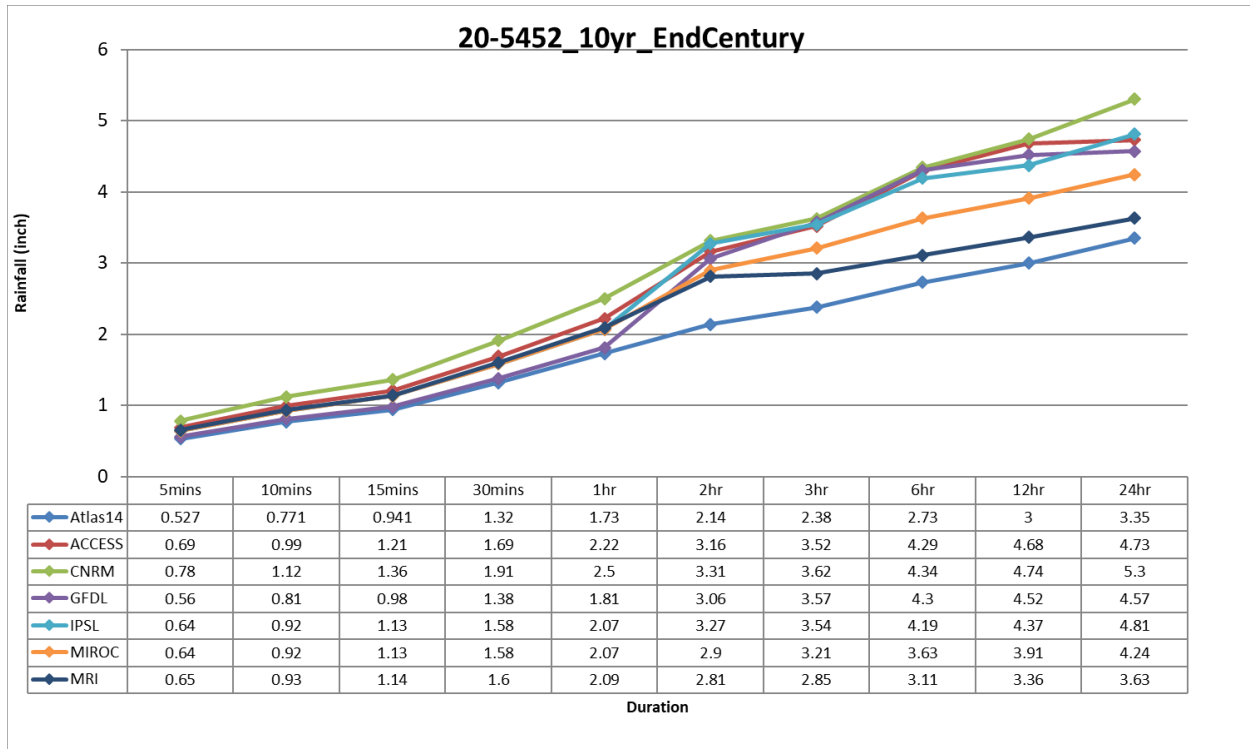


Figure 16. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-5452

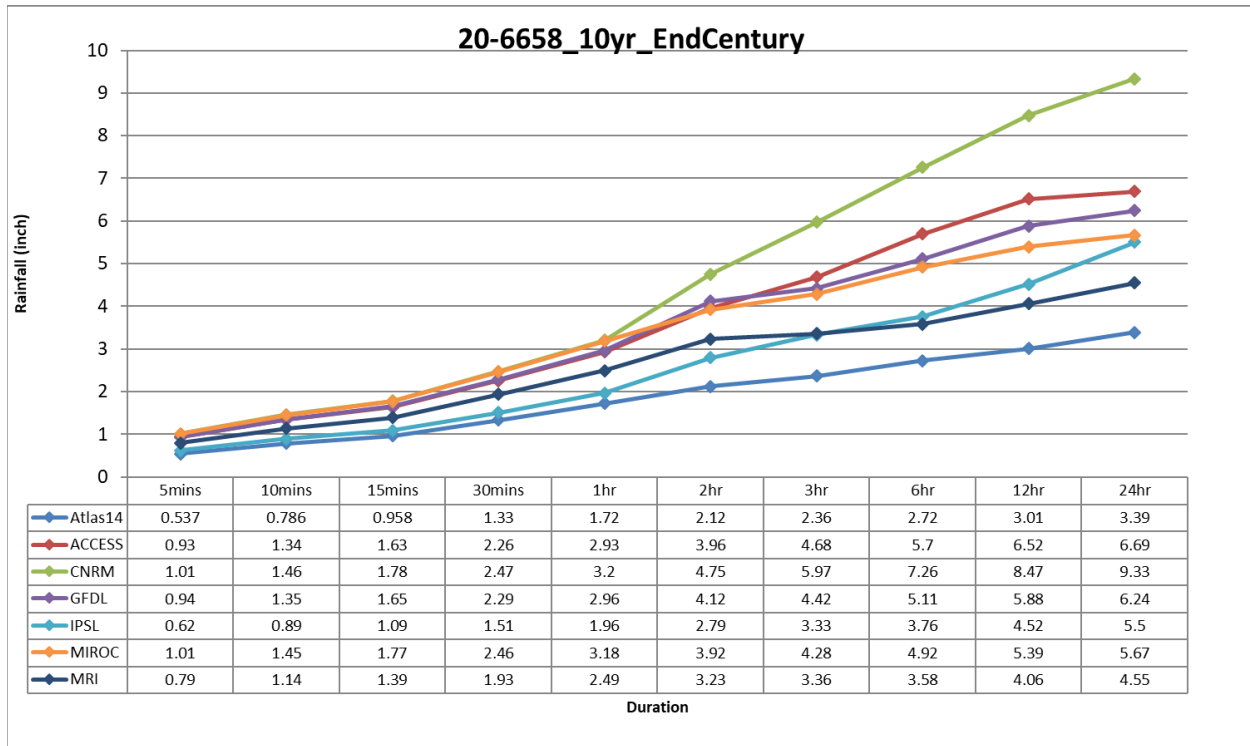


Figure 17. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-6658

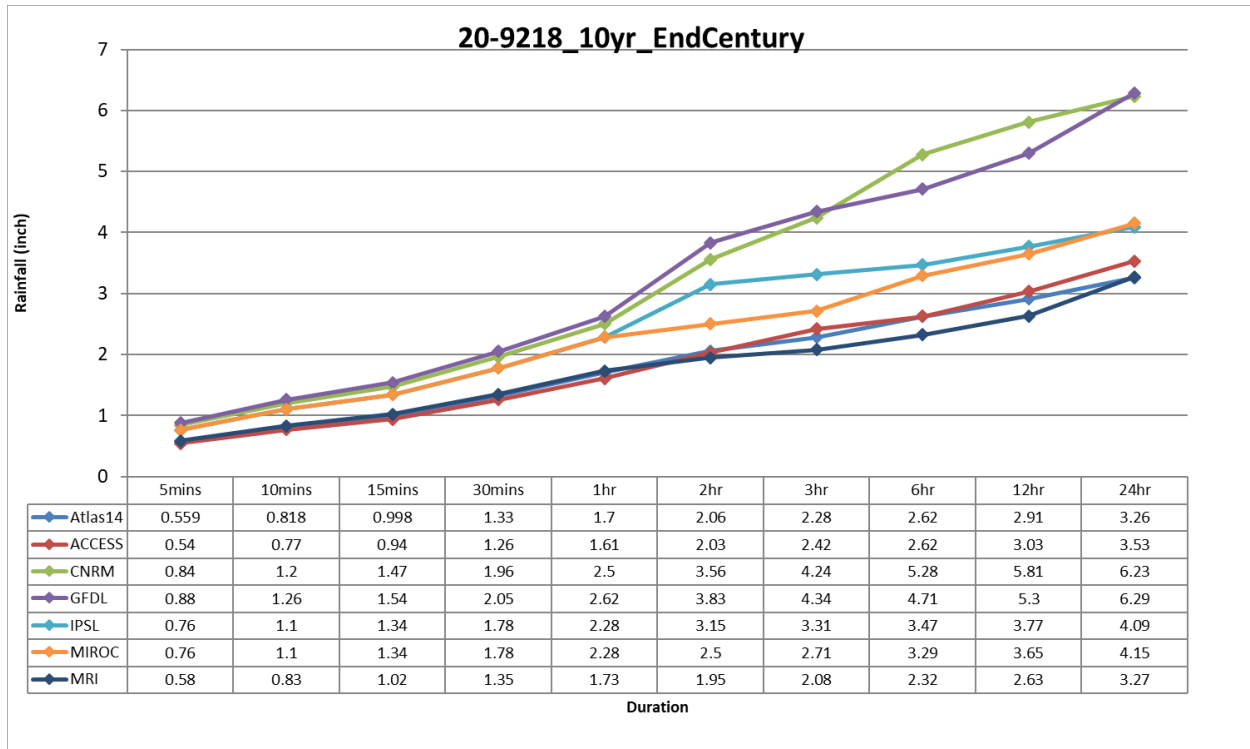


Figure 18. End-century IDF Curves for 10-year Recurrence Precipitation of site 20-9218

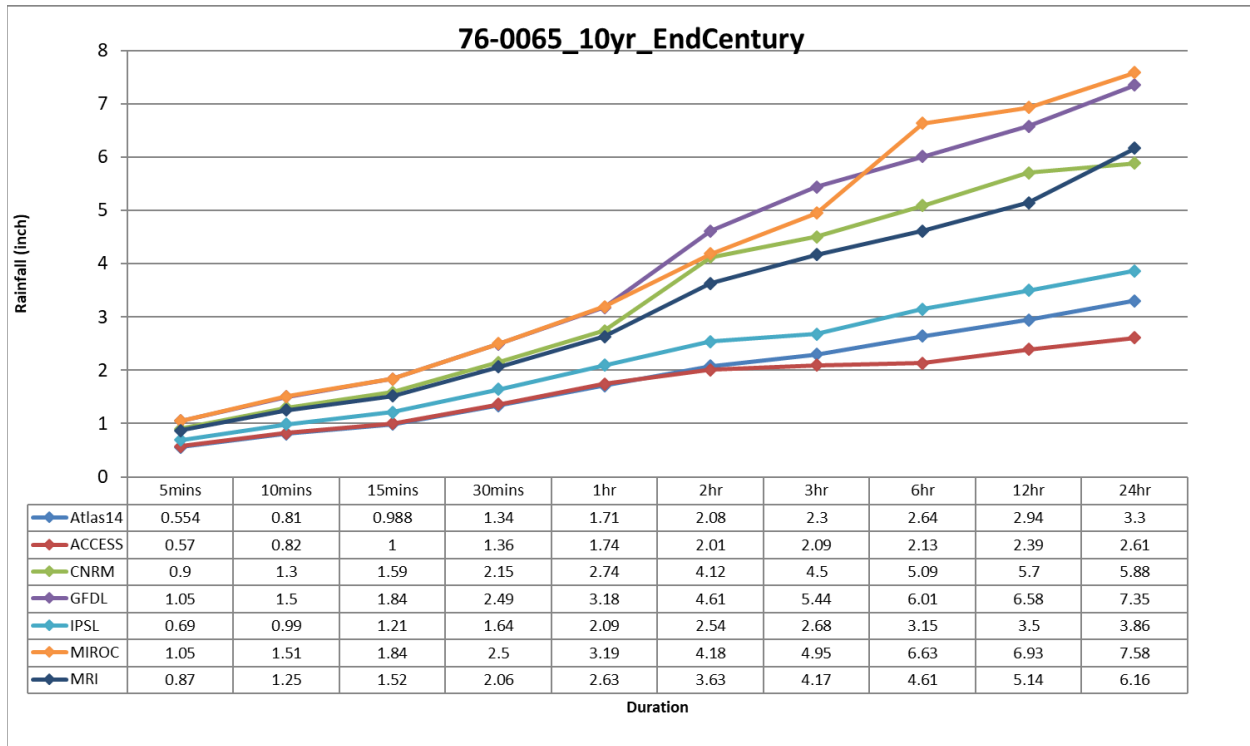


Figure 19. End-century IDF Curves for 10-year Recurrence Precipitation of site 76-0065

4.3 IDF CURVES FOR 25-YEAR RECURRENCE FOR MID-CENTURY

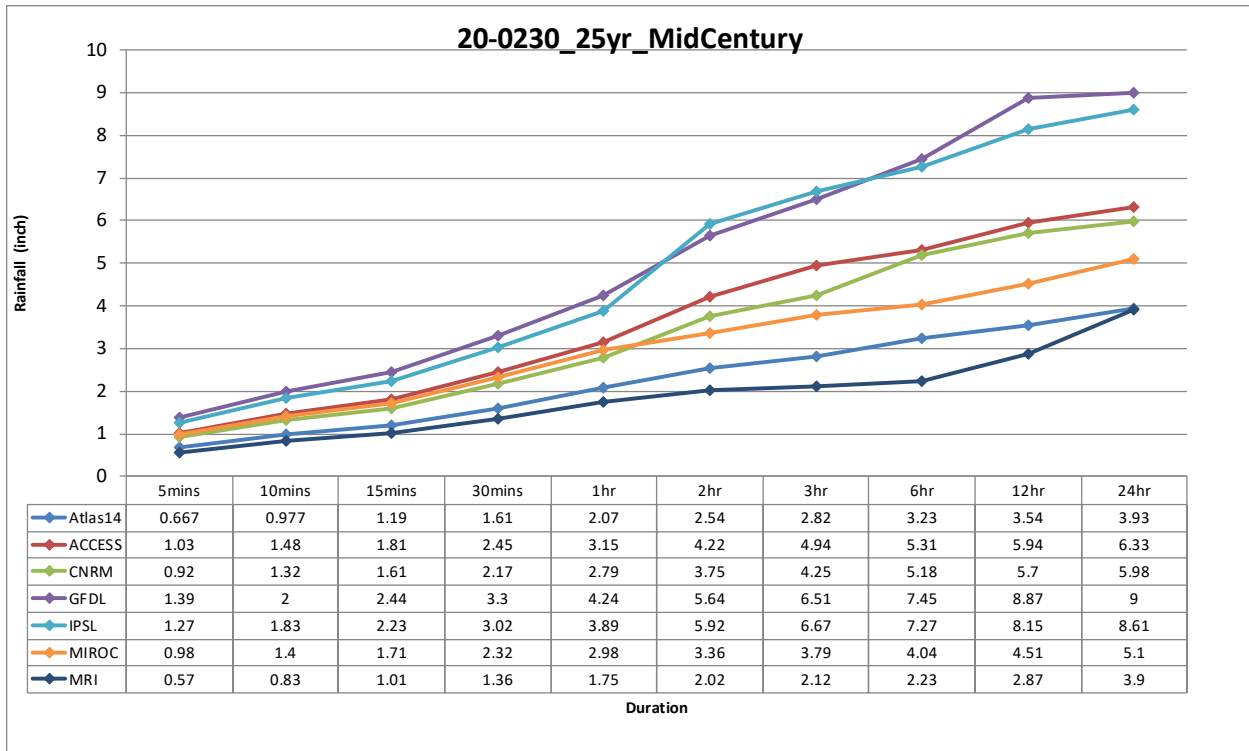


Figure 20. Mid-century IDF Curves for 25-year Recurrence Precipitation of site 20-0230

