1 NEED TO ASSESS ALTERED HYDROLOGY

One of the stressors commonly referenced as a reason for aquatic life impairments is “altered hydrology.” Altered hydrology is commonly thought to be characterized by increases in peak discharge and runoff volume for a range of precipitation events, as compared to some historic or benchmark condition. Numerous studies have suggested that this hydrologic alteration is a result of some combination of climatic variation, land use/land cover changes, or other landscape scale changes. Aquatic habitat loss, increased streambank erosion and bank failure, and increased sediment levels are some of the suggested consequences of altered hydrology. Individually and collectively these are believed to lead to the impairment of aquatic life, exhibited by lower ecological diversity.

Although a general sense of the characteristics of altered hydrology exists, a substantive challenge remains. A challenge associated with addressing altered hydrology is the lack of a common definition, including agreement on a set of science-based metrics to establish the desired (i.e., benchmark) condition, and assess whether altered hydrology has indeed occurred. **Figure 1** provides an example of hydrologic data which could be used to illustrate altered hydrology. **Figure 1** shows a flow duration curve for a streamflow gage in the Sand Hill River Watershed, within northwestern Minnesota. Two 30-year time periods are shown on the graph; i.e., 1980 – 2010 (solid line) and 1945 - 1975 (dashed line). The graph represents the likelihood of exceeding a specific daily mean discharge. The graph indicates an increase in the daily mean discharge through most of the flow range, because for the same likelihood of exceedance the daily mean discharge is greater for the more recent time periods. This suggests “altered hydrology” meaning that flow conditions in the watershed differ between the two time periods. The example illustrates one possible metric which could be used to describe altered hydrology.

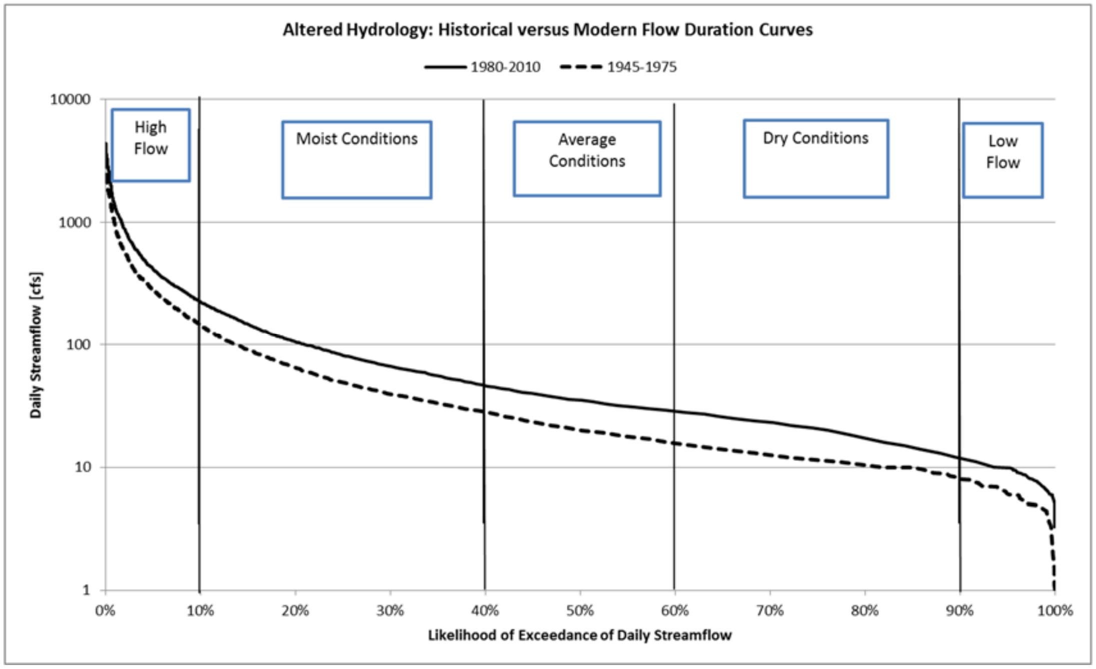

Figure 1. Flow duration curve for the Sand Hill River at Climax, Minnesota. The solid black line shows an increase in daily mean discharge for the 1980 – 2010 period, compared to the early 1945 – 1975 period.

Agreement on a set of science-based metrics to assess the extent of hydrologic alteration and the desired (i.e., benchmark) condition is needed in order to quantitatively assess changes in the hydrology of a watershed. A definition is needed to rigorously assess whether hydrology has indeed changed through time, establish goals for altered hydrology, and assess and evaluate various means, methods and projects to mitigate the adverse effects of altered hydrology.

Considerable research and technical information relative to describing altered hydrology has been completed. The recently release draft report titled "Technical Report: Protection Aquatic Life from Hydrologic Alternatives" (Novak et al., 2015) is one example. The report presents metrics which can be used to describe altered hydrology. However, causal information about how the change in hydrology results in the alteration or loss of ecological function is lacking within the report.

For the hydrology of a watershed to be altered there must be some deviation from a preferred or desired hydrologic condition; i.e., a "benchmark" condition. The benchmark for altered hydrology could be the "natural hydrologic regime" or some other condition. The natural hydrologic regime (Poff et al 1997; Arthington et al 2006; Bunn and Arthington 2002; Sparks 1995) is the characteristic pattern of water quantity, timing and variability in a natural water body. A river's hydrologic or flow regime consists of environmental flow components (Mathews and Richter, 2007; The Nature Conservancy, 2009), each of which can be described in terms of the magnitude, frequency, duration, timing and rate of change in discharge. The integrity of an aquatic system presumably depends on the natural dynamic character of these flow components to thereby driving ecological processes.

Defining altered hydrology and the benchmark condition, identifying the metrics to describe altered hydrology and translating the information into goals to mitigate the adverse consequences is technically challenging. The approach used to evaluate whether a watershed exhibits altered hydrology is presented within this document. A definition of altered hydrology is presented. Specific quantitative metrics to assess the extent of hydrologic change and the desired (i.e., benchmark) condition are also presented. No effort is made to describe the causal relationship between hydrology and the ecological, geomorphological or water quality effects. Rather, the assumption is made that the desired condition is achieved by obtaining the benchmark condition. These results are intended to be a beginning point in addressing the topic of altered hydrology in a more rigorous manner, which no doubt will evolve through time.

2 METHODS

2.1 A BRIEF HISTORY OF CHANGING HYDROLOGY

Streamflow in Minnesota (Novotny & Stefan, 2007) and across the contentious United States (Lins and Slack 1999, McCabe and Wolock, 2002) have been changing during the past century, with flows in the period starting from the 1970s to the beginning of the 21st Century tending to be higher than during the early to mid-1900s (Ryberg et al. 2014). Numerous studies have been conducted to quantify magnitude of impact and pinpoint relative importance of potential causes of these changes, but scientific consensus has currently not been achieved. The science is not at a point where specific causes can be attributed to altered hydrology with any significant certainty and public discussion about specific causes usually leads to barriers to implementation.

In general, the leading candidate causes of altered hydrology can be categorized into to two primary groups: climatic changes and changes in the landscape. Examples of climatic changes include changes in annual precipitation volumes, in surface air temperature, timing of the spring snowmelt, annual distribution of precipitation, and rainfall characteristics (timing, duration, and intensity). Examples of changes in the landscape include changes in land use/land cover, increased imperviousness (urbanization), tile drainage, wetland removal/restoration, groundwater pumpage, flow retention and regulation, and increased storage (both in-channel and upland storage).

A brief review of the scientific literature and the current scientific debate on the causes of altered hydrology is provide in Appendix A. Although it is important to water resource management to understand the mechanics behind the changes in hydrology, the focus of this analysis is developing a definition for altered hydrology, a method for assessing whether it has occurred within a watersheds, and establishing a goal for addressing altered hydrology.

2.2 ALTERED HYDROLOGY DEFINED

Altered hydrology is defined as a *discernable* change in specific metrics derived from stream discharge, occurring through an entire annual hydrologic cycle, which exceed the measurement error, compared to a benchmark condition. For this framework, *discernable* has been used as a proxy for statistical comparisons. The metrics are typically some type of hydrologic statistic derived from the annual discharge record across a long period of time, usually a minimum of 20-years (Gan et al. 1991). The amount of baseflow, the hydrograph shape, peak discharge, and runoff volume for a range of precipitation event magnitudes, intensities, and durations are specific components of or derived from the annual hydrograph.

2.3 ESTABLISHING BENCHMARK CONDITION

A reference or “benchmark” condition is needed to complete an assessment of whether hydrology is altered. A minimum of a 20-year time-periods reasonably ensures stable estimates of streamflow predictably (Gan et al. 1991; Olden & Poff 2003), sufficient duration to capture climate variability and the interdecadal oscillation typically found in climate (McCabe et al. 2004, Novonty and Stefan 2007), and is the standard timespan used for establishing “normal” climate statistics in the United States. Where the extent data allows it, the analysis is performed for two 35-year time periods; i.e., 1940 – 1975 (benchmark called “historic”) and 1980– 2015 (current or called “modern”). The 1940 – 1975 time period used to establish benchmark conditions represents the period before shifts in hydrology are commonly thought to have begun within Minnesota as a result of land use/land cover changes, or increases in the depth, intensity, and duration of precipitation (see Appendix A for further discussion).

To illustrate the change in streamflow and validity in the breakpoint period, cumulative streamflow (using annual depth values), was plotted across time (**Figure 2**) for the USGS gage at Crow River at Rockford, MN (USGS ID: 05280000). Cumulative streamflow was used instead of straight annual streamflow because (1) it linearizes streamflow relationship where the slope of a trendline would be the average annual streamflow, (2) no assumptions about multi-year dependencies (e.g. changes in storage) or autocorrelation is necessary, and (3) changes in slope can be easily visualized, showing an altered state of hydrology.

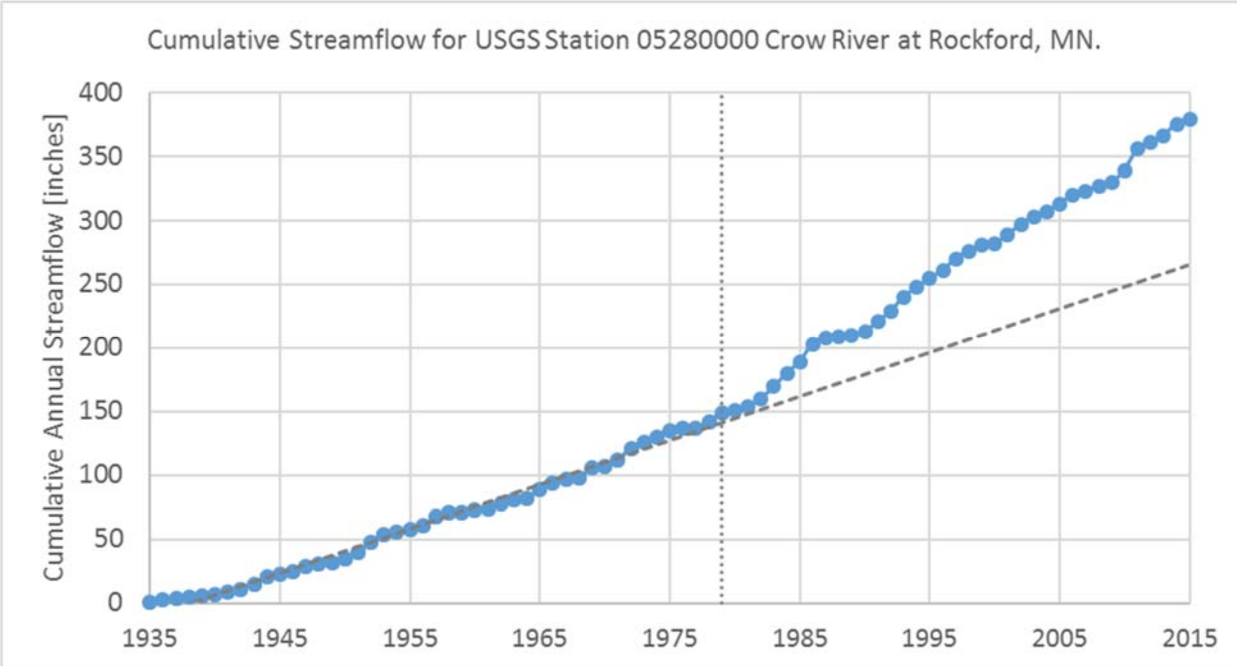

Figure 2. Cumulative streamflow for the Crow River at Rockford, MN (USGS Station 05280000).

2.4 METRICS USED TO ASSESS ALTERED HYDROLOGY

Many potential metrics can be used to describe a measurable change in the annual hydrograph. For example, the indicators of hydrologic alteration software developed by the Nature Conservancy (https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/indicators-hydrologic-alt.aspx) uses 67 different statistics derived from mean daily discharge to describe altered hydrology. Ideally, each indicator or metric could be causally linked to an ecological or geomorphological consequence, although this is technically challenging. Use of such a large number of indictors can be problematic as many of the metrics can be correlated and are therefore interdependent or lack ecological or geomorphological meaning.

The structure and therefore function of ecological systems are often “driven” by “non-normal” events; e.g., low flows associated with drought, higher flows which inundate the floodplain. Metrics used to complete this analysis were preferentially selected to reflect the variability in specific characteristics of the annual hydrograph, and include peak discharges, runoff volumes and hydrograph shape. Each metric was specifically selected to represent a flow condition believed to be of ecological or geomorphological importance, in the absence of causal information. **Table 1** shows the specific metrics used to complete the analysis. The use of these metrics is intended to identify: 1) whether the hydrology within a watershed is indeed altered: and 2) which resources may be at risk because of the alteration.

Table 1. Metrics used to define and assess whether hydrology is "altered" for a specific watershed.

Relevance	Hydrograph Feature	Frequency of Occurrence	Duration	Metric	Ecological or Geomorphic Endpoint
Condition of Aquatic Habitat	Baseflow	10-year	30 day	The minimum change between time periods is the accuracy of measuring streamflow discharge and estimating daily mean discharge. A discharge measurement accurate within 10% of the true value is considered excellent by the United States Geological Survey (USGS). Some additional error is induced through the conversion of these data to discharge. Therefore, a minimum change of 15% is needed between "historic" and "modern" period for this metric to classified as "altered."	Discharge needed to maintain winter flow for fish and aquatic life.
		Annual	30-day median (November)		
Aquatic Organism Life Cycle	Shape	Mean	Monthly average of daily means	Use the "historic" period of record to define "normal variability." Develop a histograms of daily mean discharges for each month within the period of record for the "historic" and "modern" time periods. Compare the histograms of the monthly average of daily means using an appropriate statistical test. Assume the histograms are from the same statistical population and text for significance at an appropriate significance level.	Shape of the annual hydrograph and timing of discharges associated with ecological cues.
	Timing	Julian day of minimum	1-day		
		Julian day of maximum			
Riparian Floodplain (Lateral) Connectivity	Peak discharge	10-year	24-hour and 10-day	The minimum change between time periods is the accuracy of measuring streamflow discharge and estimating daily mean discharge. A discharge measurement accurate within 10% of the true value is considered excellent by the United States Geological Survey (USGS). Some additional error is induced through the conversion of these data to discharge. Therefore, a minimum change of 15% is needed between "historic" period and "modern" period for this metric to classified as "altered."	Represents the frequency and duration of flooding of the riparian area and the lateral connectivity between the stream and the riparian area. Functions include energy flow, deposition of sediment, channel formation and surface water – groundwater interactions
		50-year			
		100-year			
	Volume	10-year	Total runoff volume for those days with a daily mean discharge exceeding the 24-hour discharge		
		50-year			
		100-year			

Relevance	Hydrograph Feature	Frequency of Occurrence	Duration	Metric	Ecological or Geomorphic Endpoint
Geomorphic Stability and Capacity to Transport Sediment	Peak Discharge	1.5 year	24 - hour	The minimum change between time periods is the accuracy of measuring streamflow discharge and estimating daily mean discharge. A discharge measurement accurate within 10% of the true value is considered excellent by the United States Geological Survey (USGS). Some additional error is induced through the conversion of these data to discharge. Therefore, a minimum change of 15% is needed between "historic" period and "modern" period for this metric to classified as "altered."	Channel forming discharge. An increase is interpreted as an increased risk of stream channel susceptibility to erosion.
	Volume	1.5 year	Cumulative daily volume exceeding channel forming discharge		
		Average daily	30-year flow duration curve		

[1] Historic period is 1940-1975 and modern period is 1980-2015. Historic period refers to "benchmark" condition.

2.5 DETERMINATION OF ALTERED HYDROLOGY

A simple weight of evidence approach is used to decide whether the hydrology of a watershed is "altered" between two time periods. A "+" is assigned to each metric if it has a discernable increase from the benchmark as defined by the metric, between the historic and modern time periods. A "-" is assigned to each metric if it has a discernable decrease from the benchmark as defined by the metric, between the historic and modern time periods. An "o" is assigned to each metric if it lacks a discernable increase or decrease from the benchmark as defined by the metric, between the historic and modern time periods. If the number of "+" values exceeds the number of "-" values, an increase in the watershed response to precipitation is implied and the hydrology is considered altered between the two time periods. If the number of "-" values exceeds the number of "+" values, the a decrease in the watershed response to precipitation is implied and the hydrology is considered altered between the two time periods. The hydrologic response of the watershed is considered "altered" if the percentage of + and – signs exceeds 50%.