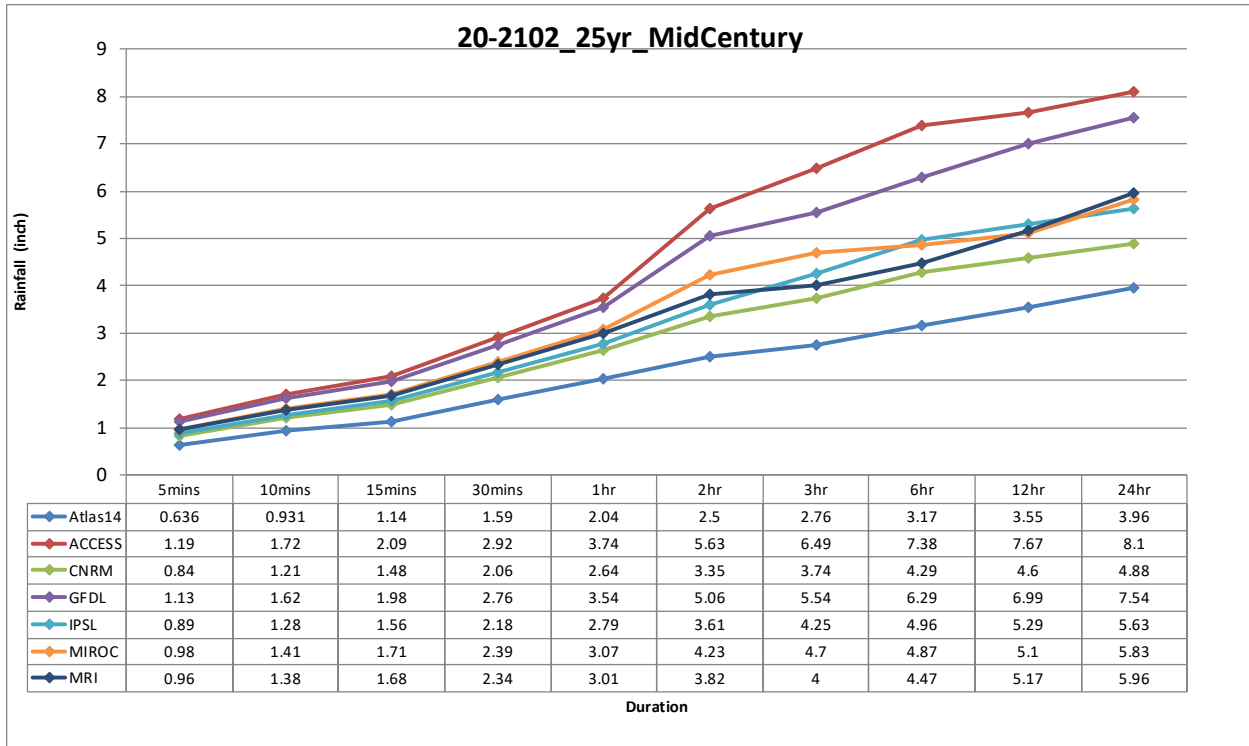


Figure 21. Mid-century IDF Curves for 25-year Recurrence Precipitation of site 20-2102