2.6 ESTABLISHING ALTERED HYDROLOGY GOALS

There are two types of goals; i.e., a qualitative and a quantitative goal. The qualitative goal is to return the hydrology to the benchmark condition. The qualitative goal is evaluated using a weight of evidence approach. The goal is simply to achieve the conditions for the historic period as defined by the metrics with **Table 1**. It is presumed the historic period is "better" from an ecological and geomorphological perspective.

The second type of goal is a quantitative storage goal. Several of the metrics within **Table 1** can be used to establish storage goals, which may be accomplished by a variety of types of projects. These project types include not only traditional storage, but increasing the organic matter content of soils. These goals are the change in volume between the historic and modern time periods. The volume needs to be described by the effective volume, which is the amount of storage required on the landscape.

2.7 METHODS FOR EVALUATING ALTERED HYDROLOGY MITIGATION STRATEGIES

Several methods can be used to develop strategies to mitigate the effects of altered hydrology. These methods include the use of continuous simulation hydrology models (like the Hydrologic Simulation Program Fortran) and the event-based hydrology approaches (like those within the Prioritize, Target and Measure Application).

3 ALTERED HYDROLOGY RESULTS

The altered hydrology analysis is completed for a single location within the Crow plan area using measured streamflow discharge. Fiscal limitations prevented applying the technique to each planning region, which is the preferred spatial scale.

Using mean daily discharge data from the USGS gage at Crow River at Rockford, MN (USGS ID: 05280000), the altered hydrology analysis was conducted, comparing two periods: a "historic" period and a "modern" period. Studies have identified the mid-1970s as an inflection point in the hydrologic record representing a "change" in the hydrologic conditions in the Upper Midwest, driven by a combination of changes in precipitation and land use/land cover (Frans et al., 2013; Schottler et al., 2013). Analysis of the cumulative runoff over time show this assumption is correct (see **Figure 2**). All metrics are computed using water years, i.e. October of the previous year through September of the reporting year (e.g. water year 2015 is October 1, 2014 through September 30, 2015).

3.1 METRICS OF ALTERED HYDROLOGY

3.1.1 CONDITION OF AQUATIC HABITAT

The condition of aquatic habitat includes a group of metrics that primarily reflect the flow characteristics of the annual hydrograph, needed to maintain adequate habitat for fish and aquatic life. The 7-day low flow, the 30-day low flow, and the median November mean daily discharge are metrics used to represent changes in the availability of flow for aquatic habitat.

3.1.1.1 ANNUAL MINIMUM 30-DAY MEAN DAILY DISCHARGE

The annual minimum 30-day mean daily discharge is the minimum of the 30-day moving mean daily discharge within a year (an annual minimum series). **Figure 3** shows the annual minimum 30-day mean daily discharge for select return periods (1.01-year, 1.5-year, 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year). **Table 2** summarizes the data shown in **Figure 3**. According to **Table 2**, the annual

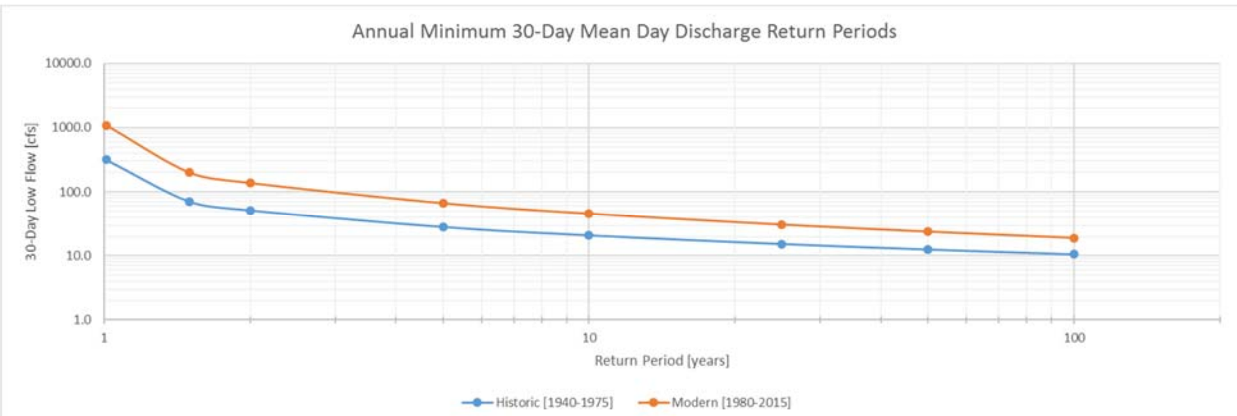

Figure 3. Historical (1940-1975) versus modern (1980-2015) annual minimum 30-day mean daily discharge versus return period for Crow River at Rockford, MN (USGS ID: 05280000).

Table 2: Summary of annual minimum 30-day mean daily discharge by return periods for the Crow River at Rockford, MN.

Return Period	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology Criterion
1.01	319.0	1096.1	243.6%	+
1.5	71.0	200.6	182.6%	+
2	51.6	137.5	166.7%	+
5	28.2	66.3	135.0%	+
10	20.8	45.5	118.4%	+
25	15.2	30.6	101.0%	+
50	12.5	23.7	89.9%	+
100	10.5	18.8	80.1%	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

minimum 30-day mean daily discharge has increased across all return periods. **Figure 3** and **Table 2** show that the modern time period exhibits an increase in the annual minimum 30-day mean daily discharge compared to the historical period. The percentage increase is greater for more frequent return periods.

3.1.1.2 ANNUAL MINIMUM 7-DAY MEAN DAILY DISCHARGE

Like the annual minimum 30-day mean daily discharge, the annual minimum 7-day mean daily discharge is the minimum of the 7-day moving average flow in the year. **Figure 4** shows the annual minimum 7-day mean daily discharges for select return periods (1.01-year, 1.5-year, 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year). **Table 3** summarizes the data shown in **Figure 4**. According to **Table 3**, the annual minimum 7-day mean daily discharge has increased across all return periods. **Figure 4** and **Table 3** show that the modern time period exhibits an increase in the annual minimum 7-day mean daily discharge compared to the historical period. The percentage increase is greater for more frequent return periods.

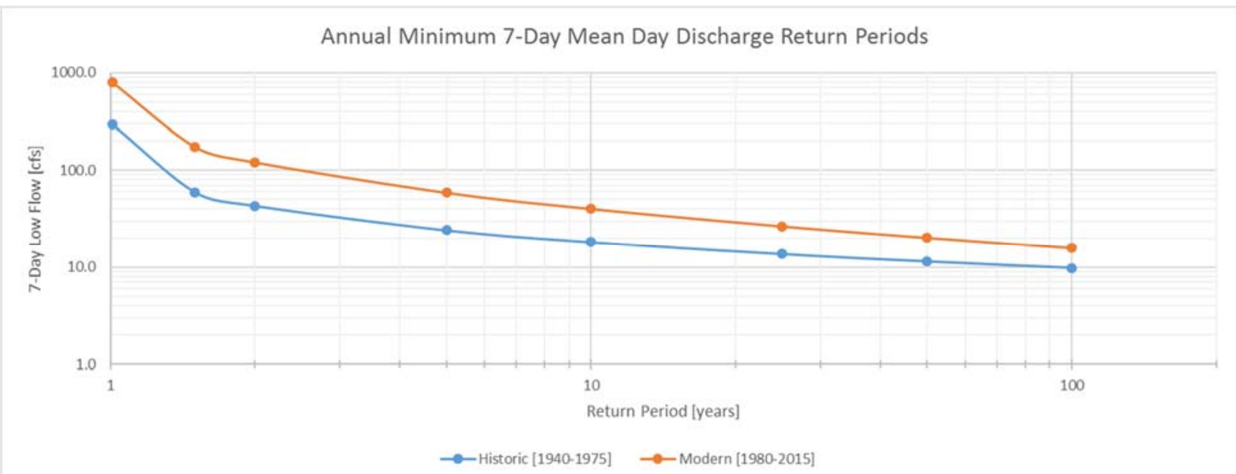

Figure 4. Historical (1940-1975) versus modern (1980-2015) annual minimum 7-day mean daily discharge return periods for Crow Rivers at Rockford, MN (USGS ID: 05280000).