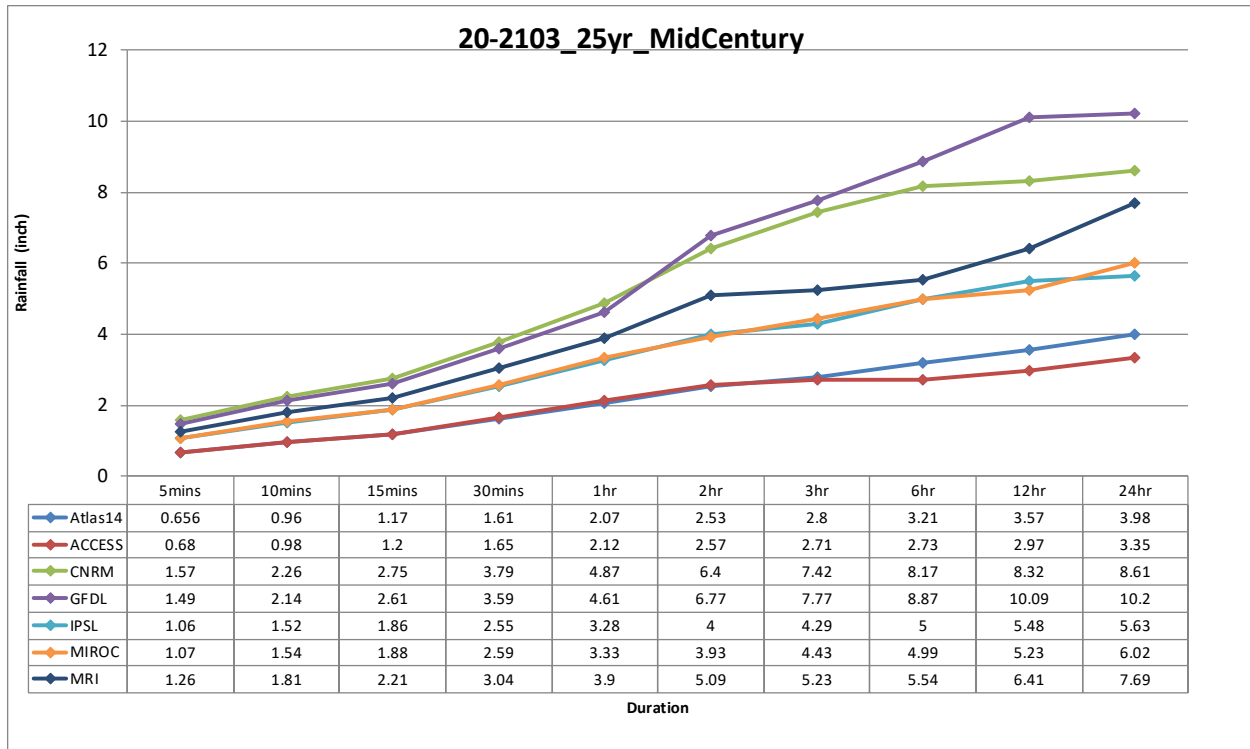


Figure 22. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2103

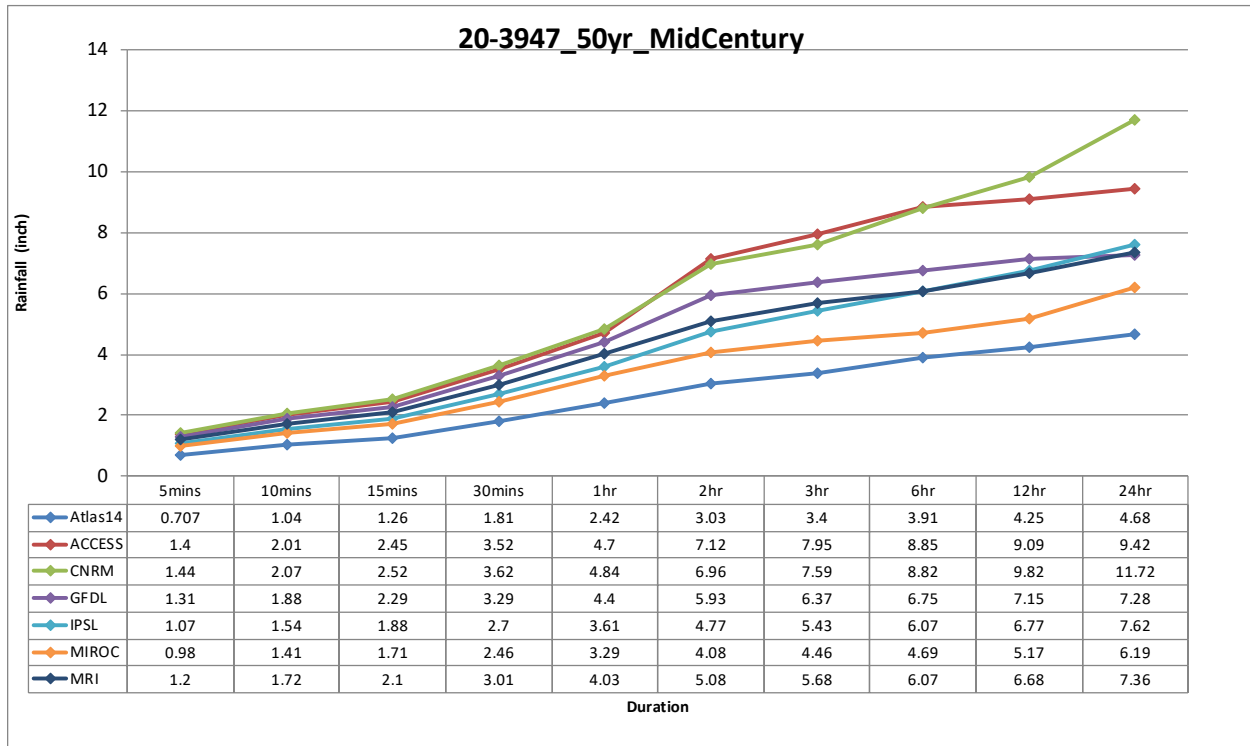


Figure 23. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-3947

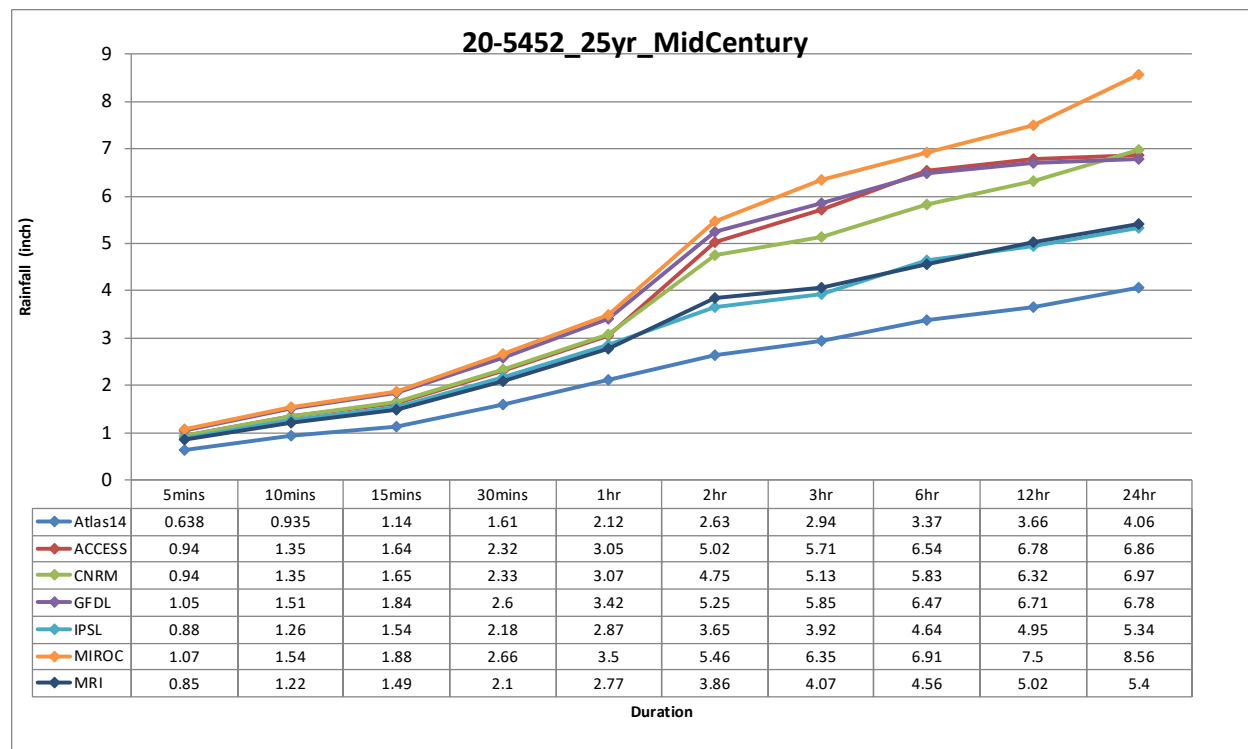


Figure 24. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-5452

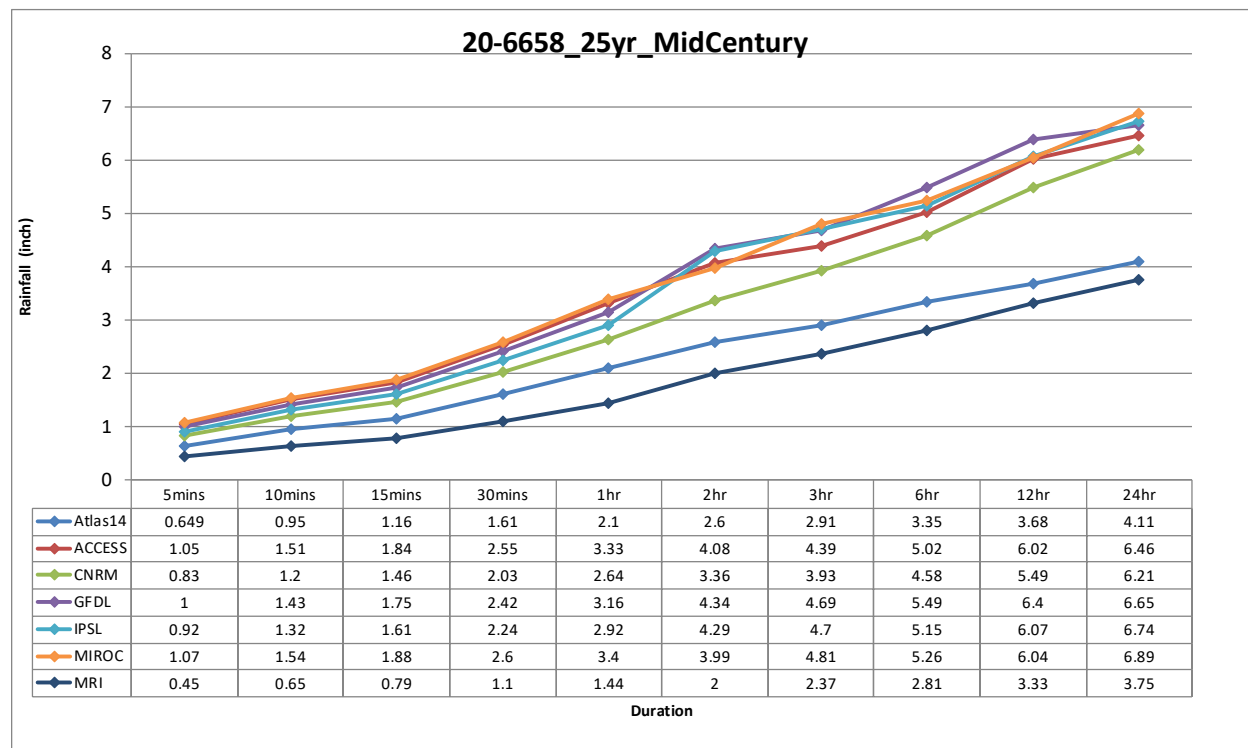


Figure 25. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-6658

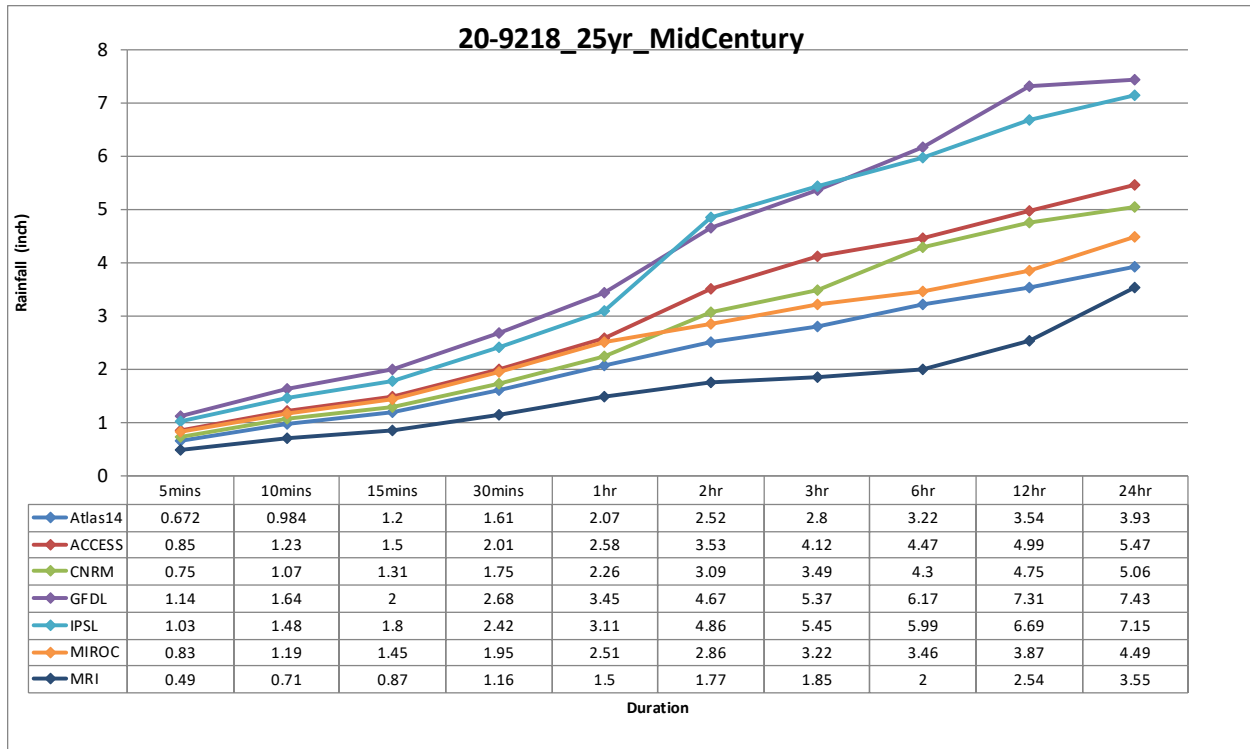


Figure 26. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 20-9218

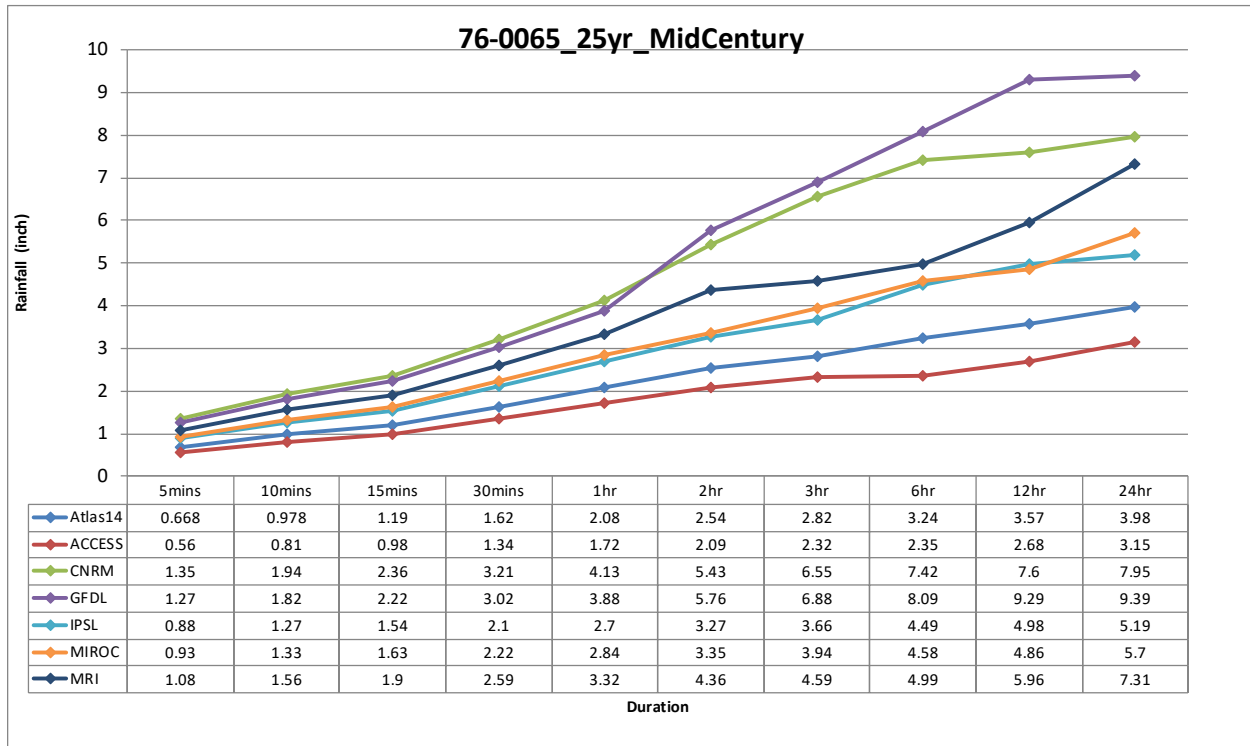


Figure 27. Mid-century IDF Curves for 25-year Recurrence Precipitation for Site 76-0065