Table 3: Summary of annual minimum 7-day mean daily discharge return periods for the Crow River at Rockford, MN.

Return Period	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology Criterion
1.0101	294.1	792.0	169.4%	+
1.5	59.4	173.3	191.7%	+
2	43.1	121.0	180.6%	+
5	24.1	59.0	145.2%	+
10	18.1	40.2	121.6%	+
25	13.7	26.6	94.5%	+
50	11.5	20.2	76.6%	+
100	9.8	15.8	60.5%	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

3.1.1.3 NOVEMBER MEDIAN DAILY DISCHARGE

The median daily mean discharge for November is another indicator of baseflow in the Crow River. This metric is intended to represent baseflow condition during the winter months. **Table 4** provides the median November flow for each period. The median November flow has increased by 330% between the historic period (1940-1975) and the modern period (1980-2015).

Table 4: Historical (1940-1975) and modern (1980-2015) median November flow for the Crow River at Rockford, MN.

Return Period	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology Criterion
Period median November flow [cfs]	114	490	329.8 %	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

3.1.2 AQUATIC ORGANISM LIFE CYCLE

The shape of the annual hydrograph and timing of discharges are associated with ecological cues. Metrics related to the aquatic organism life cycle include the shape of the annual hydrographs, timing of the annual minimum flow, and timing of the annual peak flow.

3.1.2.1 ANNUAL DISTRIBUTION OF DISCHARGES

The annual distribution of runoff is shown two ways: as average monthly runoff volume in acre-feet per month (**Figure 5**) and as a percentage of average annual runoff volume (**Figure 6**). **Figure 5** shows the magnitude of changes between the historic and modern periods and the increases of monthly average runoff volume across the year. **Figure 6** shows the distribution of volumes has changed across a year. As seen in **Figure 6**, although the magnitudes of monthly volumes (**Figure 5**) have increased the relative distribution of runoff across the year has remained relatively the same, with the exception of the increased percentage of annual flow occurring in April. **Table 5** summarized the data used to generate **Figures 5** and **6**.

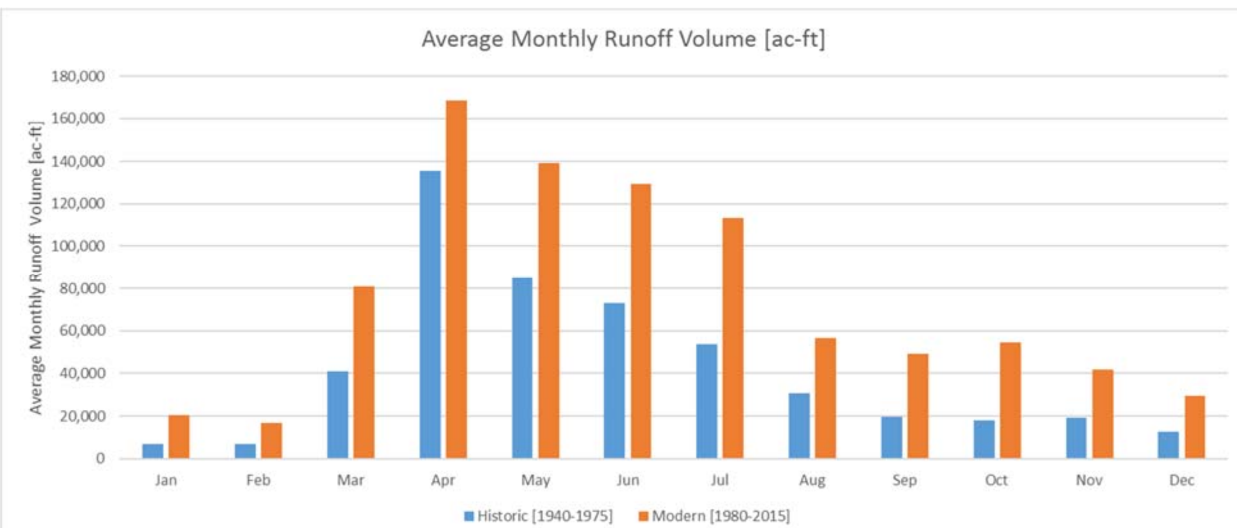

Figure 5. Average monthly runoff volume [ac-ft] in the Crow River at Rockford, MN (USGS ID: 05280000).

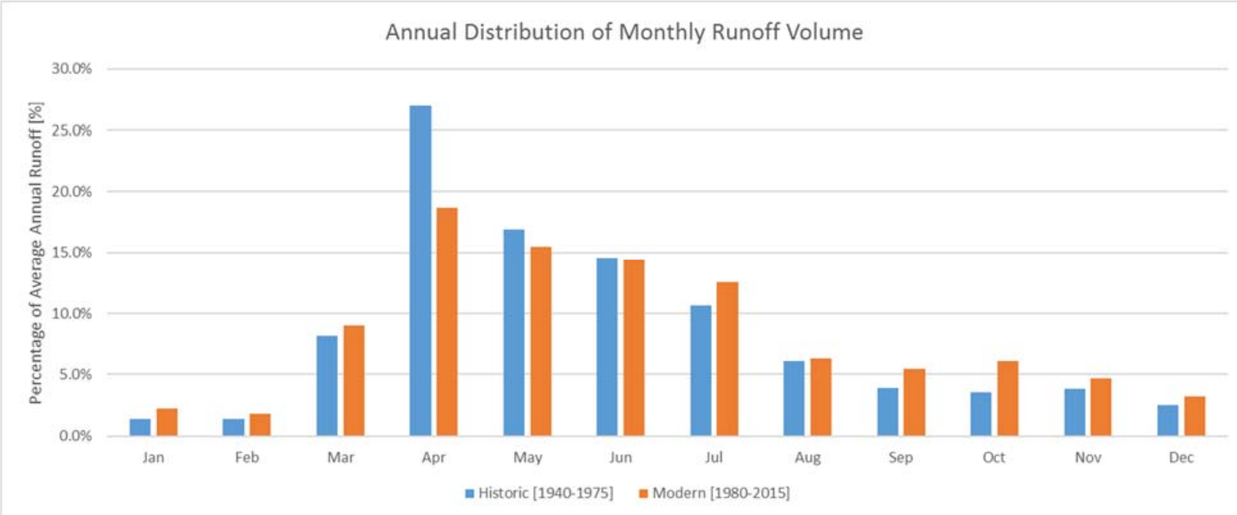

Figure 6. Annual distribution of average monthly runoff volume as a percentage of annual total volume in the Crow River at Rockford, MN (USGS ID: 05280000).

Table 5. Average monthly runoff volume and annual distribution of monthly runoff volumes in Crow River at Rockford, MN

Month	Average Monthly Volumes [ac-ft]				Distribution of Annual Volume			
	Historic Period [1940-1975]	Modern Period [1980-2015]	% diff.	AH	Historic Periods [1940-1975]	Modern Period [1980-2015]	% diff.	AH
Jan	6,981	20,361	191.7%	+	1.4%	2.3%	62.6%	+
Feb	7,017	16,773	139.0%	+	1.4%	1.9%	33.2%	+
Mar	40,782	80,849	98.2%	+	8.1%	9.0%	10.5%	+
Apr	135,456	168,368	24.3%	+	27.0%	18.7%	-30.7%	-
May	84,974	139,401	64.1%	+	16.9%	15.5%	-8.6%	O
Jun	73,102	129,509	77.2%	+	14.6%	14.4%	-1.3%	O
Jul	53,535	113,382	111.8%	+	10.7%	12.6%	18.0%	+
Aug	30,685	56,547	84.3%	+	6.1%	6.3%	2.7%	O
Sep	19,701	49,077	149.1%	+	3.9%	5.5%	38.8%	+
Oct	17,758	54,655	207.8%	+	3.5%	6.1%	71.5%	+
Nov	19,130	41,912	119.1%	+	3.8%	4.7%	22.1%	+
Dec	12,637	29,391	132.6%	+	2.5%	3.3%	29.6%	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period
AH means altered hydrology criterion

3.1.2.2 TIMING OF ANNUAL MAXIMUM AND MINIMUM FLOWS

The timing of the annual maximum daily discharge and annual minimum daily discharge are important metrics of the annual distribution of flows. The timing of the annual maximum typical occurs during the spring flood and the timing of the annual minimum usually occurs during the winter months. **Table 6** provides statistics on the Julian day of the annual maximum flow and **Table 7** provides the Julian day for the annual minimum flow. The statistics include the average, the median, and the mode. The mode is the Julian day that occurs the most during the period. These data suggest the maximum peak discharge is occurring later, but no changed has occurred in the timing of the minimum peak discharge.