4.4 IDF CURVES FOR 25-YEAR RECURRENCE FOR END-OF-THE-CENTURY

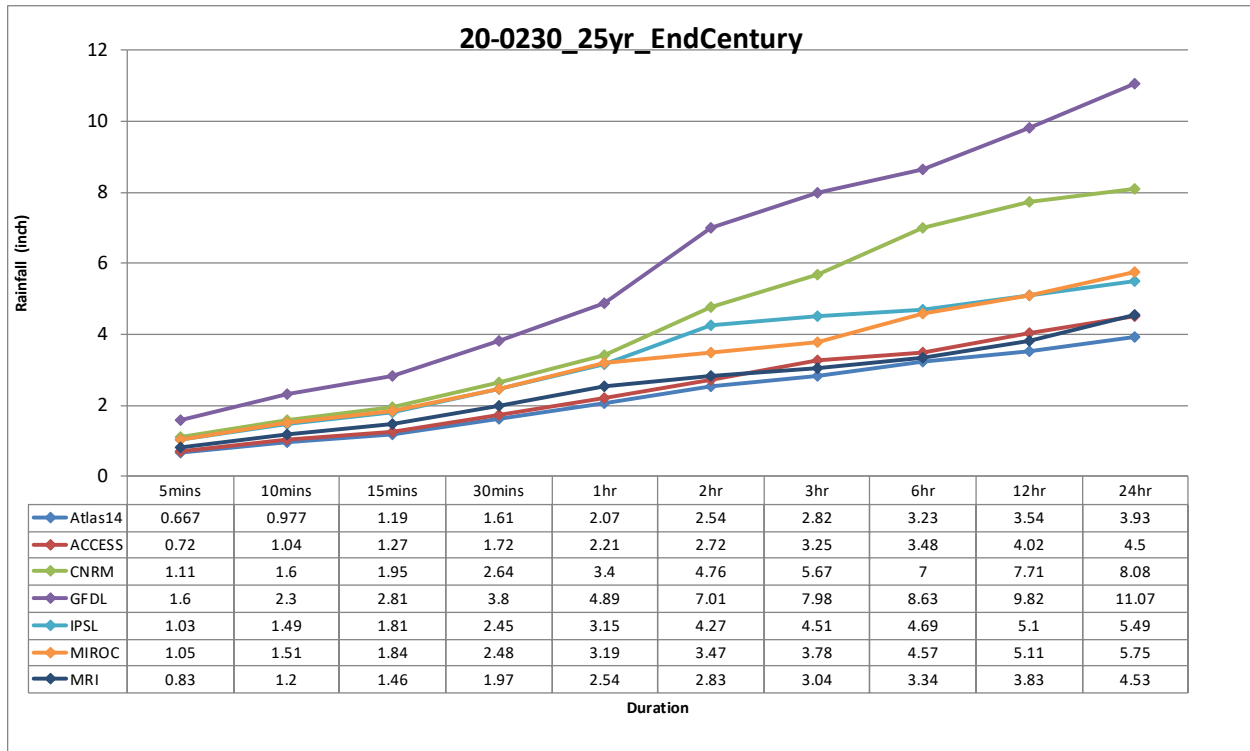


Figure 28. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-0230

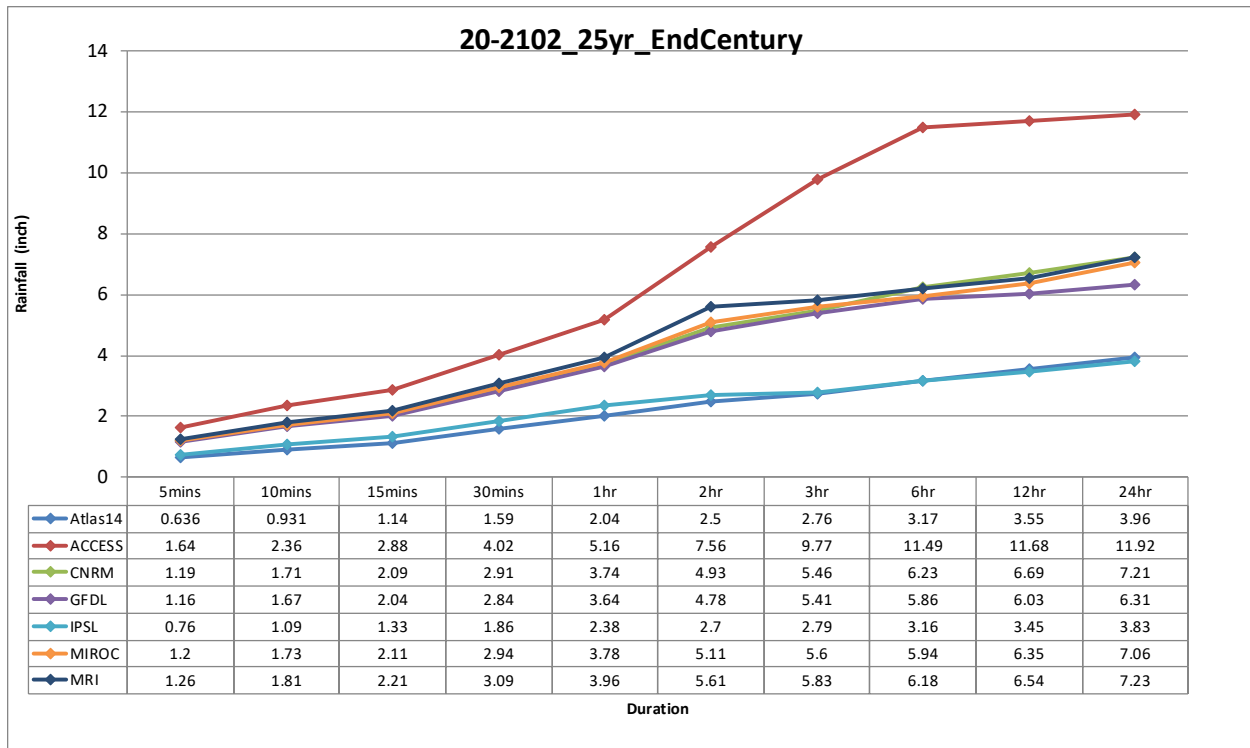


Figure 29. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2102

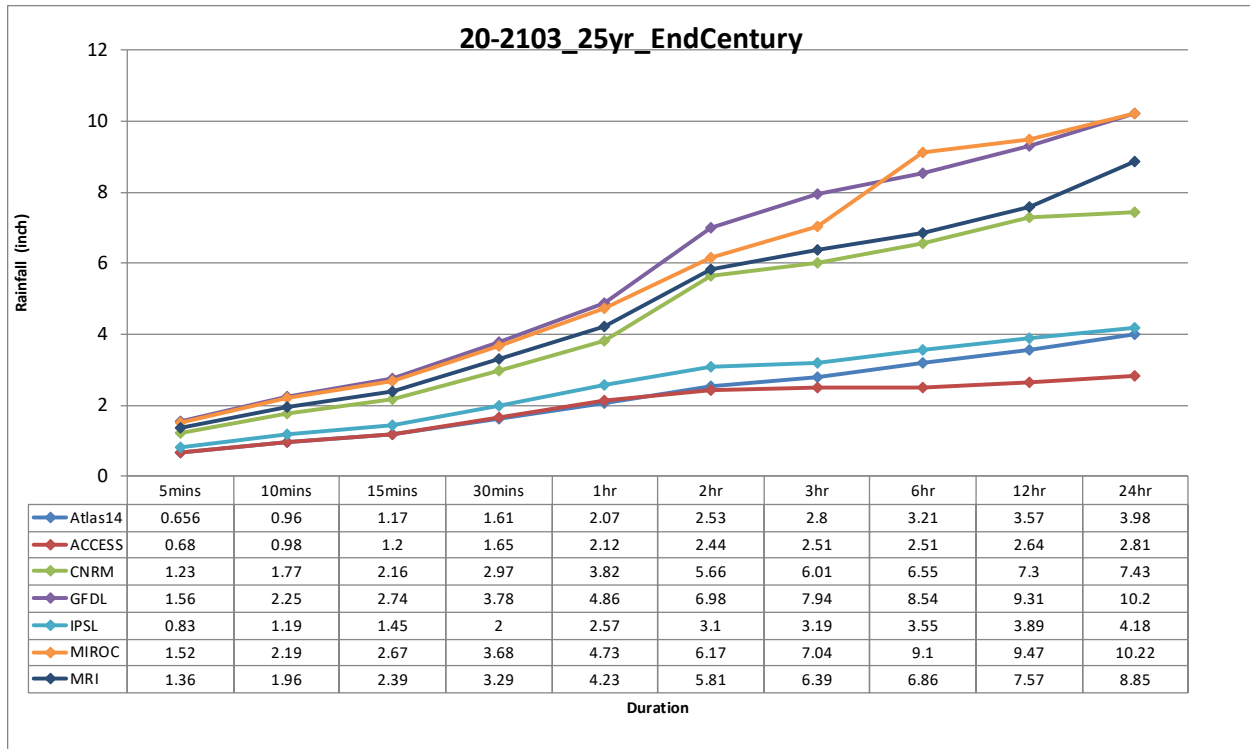


Figure 30. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-2103

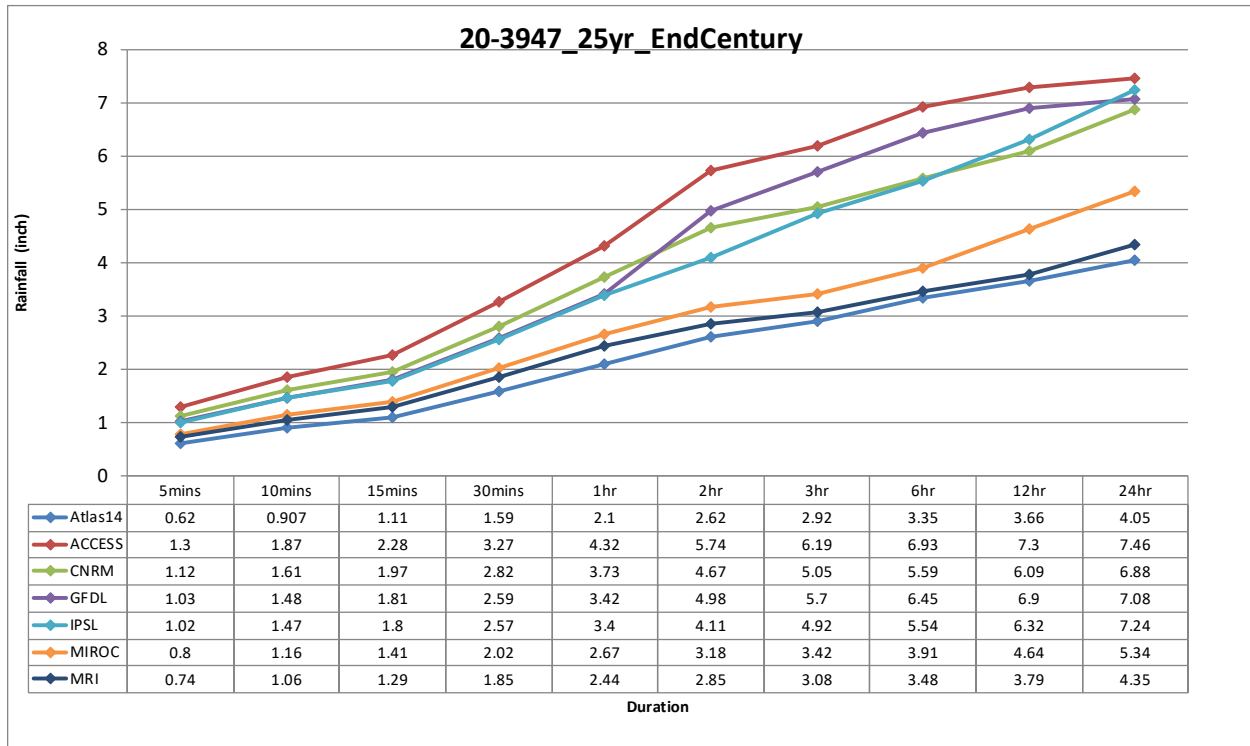


Figure 31. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-3947

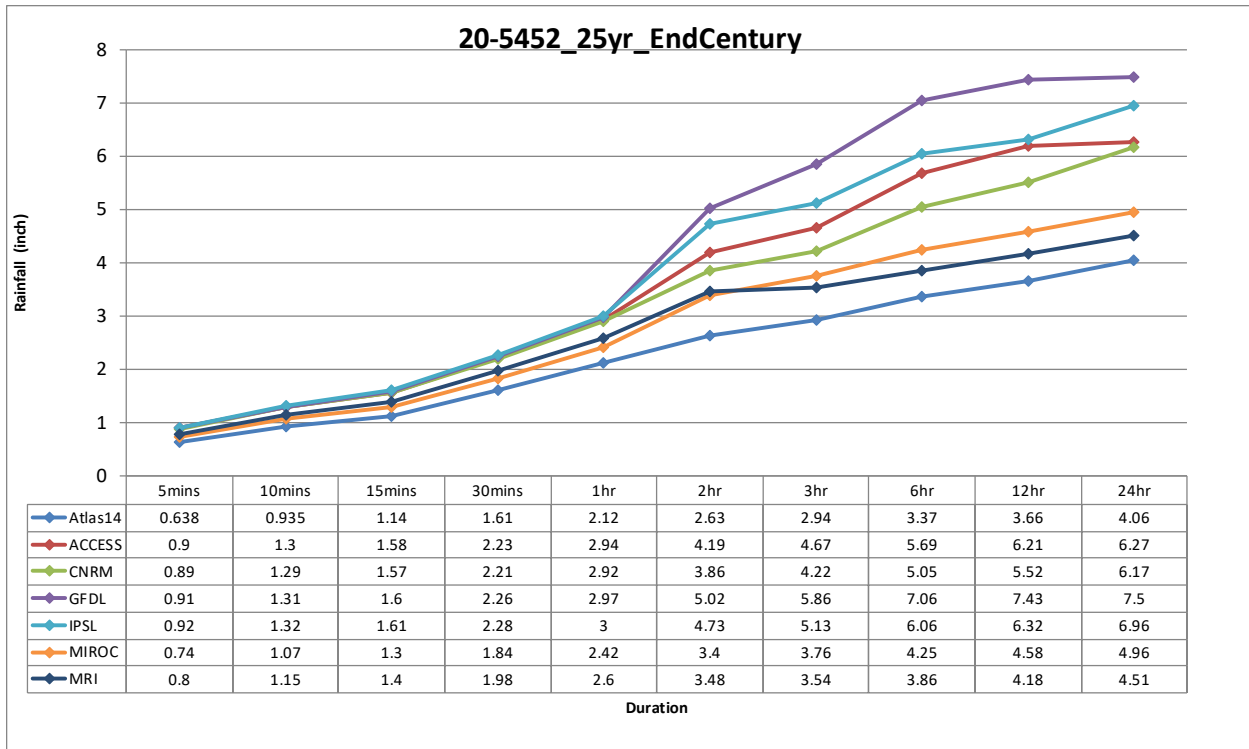


Figure 32. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-5452

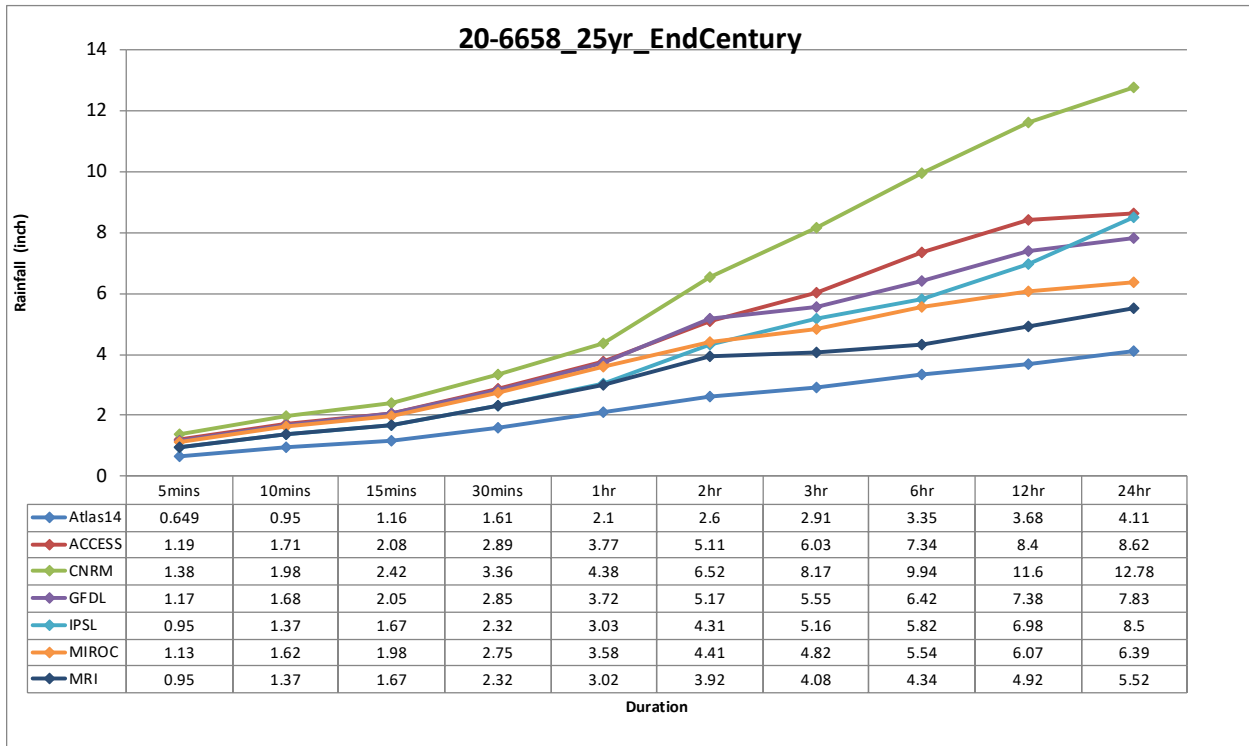


Figure 33. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-6658

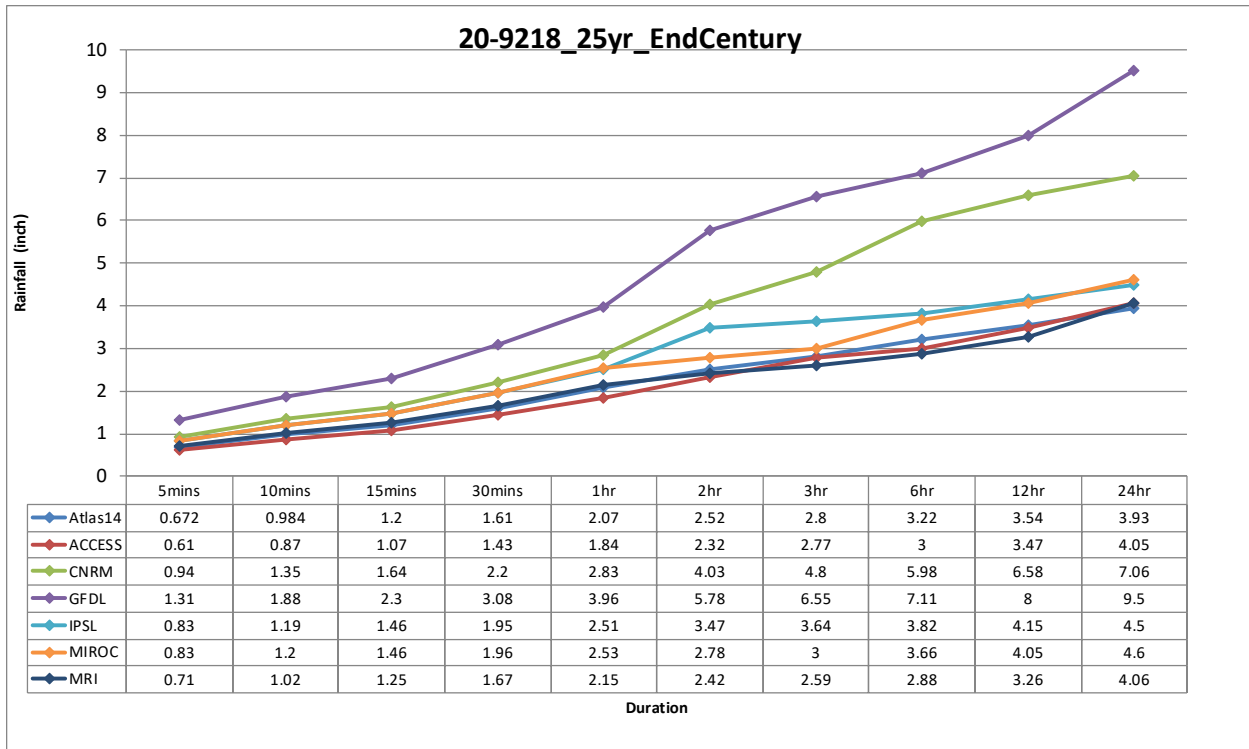


Figure 34. End-century IDF Curves for 25-year Recurrence Precipitation for Site 20-9218

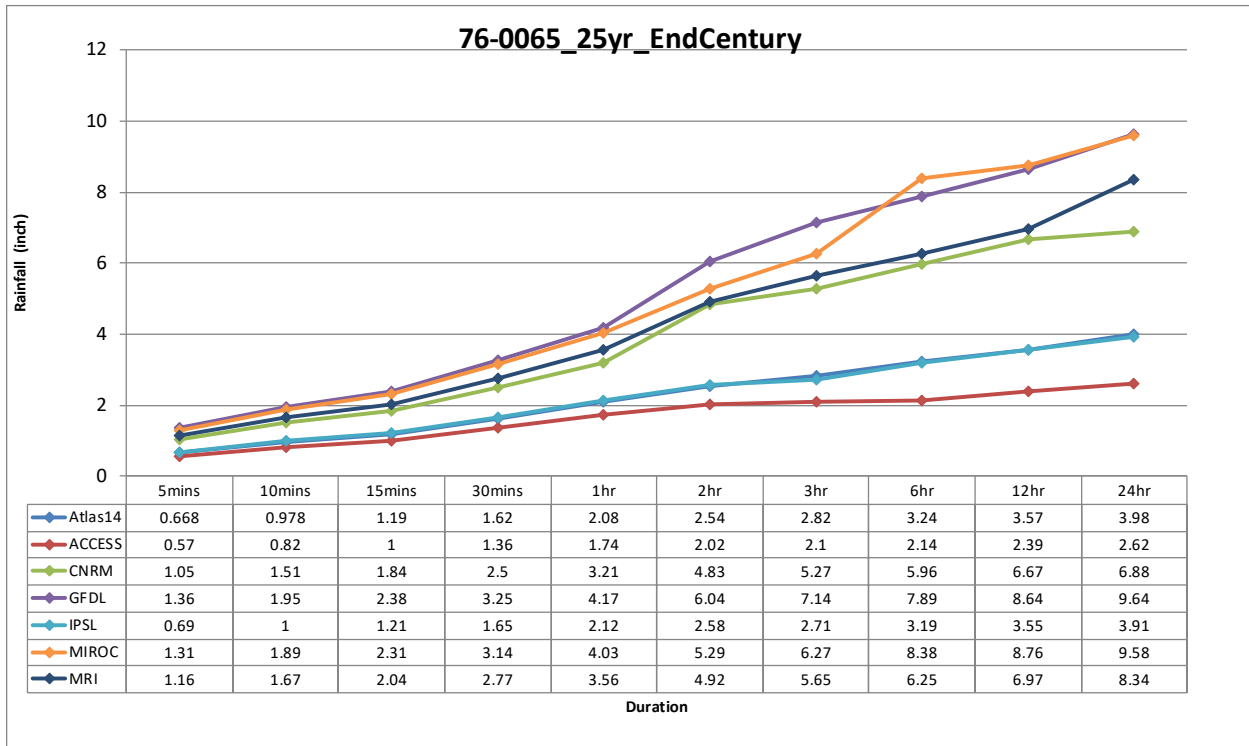


Figure 35. End-century IDF Curves for 25-year Recurrence Precipitation for Site 76-0065