Table 6. Julian Day of annual maximum in the Crow River at Rockford, MN.

Statistic	Historic Period[1] [1940-1975]	Modern Period [1] [1980-2015]	% diff.	AH
Average	May 5	May 18	10.7%	+
Median	April 16	May 7	19.8%	+
Mode	March 18	April 1	18.2%	+

[1]Based on 365-day year.
+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period
AH means altered hydrology criterion

Table 7. Julian Day of annual minimum flow in the Crow River at Rockford, MN.

Statistic	Historic Period[1] [1940-1975]	Modern Period[1] [1980-2015]	% diff.	AH
Average	July 9	July 17	4.5%	o
Median	Sept 10	Sept 6	-1.4%	o
Mode	Sept 30	Sept 30	0.0%	o

[1]Based on 365-day year.
+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period
AH means altered hydrology criterion

3.1.3 RIPARIAN FLOODPLAIN (LATERAL) CONNECTIVITY (PEAK FLOWS)

The riparian floodplain connectivity metrics represent the frequency and duration of flooding of the riparian area and the lateral connectivity between the stream and the riparian area. Functions include energy flow, deposition of sediment, channel formation and surface water – groundwater interactions. The riparian floodplain connectivity metrics include the discharge rates for the 10-year, the 25-year, the 50-year, and the 100-year peak discharges. The annual peak discharge rates for select return periods (1.01-year, 1.5-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 200-year) are shown in **Figure 7**. It should be noted that the discharge rates in **Figure 7** were computed using the USGS's annual maximum flow rates and not the daily average discharge rates.

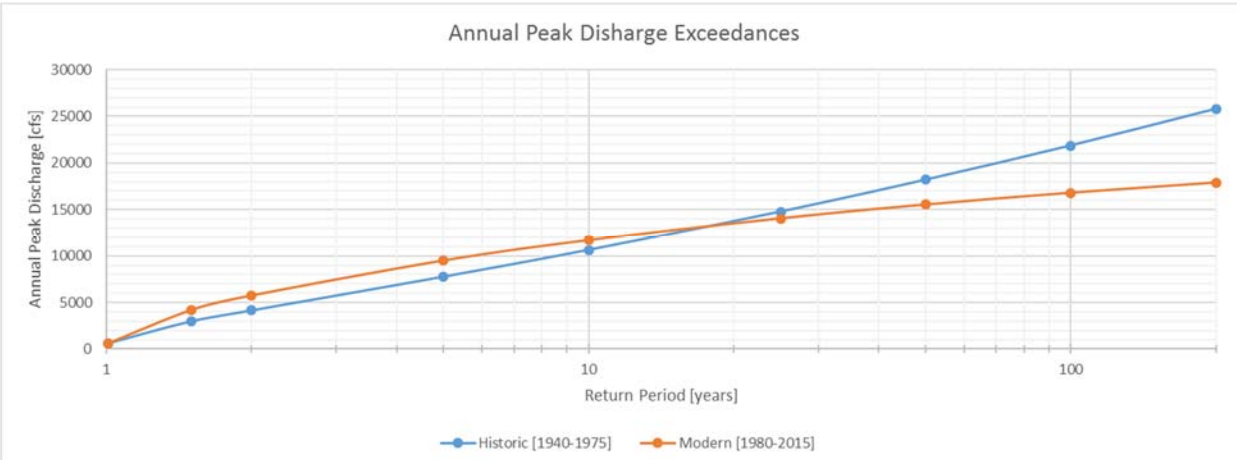

Figure 7. Historical (1940-1975) versus modern (1980-2015) peak discharge return periods for Crow Rivers at Rockford, MN (USGS ID: 05280000).

In addition, the number of years with discharges exceeding the historic peak discharge within a period, the average number of days above the historic peak discharge rates, and the average cumulative volume of discharge above the historic peak discharges are provide (**Table 8**). The data provided in **Table 8** were computed using the daily mean discharge time series and may show slight differences from **Figure 7**.

Table 8. Riparian floodplain connectivity metrics for the Crow River at Rockford, MN

Flow Metric	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology
5-Year Peak Discharge, Q(5) [cfs]	7,710	9,432	22.3%	+
Number of years with Discharge (Q) > Q_{pre} (5)	5	10	100%	+
Average number of days per year Q > Q_{pre} (5)	13	13	1.6%	o
Average annual cumulative volume > Q_{pre} (5) [ac-ft]	104,469	49,795	-52.3%	-
10-Year Peak Discharge, Q(10) [cfs]	10,569	11,388	7.7%	o
Number of years with Discharge (Q) > Q_{pre} (10)	4	6	50.0%	+
Average number of days per year Q > Q_{pre} (10)	9	7	-22.2%	-
Average annual cumulative volume > Q_{pre} (10) [ac-ft]	62,945	12,440	-80.2%	-
25-Year Peak Discharge, Q(25) [cfs]	14,646	13,431	-8.3%	o
Number of years with Discharge, (Q) > Q_{pre} (25)	2	0	NA[1]	o
Average number of days per year Q > Q_{pre} (25)	5	0	NA[1]	o

Flow Metric	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology
Average annual cumulative volume > Q_{pre} (25) [ac-ft]	34,352	0	NA[1]	o
50-Year Peak Discharge, Q(50) [cfs]	17,983	14,676	-18.4%	-
Number of years with Discharge (Q) > Q_{pre} (50)	1	0	NA[1]	o
Average number of days per year Q > Q_{pre}(50)	5	0	NA[1]	o
Average annual cumulative volume > Q_{pre} (50) [ac-ft]	26,153	0	NA[1]	o
100-Year Peak Discharge, Q(100) [cfs]	21,550	15,719	-27.1%	-
Number of years with Discharge (Q) > Q_{pre} (100)	1	0	NA[1]	o
Average number of days per year Q > Q_{pre} (100)	2	0	NA[1]	o
Average annual cumulative volume > Q_{pre} (100) [ac-ft]	1,784	0	NA[1]	o

[1]No events occurred above return period discharge.
+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

3.1.4 GEOMORPHIC STABILITY AND CAPACITY TO TRANSPORT SEDIMENT

The geomorphic stability and capacity to transport sediment metrics are related to the channel forming discharge. An increase in these metrics would be interpreted as an increase in the risk of the stream channel susceptibility to erosion. These metrics include changes to the flow duration curves, the 1.5-year peak flow, the 2-year peak flow. The 1.5-year to 2-year peak flows are generally consider the range of channel forming flow. In addition, the number of years within a period exceeding the historic peak flows, the average number of days above the historic peak flow rates, and the average volume of flow above the historic peak flows are provide (**Table 9**).

Figure 8 is the flow duration curves for the historic (1940-1975) and modern (1980-2015) periods and **Table 9** provides a summary of flows for select percent exceedances. Both show that discharges across

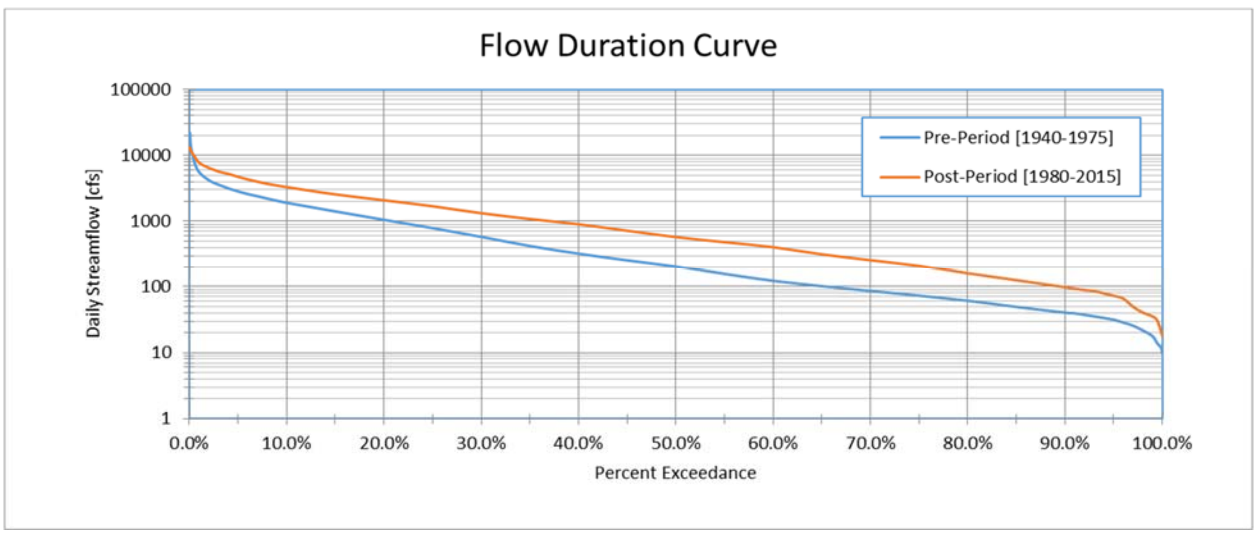

Figure 8. Historical (1940-1975) versus modern (1980-2015) flow duration for Crow Rivers at Rockford, MN (USGS ID: 05280000).