4.5 IDF CURVES FOR 100-YEAR RECURRENCE FOR MID-CENTURY

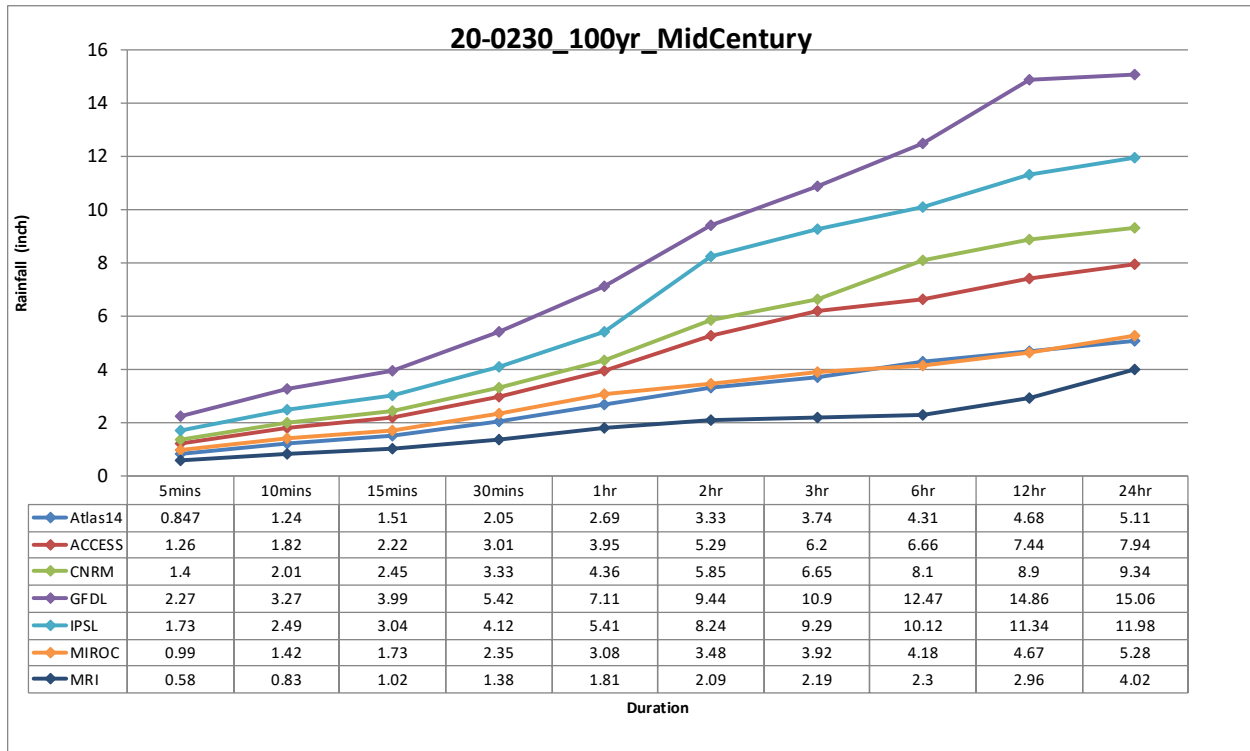


Figure 36. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-0230

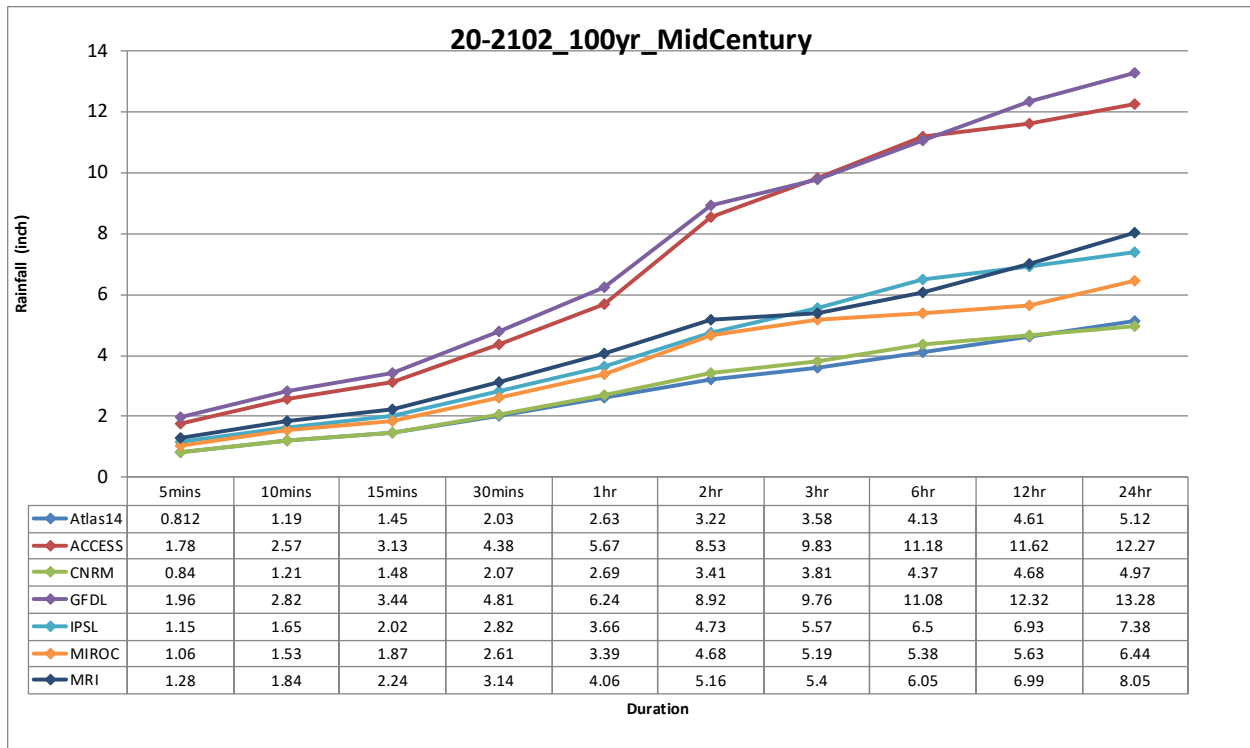


Figure 37. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2102

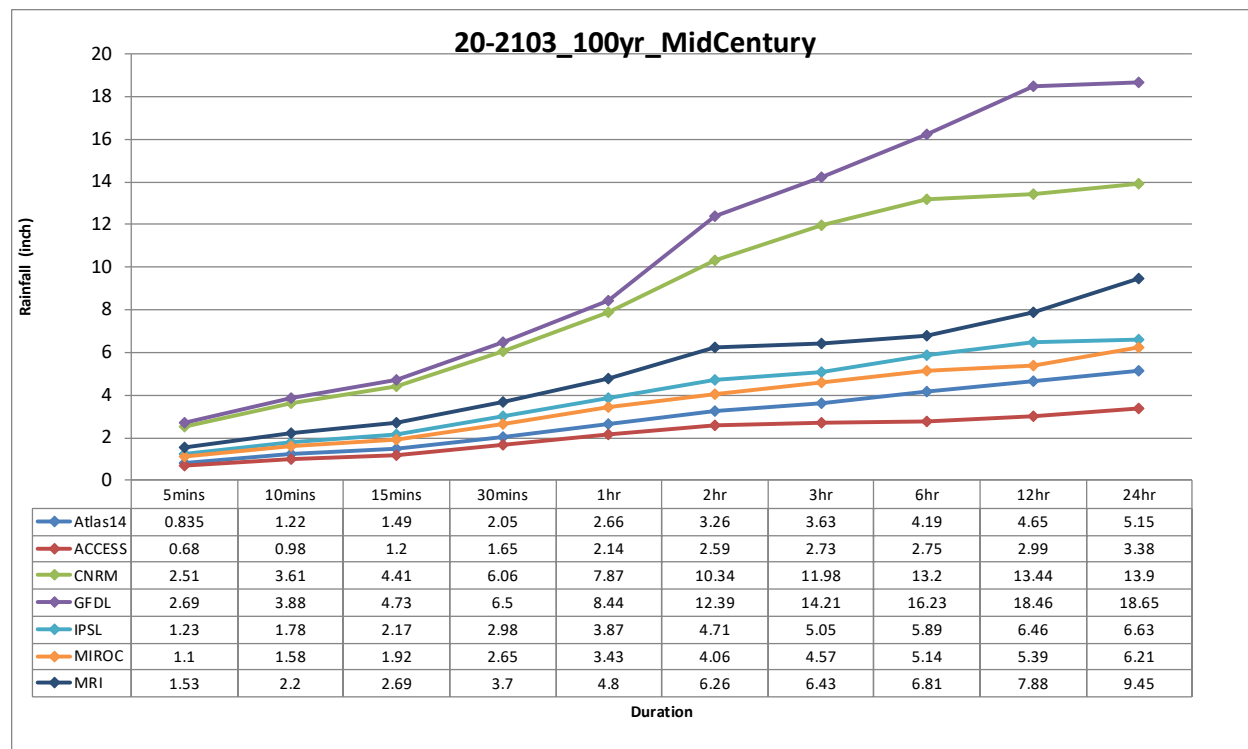


Figure 38. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2103

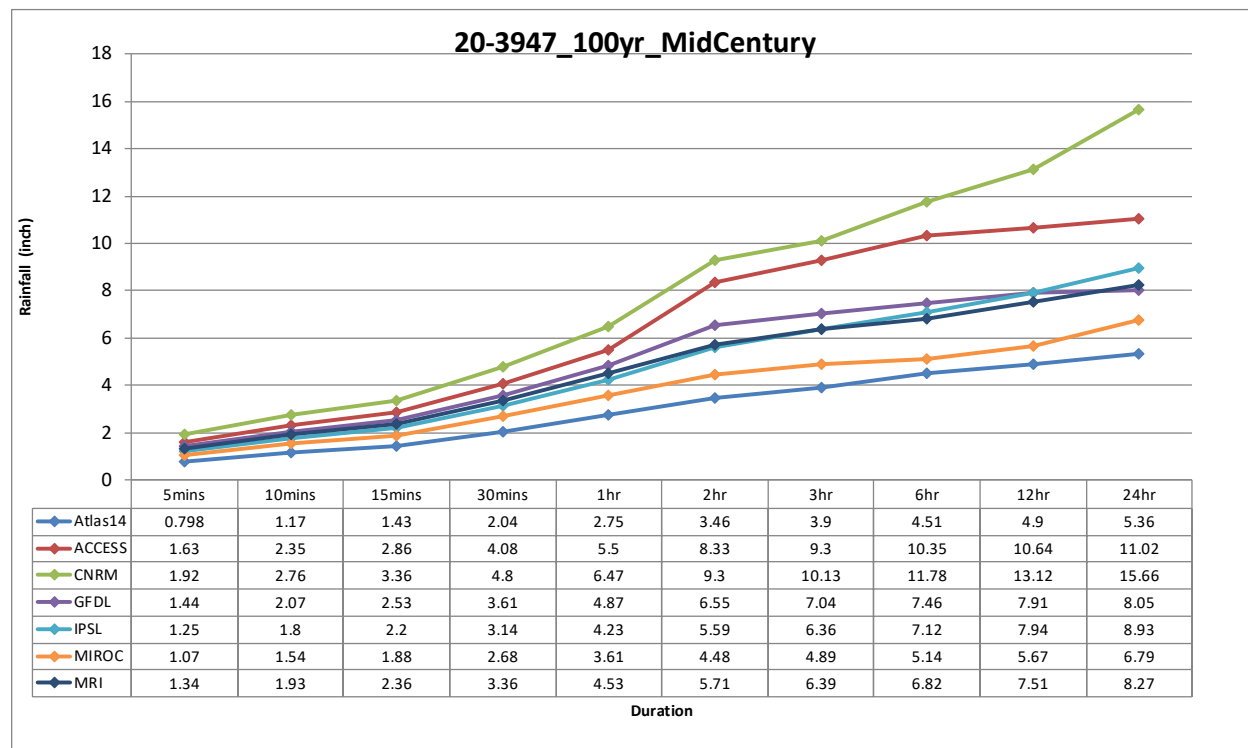


Figure 39. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-3947

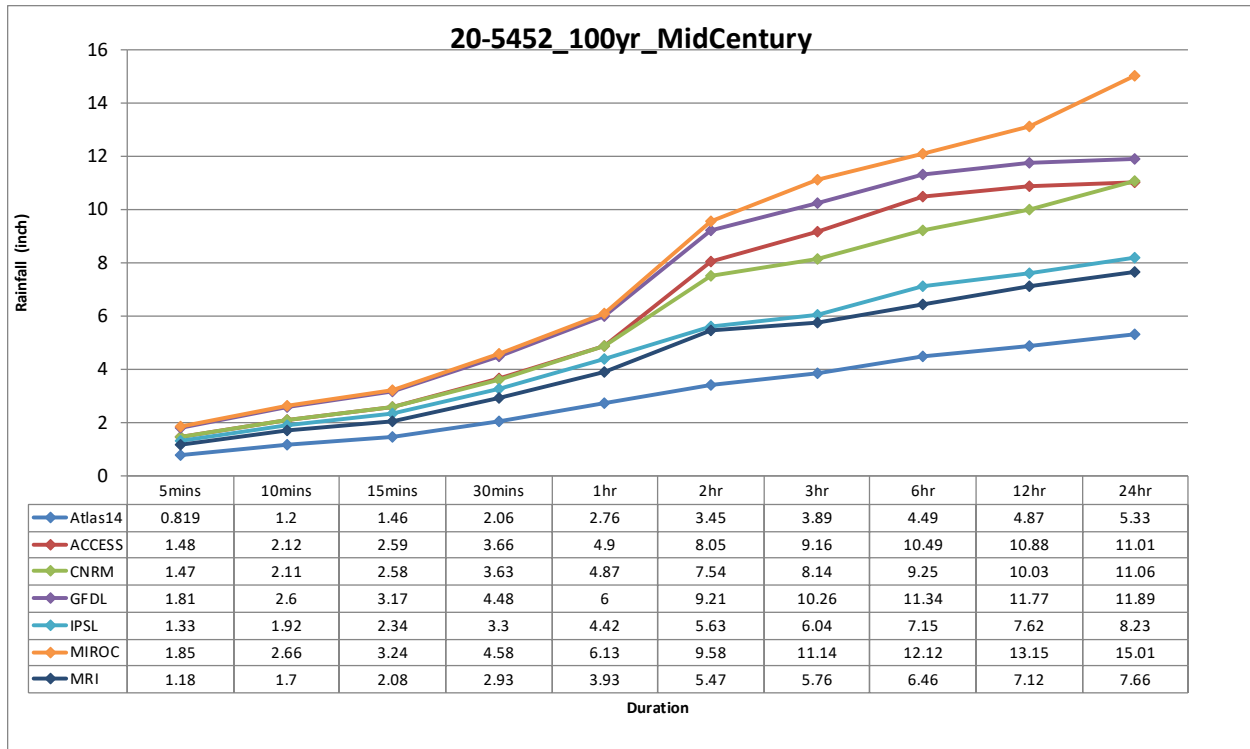


Figure 40. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-5452

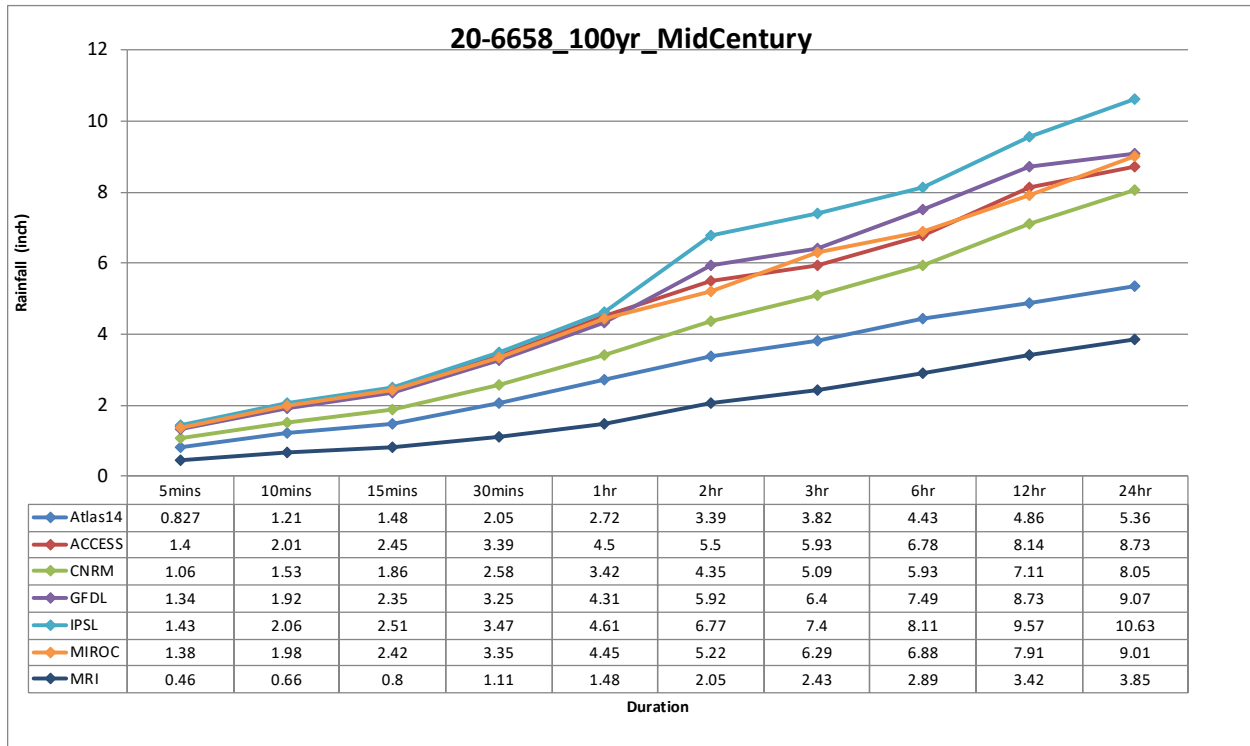


Figure 41. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-6658

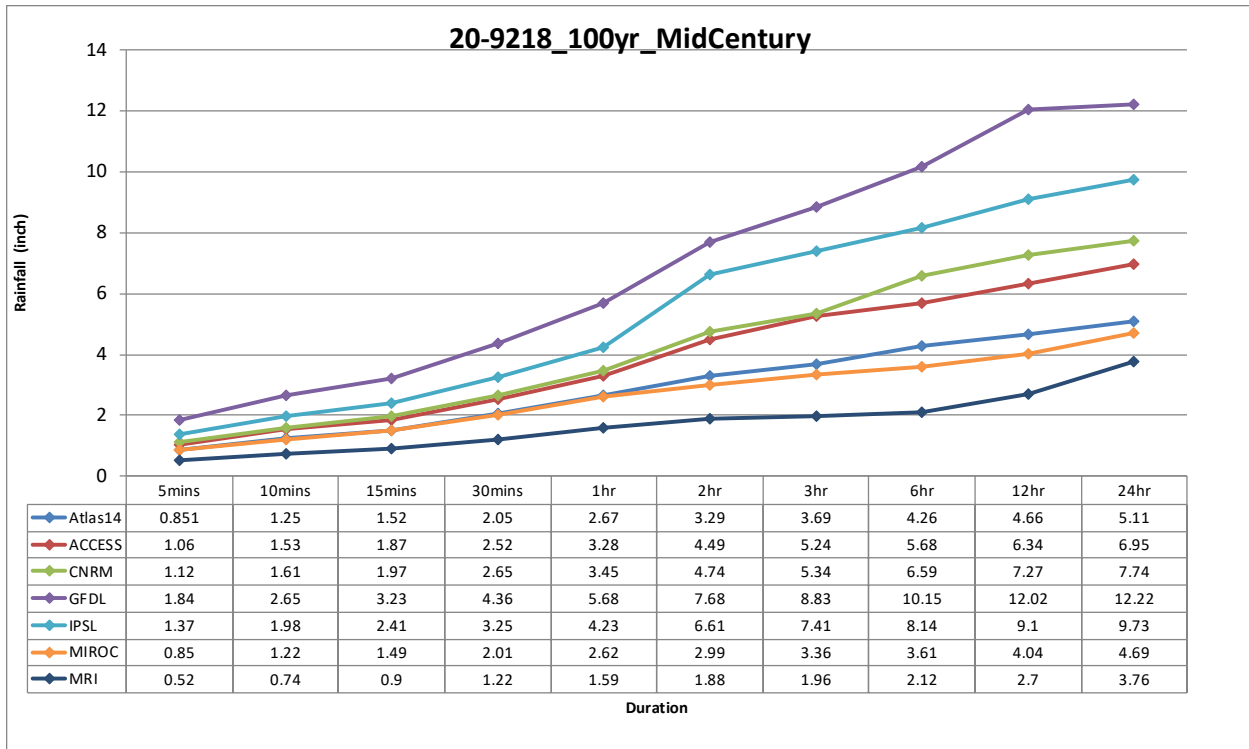


Figure 42. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 20-9218

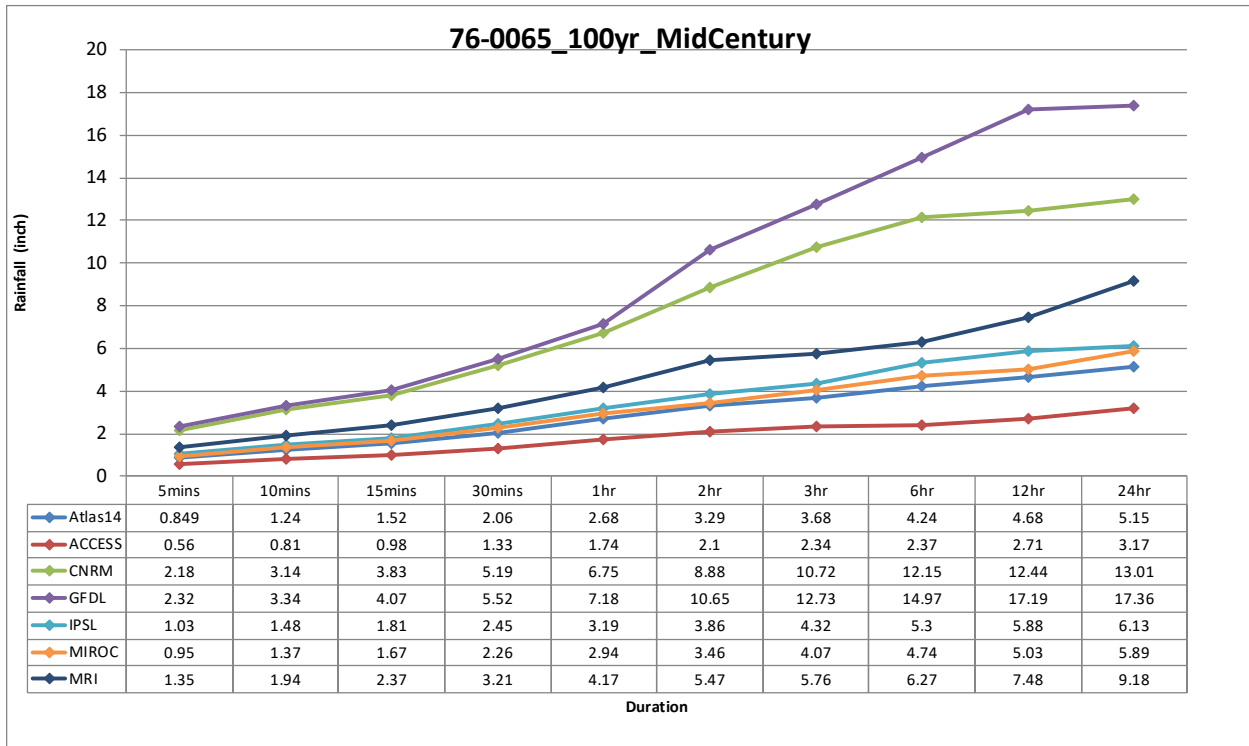


Figure 43. Mid-century IDF Curves for 100-year Recurrence Precipitation for Site 76-0065

4.6 IDF CURVES FOR 100-YEAR RECURRENCE FOR END OF THE CENTURY

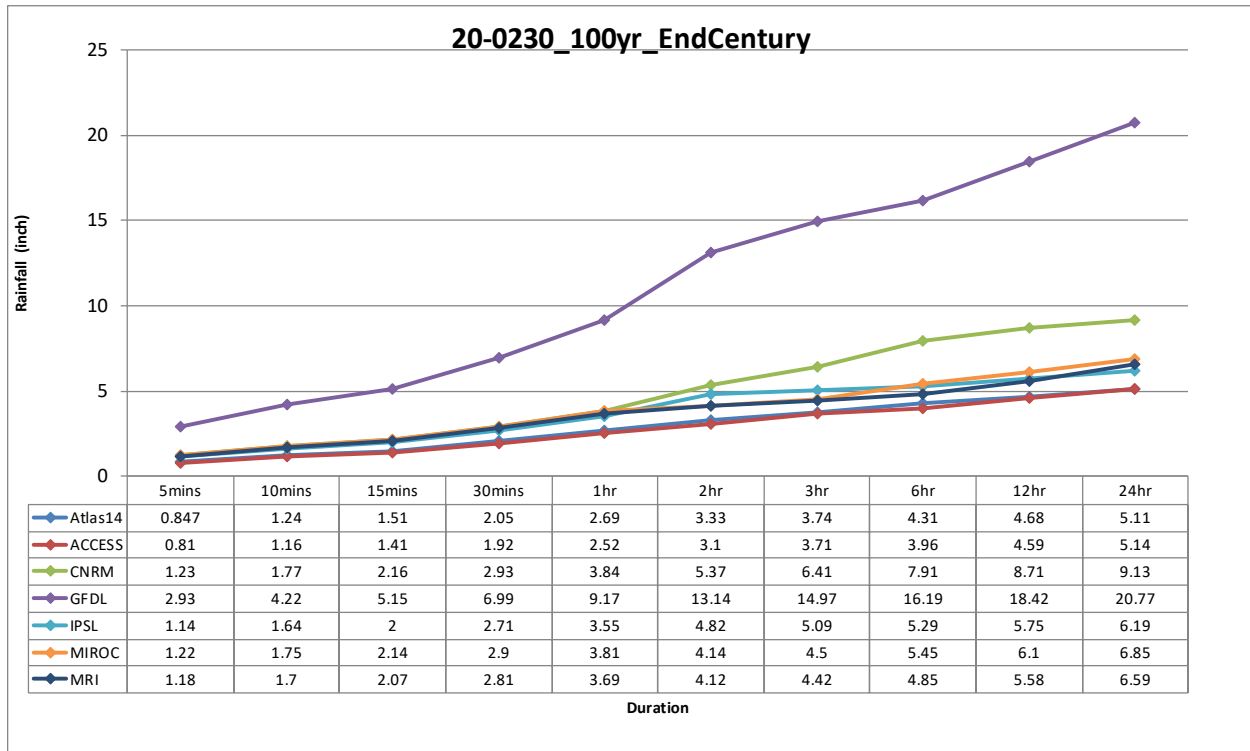


Figure 44. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-0230

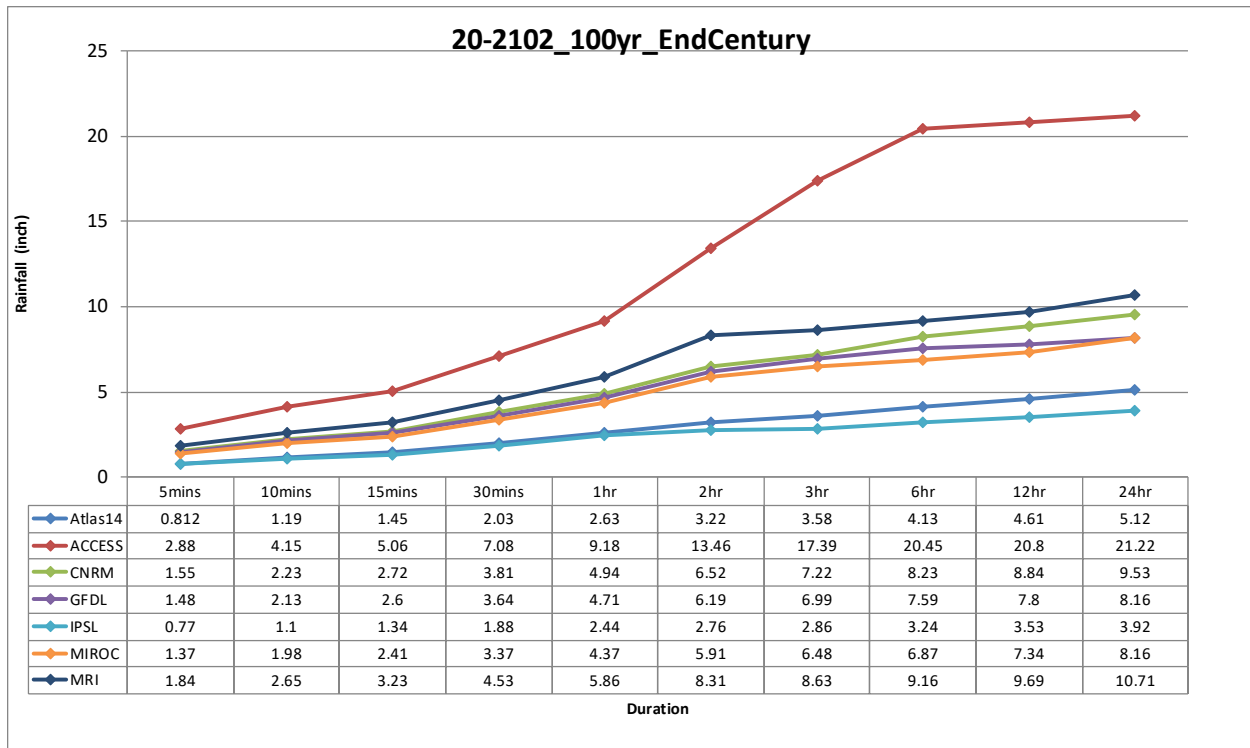


Figure 45. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2102

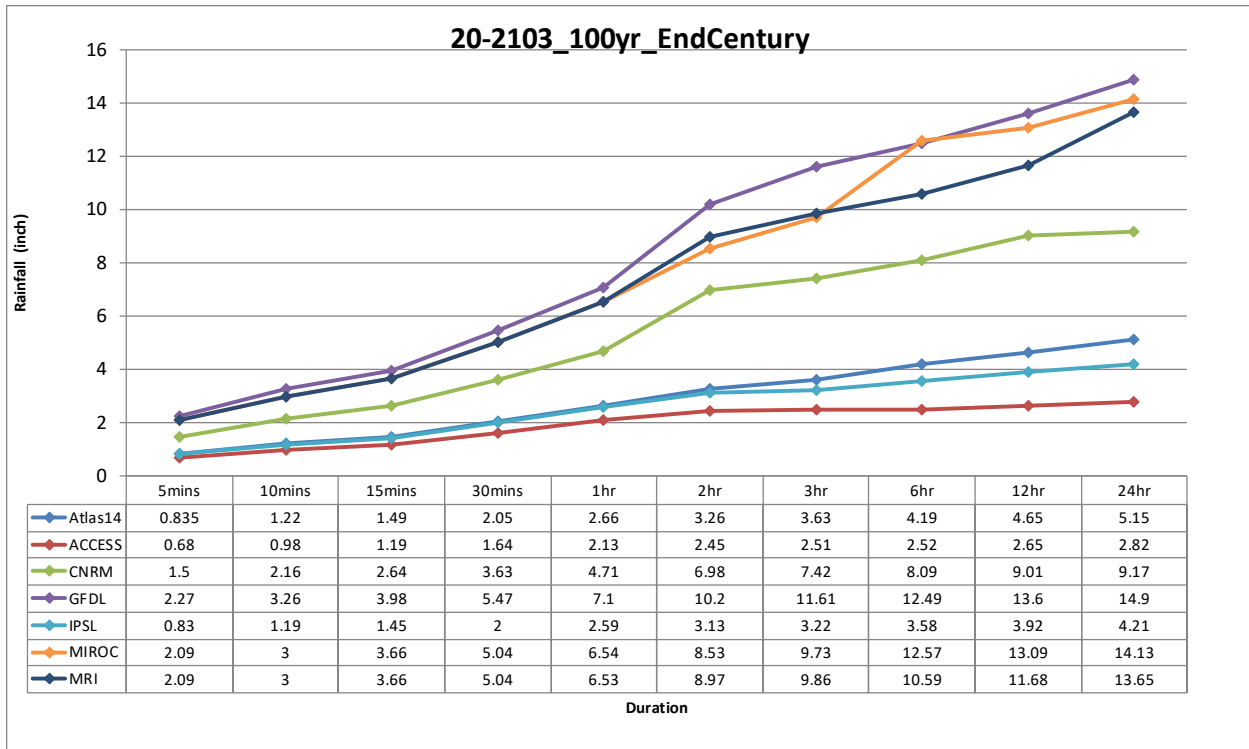


Figure 46. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-2103

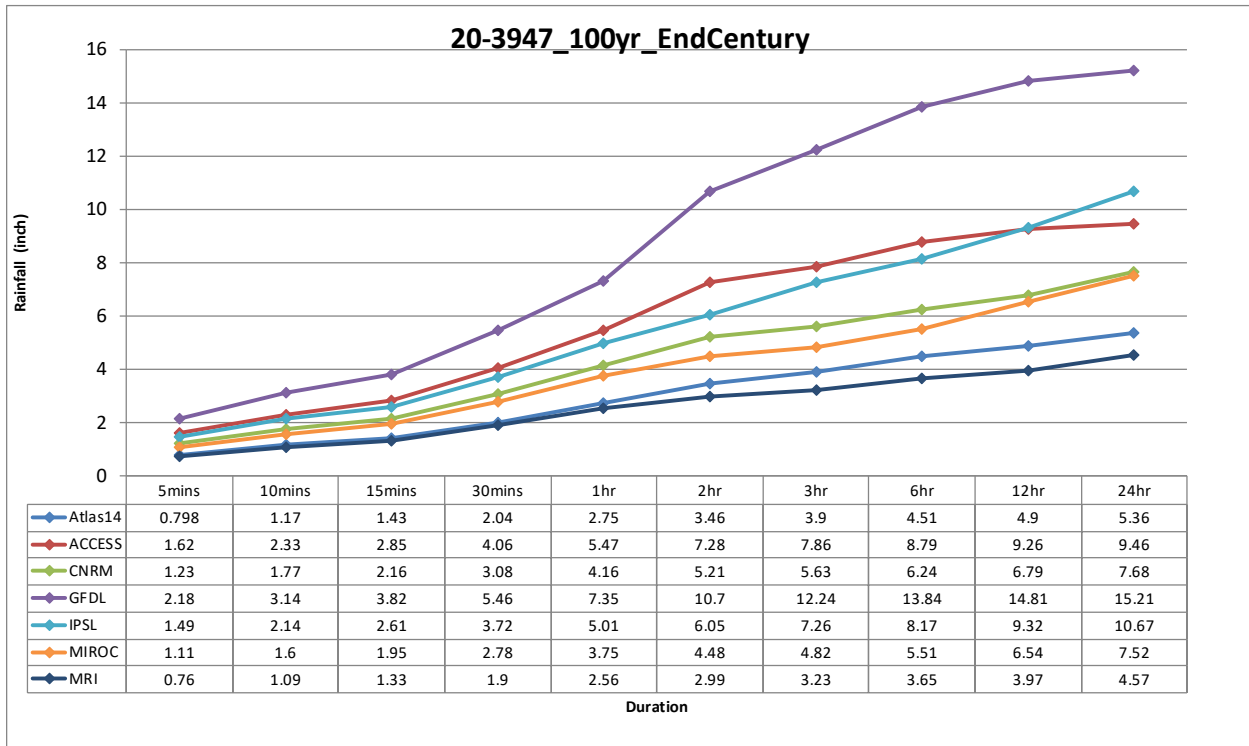


Figure 47. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-3947

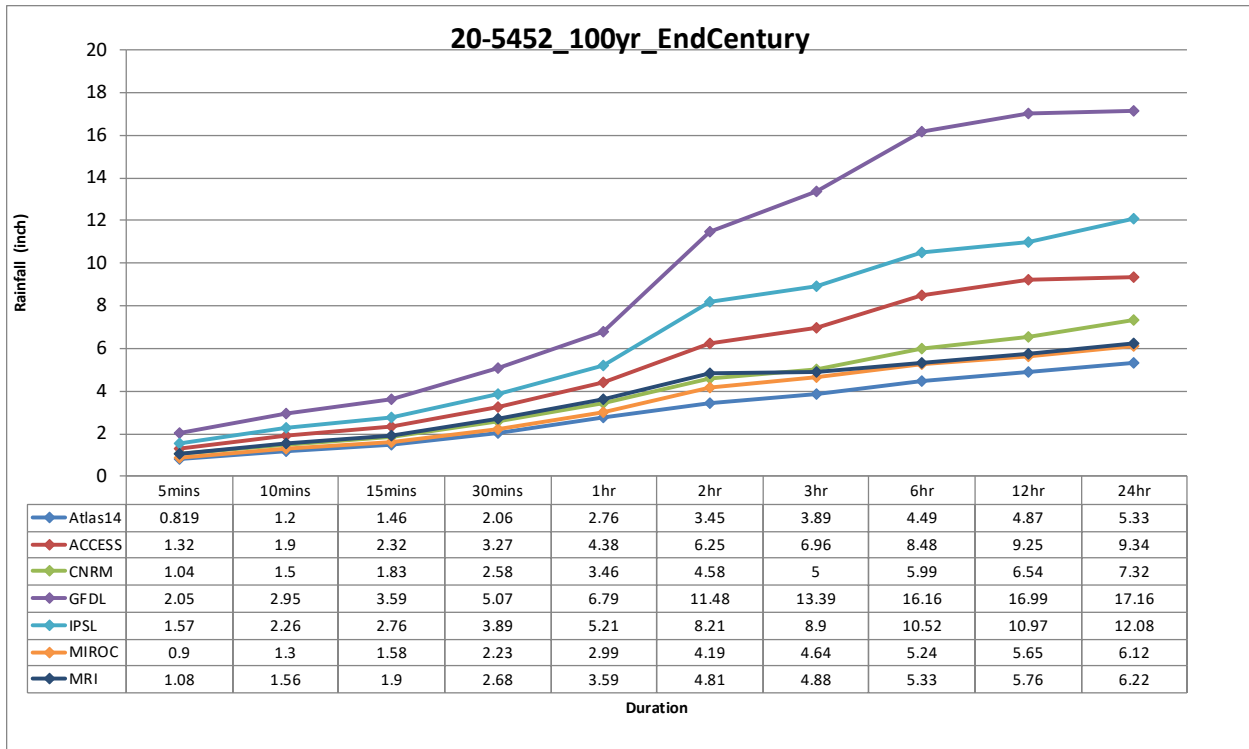


Figure 48. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-5452

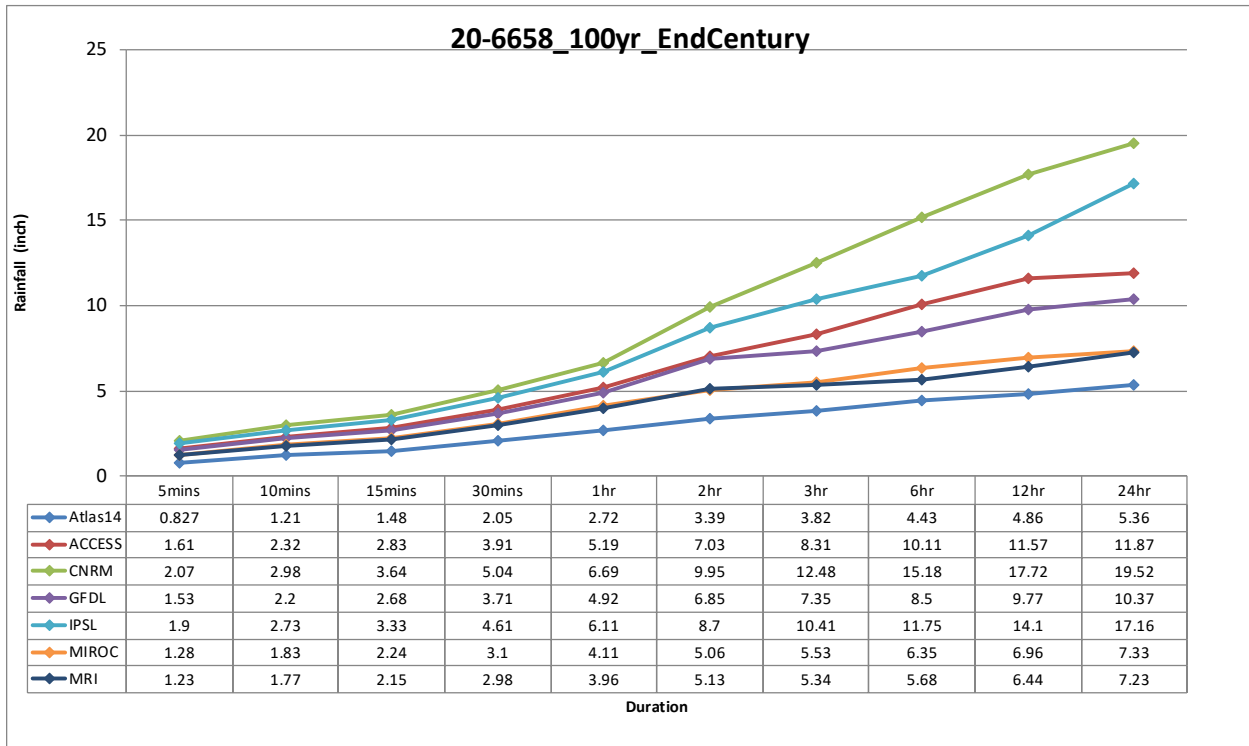


Figure 49. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-6658

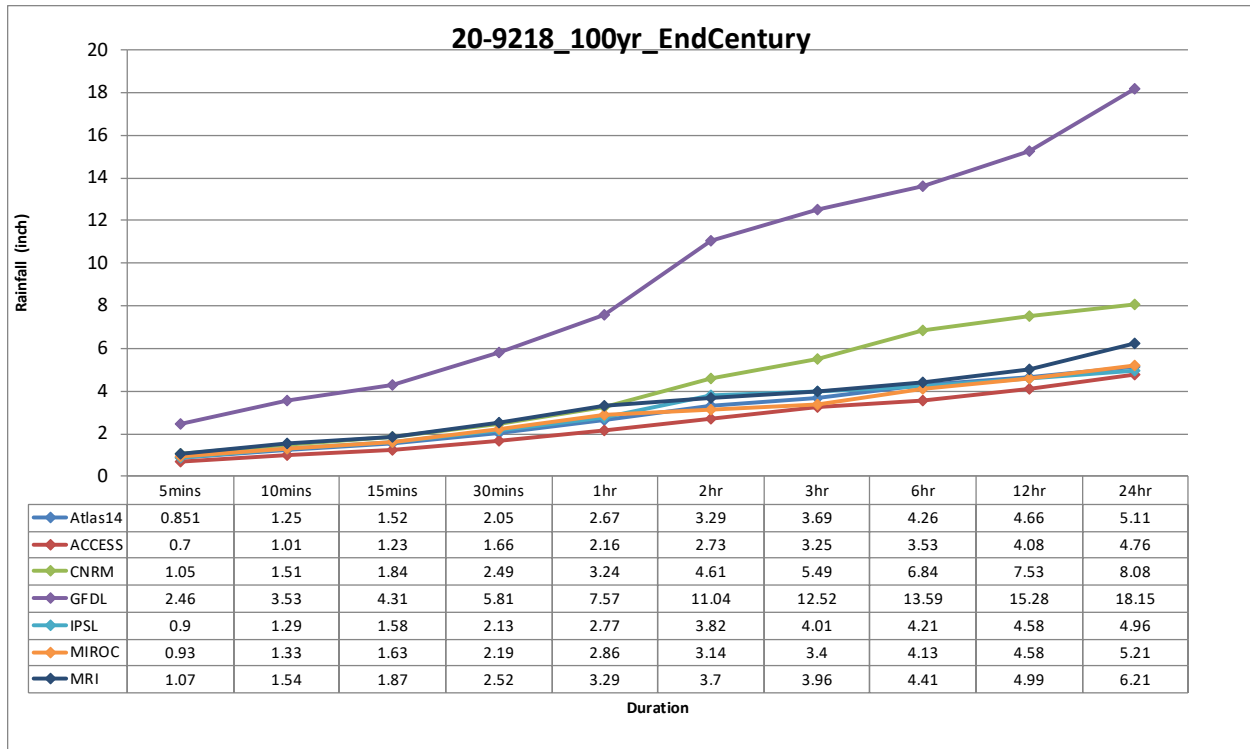


Figure 50. End-century IDF Curves for 100-year Recurrence Precipitation for Site 20-9218

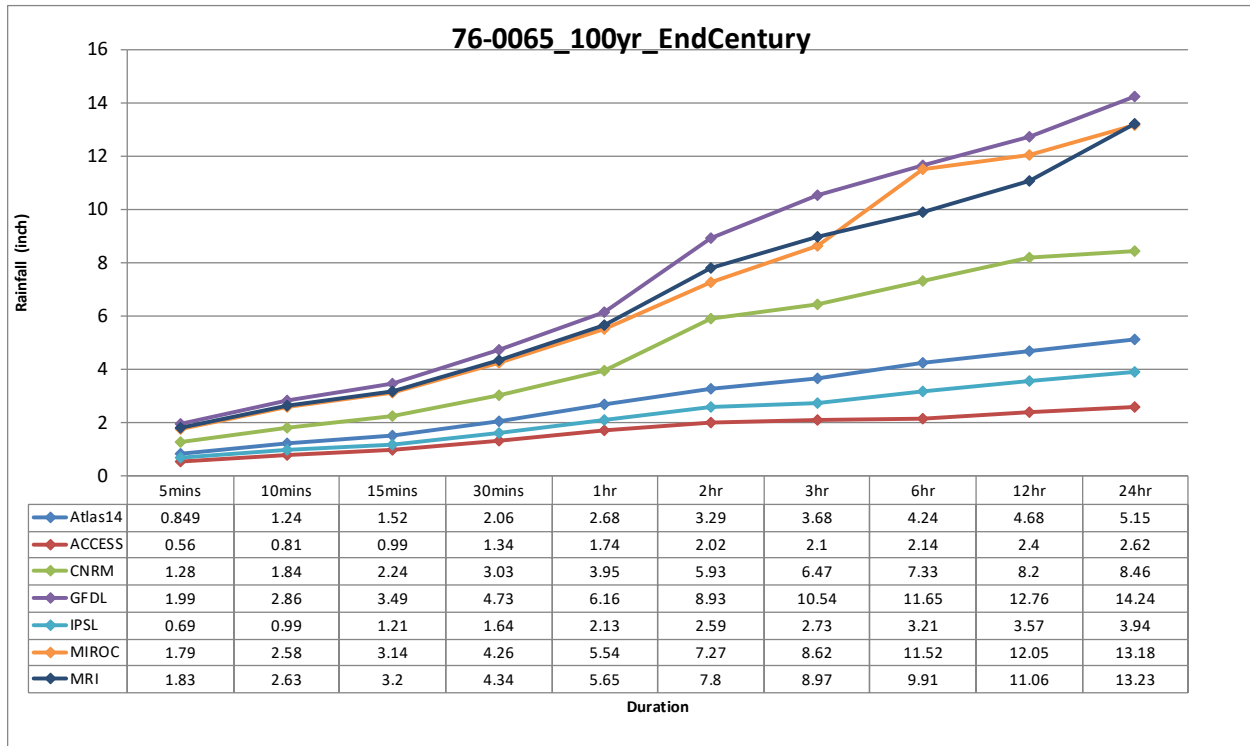


Figure 51. End-century IDF Curves for 100-year Recurrence Precipitation for Site 76-0065

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5 Discussion

Results of these analyses suggest that the intensity of storms of a given duration and frequency is likely to continue to increase in the future. (Alternatively, the frequency of a storm of a given duration and intensity is likely to increase). For the 25-year recurrence storm at mid-century, at three of eight Atlas 14 sites all six climate models predict higher rainfall intensity for a given duration. For the other five sites, all but one climate model predicts higher intensity for this recurrence interval at mid-Century. In those cases, either the MRI or ACCESS GCM predicts a decline in intensity. End-century results tend to show more spread between models.