Table 9. Select summary of the flow duration curves for the Crow River at Rockford, MN

Percent Exceedance	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology
0.1%	13,785	11,700	-15.1%	-
1.0%	5,500	7,580	37.8%	+
10.0%	1,920	3,260	69.8%	+
25.0%	793	1,670	110.6%	+
50.0%	207	569	174.9%	+
75.0%	87	253	190.8%	+
90.0%	41	97	136.6%	+
99.0%	18	35	94.4%	+
99.9%	12	20	66.7%	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

the flow spectrum have increased substantially, with the exception of the very high flows.**Table 10** provides the 1.5-year and 2-year annual peak flows and flow statistics. It shows that the magnitude, the occurrences, and durations of the channel forming flows have significantly increased between the two periods. This may lead to increase instability of the channel and lead to increase erosion risk.

Table 10. Geomorphic stability and capacity to transport sediment metrics for the Crow River at Rockford, MN

Flow Metric	Historic Period [1940-1975]	Modern Period [1980-2015]	% Diff.	Altered Hydrology
1.5-Year Peak Discharge, Q(1.5) [cfs]	2,937	4,435	51.0%	+
Number of years with Discharge (Q) > Q_{pre} (1.5)	24	29	20.8%	+
Average number of days per year Q > Q_{pre}(1.5)	26	54	108.0%	+
Average annual cumulative volume > Q_{pre} (1.5) [ac-ft]	102,304	205,439	100.8%	+
2-Year Peak Discharge, Q(2) [cfs]	4,109	5,942	44.6%	+
Number of years with Discharge (Q) > Q_{pre} (2)	14	27	92.9%	+
Average number of days per year Q > Q_{pre} (2)	14	31	125.2%	+
Average annual cumulative volume > Q_{pre} (2) [ac-ft]	73,250	121,132	65.4%	+

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

3.2 SUMMARY OF ALTERED HYDROLOGY IN THE CROW RIVER AT ROCKFORD, MN

Table 11 provides a summary of the altered hydrology metrics. Overall, the streamflow metrics in the Crow River at the USGS gaging station at Rockford have increased, with the exception of peak discharge with a return period greater than 10-years. **Table 12** shows that the hydrology of the watershed has been altered for the modern period compared to the historic (benchmark) period.

Table 11. Summary of altered hydrology metrics.

Group	Metric	% Difference	Altered Hydrology Metric	Evidence of Altered Hydrology for Group
Aquatic Habitat	10-year, Annual Minimum 30-day Mean Daily Discharge	118.40%	+	Yes - increase
	10-year, Annual Minimum 7-day Mean Daily Discharge	121.60%	+	
	Median November (Winter Base) Flow	329.80%	+	
Aquatic Organism Life Cycle	Magnitude of Monthly Runoff Volumes	77.2% - 207.8%	+	Maybe - increase
	Distribution of Monthly Runoff Volumes	-30.7% - 71.5%	O	
	Timing of Annual Peak Discharge	10.70%	+	
	Timing of Annual Minimum Discharge	4.50%	O	
Riparian Floodplain (Lateral) Connectivity	10-year Peak Discharge Rate	7.70%	O	Yes - decrease
	50-year Peak Discharge Rate	-18.4%	-	
	100-year Peak Discharge Rate	-27.1%	-	
	Average Cumulative Volume above the Historic 10-year Peak Discharge	-52.3%	-	
	Average Cumulative Volume above the Historic 50-year Peak Discharge	-100%	-	
	Average Cumulative Volume above the Historic 100-year Peak Discharge	-100%	-	
Geomorphic Stability and Capacity to Transport Sediment	1.5-year Peak Discharge Rate	51.0%	+	Yes - increase
	2-year Peak Discharge Rate	44.6%	+	
	Average Cumulative Volume above the Historic 1.5-year Peak Discharge	100.8%	+	
	Average Cumulative Volume above the Historic 2-year Peak Discharge	65.4%	+	
	Duration above the Historic 1.5-year Peak Discharge	108.0%	+	
	Duration above the Historic 2-year Peak Discharge	125.2%	+	
	Flow Duration Curve	-15.1% - 190.8%	+	

+ symbol indicates metric exhibits altered hydrology and an increase for the modern period compared to the historic period
o symbol indicates fails to exhibit altered hydrology for the modern period compared to the historic period
- symbol indicates metric exhibits altered hydrology and a decrease for the modern period compared to the historic period

Table 12. Summary of altered hydrology metrics. Hydrology is considered altered if percent of the total metrics exceeding the altered hydrology metrics is greater than 50%.

Category	Number (% of total)
No. of Metrics Used	20
No. of Positive Metrics Exceeding Altered Hydrology Criteria	12 (60%)
No. of Neutral Metrics	3 (15%)
No. of Negative Metrics Exceeding Altered Hydrology Criteria	5 (25%)
No. of Metric Exceeding Altered Hydrology Criteria	17 (85%)

4 ALTERED HYDROLOGY GOAL

Goals for addressing the change in hydrology were estimated using three methods. Each method is based on different assumptions and altered the metrics for a specific "altered hydrology" group (see Table 11). The first method is focused on the aquatic habitat and geomorphic and ability to transport sediment metric group and uses the change in the cumulative volume for mean daily discharges, exceeding the 1.5-year return period event. The cumulative total volume when the daily average discharge exceeds the 1.5-year peak discharge includes all flows above the 1.5-year peak, i.e. can include storms with much larger return periods. The change in average annual cumulative volume above the 1.5-year peak flow for the Crow River is ~104,000 acre-feet (see **Table 10**) or 0.75 inches across the entire watershed draining to the gage. This method is based on the changes in the observed data and since it includes all flows above the 1.5-year flow relies on the two periods to have a similar distribution of flows. Since the flow record in the Crow River includes flow above the 10-year flow in the historic period only, this estimate may be underestimated.

The second method is based on the changes in hydrology across the entire annual hydrograph, and integrates the differences in return period discharges between the modern and historic period (see **Table 13**) and finding a probability-weighted representative change in flow rate. A volume is then found by assuming a flow period equal to the change in flow period for the 1.5-year flow (i.e. the change in the number of days above the 1.5-year flow, 28 days; see **Table 10**). The estimated goal for the Crow River upstream of Rockford using the second method is ~130,000 acre-feet (**Table 13**). This corresponds to an average depth of 0.93 inches across the watershed. This method assumes a constant flow over a representative duration to estimate the storage goal. Since a hydrograph typically changes over time, this method may over-estimate the storage goal.

Table 13. Estimated goal for the Crow watershed upstream of Rockford, MN using method 2.

Return Period	Historic Period Discharges (cfs)	Modern Period Discharges (cfs)	Difference (cfs)	Probability of Occurrence	Difference* Probability (cfs)
1.5	2,937	4,435	1,498	0.67	1,003.7
2	4,109	5,942	1,834	0.5	917.0
5	7,710	9,432	1,722	0.2	344.3
10	10,569	11,388	819	0.1	81.9
25	14,646	13,431	-1,215	0.04	-
50	17,983	14,676	-3,307	0.02	-
100	21,550	15,719	-5,831	0.01	-
				Sum	2,346.9 cfs
					4,656.2 ac-ft/day
Change in average number of days above the Q(1.5)			28	**Total Volume Goal**	**130,373 ac-ft (0.93-inch)**

The third method is also based on addressing the effects through the entire flow range and is a revision to Method 2. Method 3 considers incorporates the observed change in the timing of the peak discharge for each return period event. This method uses the probability-weighted representative change in flow rate and multiples the flow rates by the change in the number of days exceeding the return period flow for each return period (see **Table 14**). Using this method, the storage goal for the Crow River at Rockford is ~96,500 acre-feet or 0.7 inches across the watershed.

This analysis presents a preliminary framework for defining altered hydrology, applying a method to determine whether altered hydrology has occurred, and establishing a goal for relating to proposed projects. The goal ranges from 96,500 acre-feet to 130,000 acre-feet or depths of 0.69 inches to 0.93 inches across the watershed. For planning purposes, we recommend a preliminary goal of 0.75 inches across the watershed, realizing that the altered hydrology goals should ideally be established at the 12-digit HUC scale. The actual amount of mitigation needed may exceeds the estimated range, as the methods used to achieve the goal are not expected to be 100% effective in removing volume from peak of the hydrograph. The means to achieve the estimated mitigation goal may include the use of structural practices and management practices and should be specifically evaluated through completion of a hydrologic study or the use of appropriate tools and models.

Table 14. Estimated goal for the Crow watershed upstream of Rockford, MN using method 3.

Return Period (Years)	Change in flow (Q_m-Q_h) (cfs)	Probability of Occurrence	Change in flow* Probability (cfs)	Probability weighted flow (AF/Day)	Change in the number of days above flow (days)	Storage Volume (AF)
1.5	1,498	0.67	1,004	1,991	28	55,757
2	1,834	0.5	917	1,819	17	30,928
5	1,722	0.2	344	683	0.2	137
10	819	0.1	82	162	0	0
					Total Volume Goal	**96,469 AF 0.69 inches**

5 REFERENCES

Angel, J. R., and F. A. Huff (1997), Changes in heavy rainfall in the Midwestern United States, *Journal of Water Resources Planning and Management* 123(4) 246-249.

Arthington, A.H., Bunn, S.E., Poff, N.L., and Naiman, R.J., 2006, The challenge of providing environmental flow rules to sustain river ecosystems: Ecological Applications, v. 16, p. 1,311–1,318. [Also available at http://dx.doi.org/10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2]

Bunn, S.E., and Arthington, A.H., 2002, Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity: Environmental Management, v. 30, no. 4, p. 492–507. [Also available at http://dx.doi.org/10.1007/s00267-002-2737-0.]

Baker, J.M, T.J. Griffis, and T.E. Ochsner (2012), Coupling landscape water storages and supplemental irrigation increase productivity and improve environmental stewardship in the U.S. Midwest. *Water Resources Research* 48: WR05301

Blann, K. L., J. L. Anderson, G. R. Sands, and B. Vondracek (2009), Effects of agricultural drainage on aquatic ecosystems: A review, *Critical Reviews in Environmental Science and Technology* 39(11): 909-1001.

Changnon, S. A., and K. E. Kunkel (1995), Climate-related fluctuations in Midwestern floods during 1921–1985. *Journal of Water Resources Planning and Management* 121(4), 326–334.

Danesh-Yazdi, M., E. Foufoula-Georgiou, D. L. Karwan, G. Botter, (2016), Inferring Changes in Water Cycle Dynamics of Intensively Managed Landscapes via the Theory of Time-Variant Travel Time Distributions, *Water Resources Research*, 52, doi:10.1002/2016WR019091

Donner, S.D., Kucharik, C.J., 2008. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proc. Natl. Acad. Sci. USA* 105, 4513–4518.

Donner, S.D. et al., 2004. Impact of changing land use practices on nitrate export by the Mississippi River. *Global Biogeochemistry.* Cy 18.

Foufoula-Georgiou, E., Z. Takbiri, J. A. Czuba, and J. Schwenk (2015), The change of nature and the nature of change in agricultural landscapes: Hydrologic regime shifts modulate ecological transitions, *Water Resources Research* 51, 6649–6671, doi:10.1002/2015WR017637.

Gan K.G., T.A. McMahon, and B.L. Finlayson. (1991). Analysis of periodicity in streamflow and rainfall data by Colwell's indices. *Journal of Hydrology* 123: 105–118.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore (2004), Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5(1): 64–85

Groisman, P. Y., R. W. Knight, and T. R. Karl (2012), Changes in intense precipitation over the central United States. *Journal of Hydrometeorology* 13(1): 47–66

Gupta, S.C., A.C. Kessler, M.K, Brown, and F. Zvomuya (2015). Climate and agricultural land use impacts on streamflow in the upper Midwestern United States. *Water Resources Research* 51, 5301–5317, doi:10.1002/2015WR017323.

Higgins, R. W., and V. E. Kousky (2013), Changes in observed daily precipitation over the United States between 1950-79 and 1980–2009. *Journal of Hydrometeorology* 14(1): 105–121

Karl, T. R., R. W. Knight, D. R. Easterling, and R. G. Quayle (1996), Indices of climate change for the United States, Bulletin of the American Meteorological Society. 77(2), 279–292

Karl, T.R. and R.W. Knight. (1998). Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society* 79(2): 231-241.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis (1994), Hydro-climatological trends in the continental United States, 1948-88, Journal of Climate. 7(4): 586–607

Lins, H. F., and J. R. Slack (1999), Streamflow trends in the United States, Geophysical Research Letters. 26(2): 227–230

Lins, H.F. and J.R. Slack, J.R. (2005). Seasonal and regional characteristics of US streamflow trends in the United States from 1940 to 1999. *Physical Geography* 26 (6): 489–501.

Mathews R. & Richter B. (2007) Application of the Indicators of Hydrologic Alteration software in environmental flow-setting. Journal of the American Water Resources Association, 43, 1–14.

McCabe, G.J. and Wolock, D.M., 2002. A step increase in streamflow in the conterminous United States. *Geophysical Research Letters* 29(24) 38-1 - 38-4.

McCabe, G.J., Palecki, M.A., and Betancourt, J.L. 2004. Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States. Proceedings of the National Academy of Sciences. V. 101, no. 12 4136-4141.

Novak, Rachael, Kennen, J.G., Abele, R.W., Baschon, C.F., Carlisle, D.M., Dlugolecki, Laura, Flotermersch, J.E., Ford, Peter, Fowler, Jamie, Galer, Rose, Gordon, L.P., Hansen, S.N., Herbold, Bruce, Johnson, T.E., Johnston, J.M., Konrad, C.P., Leamond, Beth, and Seelbach, P.W, 2015, Draft: EPA-USGS Technical Report: Protecting Aquatic Life from Effects of Hydrologic Alteration: U.S. Geological Survey Scientific Investigations Report 2015–5160, U.S. Environmental Protection Agency EPA Report 822-P-15-002, 163 pp., http://pubs.usgs.gov/sir/2015/5160/ and http://www2.epa.gov/wqc/aquatic life-ambient-water quality-criteria

Michaels, P. J., P. C. Knappenberger, O. W. Frauenfeld, and R. E. Davis (2004). Trends in precipitation on the wettest days of the year across the contiguous USA. *International Journal of Climatology* 24(15): 1873–1882

Milly, P. C. D., and K. A. Dunne (2001), Trends in evaporation and surface cooling in the Mississippi River Basin. *Geophysical Research Letters* 28(7): 1219–1222

Novotny, E. V., and H. G. Stefan (2007). Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology* 334(3–4): 319–333

Olden J.D. and N.L. Poff. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101-121.

Poff N.L. (1996). A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36: 71–91.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime—A paradigm for river conservation and restoration: Bioscience, v. 47, no. 11, p. 769–784. [Also available at http://www.americanrivers.org/assets/pdfs/water-supply/the-natural-flow-regime.pdf?bf5c96.]

Pryor, S. C., J. A. Howe, and K. E. Kunkel (2009). How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *International Journal of Climatology* 29(1): 31–45

Raymond, P. A., N.-H. Oh, R. E. Turner, and W. Broussard (2008). Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. *Nature* 451: 449–452

Ryberg, K. R., W. Lin, and A. V. Vecchia (2014). Impact of climate variability on runoff in the North-Central United States. *Journal of Hydrologic Engineering* 19: 148‐158, doi:10.1061/(ASCE)HE.1943-5584.0000775.

Ryberg, K. R., W. Lin, and A. V. Vecchia (2014), Impact of climate variability on runoff in the North-Central United States, *Journal of Hydrologic Engineering* 19:148‐158, doi:10.1061/(ASCE)HE.1943-5584.0000775.

Schilling, K. E. (2003), Relationship of increasing baseflow, changing land use and nitrate concentrations in Iowa's streams, paper presented at Spring Specialty Conference, American Water Resources Association, Kansas, Mo, 12–14 May.

Schilling, K. E. (2005). Relation of baseflow to row crop intensity in Iowa. *Agriculture, Ecosystems, and Environment* 105: 433–438, doi:10.1016/j.agee.2004.02.008.

Schilling, K. E., and R. D. Libra (2003). Increased baseflow in Iowa over the second half of the 20th century. *Journal of American Water Resources Association* 39: 851–860.

Schilling, K. E., M. K. Jha, Y.-K. Zhang, P. W. Gassman, and C. F. Wolter (2008), Impact of land use and land cover change on the water balance of a large agricultural watershed Historical effects and future directions, *Water Resources Research* 48: W00A09, doi:10.1029/2007WR006644.