The different GCMs show some divergent spatial patterns in rainfall extremes that are not observed under historic climate. For instance, the 24-hr 25-year storm in Atlas 14 is 3.93 in at Ann Arbor Airport (20-0230) and 3.98 inches at Detroit Metro Airport (20-2103). By mid-century, the ACCESS model diverges strongly between these locations, with 6.33 inches at Ann Arbor and only 3.35 inches at Detroit Metro. The ACCESS model shows a decline in the 24-hr event at both sites by end-century but continues to predict a much smaller volume at Detroit Metro than at Ann Arbor. Whether these predicted spatial differences are realistic is open to question.

Some of the models predict extreme event depths for end-century conditions, exceeding 10 inches for the 24-hr 25-year storm and up to 21 inches for the 100-year storm. These extreme results generally diverge from the trend of other models and are most frequently associated with the ACCESS and GFDL models. These estimates clearly have increased uncertainty due to the relatively short, 20-year time chunks used in the analysis. For example, the GFDL model AMS output for station 20-5452 (Milford GM Proving Ground) produces an estimate of 17.4 inches in 24-hours for nominal year 2087, with all other annual peaks less than 6.4 inches. Even if the 17.4-inch storm is physically possible, estimating where it should fit on a frequency basis from only 20-years of output is obviously difficult.

The approach we have used – adjusting the Atlas 14 estimates by the relative change in model output - is relatively robust and helps minimize the uncertainty in the climate model output. But, model predictions of the future cannot be validated until the future arrives. The ensemble range of results instead provides an indication of the types of potential futures to which adaptation may be needed.

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