Schilling, K. E., K.-S. Chan, H. Liu, and Y.-K. Zhang (2010), Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River, *Journal of Hydrology* 387: 343–345, doi:10.1016/j.jhydrol.2010.04.019.

Schottler, S. P., J. Ulrich, P. Belmont, R. Moore, J. W. Lauer, D. R. Engstrom, and J. E. Almendinger (2014), Twentieth century agricultural drainage creates more erosive rivers, *Hydrologic Processes* 28: 1951–1961, doi:10.1002/hyp.9738.

Sparks, Richard E., 1995 Need for Ecosystem Management of Large Rivers and Their Floodplains-These phenomenally productive ecosystems produce fish and wildlife and preserve species. Bioscience, v. 45, no. 3, p. 168–182.

Sugg Z. 2007. Assessing U.S. Farm Drainage: Can GIS Lead to Better Estimates of Subsurface Drainage Extent. *World Resources Institute*. Washington D.C. 1–8. August.

Tomer, M. D., and K. E. Schilling (2009), A simple approach to distinguish land-use and climate‐change effects on watersheds hydrology, *Journal of Hydrology* 376: 24‐33, doi:10.1016/j.jhydrol.2009.07.029.

Villarini, G., J. A. Smith, M. L. Baeck, R. Vitolo, D. B. Stephenson, and W. F. Krajewski (2011), On the frequency of heavy rainfall for the Midwest of the United States *Journal of Hydrology* 400(1–2): 103–120, doi:10.1016/j.jhydrol.2011.01.027.

Walsh, J., et al. (2014), Our changing climate, in *Climate Change Impacts in the United States: The Third National Climate Assessment*, edited by J. M. Melillo, T. C. Richmond, and G. W. Yohe, chap. 2, pp. 19–67, U.S. Global Change Res. Program, Washington, D. C., doi:10.7930/J0KW5CXT.

Zhang, Y.-K., and K. E. Schilling (2006). Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change. *Journal of Hydrology* 324: 412–422, doi:10.1016/j.jhydrol.2005.09.033.

APPENDIX A: A CHANGING HYDROLOGY-THE SCIENTIFIC DEBATE

It is the position of the authors that, although as helpful as it would be, understanding the causes of altered hydrology is not needed to quantify level of changes and develop mitigation goals. Although not necessary to quantify altered hydrology and set mitigation goals, understanding the causes of altered hydrology can be useful for water resources managers and stakeholders within a watershed. The following summarizes the ongoing discussion on the potential causes of altered hydrology in order to provide background on the research that has been conducted on the subject.
Numerous studies have investigated the links between changes in climate and the landscape to changes in the hydrologic response in a variety of watersheds (see References Section) but the science is not at point where causes of the alterations can be definitively linked to specific causes and quantified. The scientific discussion has circulated around two opposing viewpoints: altered hydrology is mainly driven by climatic changes, or is mainly driven by changes to the landscape, i.e. man-made or anthropomorphic changes. The complex nature of the relationship between precipitation and streamflow drives these conflicting viewpoints. *Poff et al.* (1996) summarizes the complex nature of streamflow as: *All river flow derives ultimately from precipitation but in any given time and place a river's flow is derived from some combination of surface water, soil water, and groundwater. Climate, geology, topography, soils, and vegetation help to determine both the supply of water and the pathways by which precipitation reaches the channel*.

Even though the main drivers of altered hydrology are still being debated, all agree that streamflow in Minnesota's streams, as well as the contiguous United States, have been increasing since the middle of the twentieth century (*Novotny and Stefan 2007, Lins and Slack 1999 & 2005*). *McCabe and Wolock* (2002) noticed a discernable step change in streams across the conterminous United States during the 1970s. The mid-1970s is typically viewed as the breakpoint in hydrology and corresponds to numerous compounding factors occurring, in general, around the same period. Those factors include the widespread replacement of grasses and small grains as the predominate crops to row crops, such as corn and soybeans in the Midwest (S*chilling, 2003, 2005; Zhang and Schilling, 2006; Foufoula-Georgiou et al.; 2016*), as well as the conversion of forest and wetlands to agricultural lands, and was accompanied by wide spread adoption of plastic tile drainage (*Gupta et al, 2015*). Artificial surface and subsurface drainage is viewed by many as a major contributor to increased streamflow (see *Shilling & Libra 2003; Raymond et al, 2008; Schottler et al, 2014* as examples). In addition, the following decades have seen documented climatic trends, including of warmer temperatures, earlier snowmelt, increased annual precipitation, and rainfall events of higher intensity and shorter duration (*Karl et al., 1996; Karl and Knight, 1998; Groisman et al., 2004; Villarinni et al., 2011; Danesh-Yazdi et al., 2016*). The following will discuss the literature linking climate changes to altered hydrology, followed by the literature linking anthropomorphic changes to altered hydrology, and a brief description of some issues within the current science.

Climate, specifically precipitation, is the main driver (over both space and time) for the generation of runoff, as all other components of runoff generation translate precipitation into runoff (see *Poff et al. 1996*). Increases in intensity, duration, and frequency of precipitation, changes in the timing of the spring snowmelt, and increases in magnitude and timing of seasonal temperatures can all play a role changing hydrology in a watershed. *Novonty and Stefan* (2007) correlated trends seen in Minnesota's streamflows to changes in observed climate. *Tomer and Schilling* (2009) concluded that climate change has been the larger of the two main drivers (climate change and land use change) for increased streamflows in the Midwestern United States. Using a non-linear water-balance approach, *Ryberg et al.* (2014) show that changes in precipitation and potential evapotranspiration explain the majority of multidecadal spatial/temporal variability in runoff and flood magnitudes, with precipitation being the main driver, and that historical changes in climate and runoff appear to be more consistent with complex transient shifts in seasonal climate conditions than with gradual climate changes. According to Foufoula-Georgiou et al. (2015), two major trends have been observed: (1) higher temperatures leading to earlier snowmelt and a longer growing season and (2) an increase in precipitation with an intensification of extreme storms (e.g., Lettenmaier et al., 1994; Changnon and Kunkel, 1995; Karl et al., 1996; Angel and Huff, 1997; Michaels et al., 2004; Groisman et al., 2004, 2012; Pryor et al., 2009; Villarini et al., 2011; Higgins and Kousky, 2013; Walsh et al., 2014). Changes in evaporative and radiative cooling have also been reported and attributed to the enhanced seasonal precipitation signal (Milly and Dunne, 2001).

In addition to climatic changes, researchers have stipulated that streamflows have been increasing more than the increased precipitation alone can explain (*Raymond et al., 2008; Zhang and Schilling, 2006; Schillings et al., 2010*). Raymond et al. (2008) argued that changing agricultural practices have led to a 50 $km^3 yr^{-1}$ increase in water flux from the Mississippi River from a pre- to post-disturbance period (before and after 1940). Zhang and Schilling (2006) concluded that increasing discharge since the 1940s was mainly due to an increase in baseflow resulting from the rapid expansion of soybean cultivation that occurred in the Mississippi River basin during the middle of the 20th century (343% increase from 1950 to 1992; Donner et. al., 2003). Agricultural landscape changes can significantly change seasonal evapotranspiration (ET) potential (Zhang and Schilling, 2006; Schilling et al., 2008). Wang and Hejazi (2011) found human activities contributed more to increasing flows than climate and showed the increases were correlated with the fractional area in cropland. Given the extent of past wetland drainage and current widespread use of tile drainage (Sugg, 2007; Blann et al., 2009), artificial drainage networks have the potential to alter the plumbing in a watershed. Schottler et al. (2014) examined the residuals of the water budget for 21 agricultural watersheds and determined that climate and crop conversion could explain less than half of the observed changes in streamflow and concluded that artificial tile drainage was the main driver behind increasing streamflows. In addition to agricultural landscape changes, numerous other factors may play a role in a changing hydrology, including impoundments and flow regulation (e.g. dams), increased imperviousness and urbanization, groundwater pumpage, and changes in alternative supplies (i.e. wastewater outflows or irrigation), to name a few.

Gupta et al. (2015) evaluated the findings of numerous papers claiming of the importance of landscape changes and the impacts of artificial drainage driving the observed changes in streamflow. The authors indicated that the majority of the research showing the impacts of agricultural influences (*Schilling, 2003; Schilling and Libra, 2003; Schilling et al., 2008; Zhang and Schilling, 2006*) are strictly based on empirical approaches that fail to account for the underlying principles of soil water storage, water infiltration, and surface runoff*. Schottler et al.* (2014) showed that runoff ratios increased primarily due to landscape modification, but failed to recognize that the changes could be due to increased soil wetness from the increased precipitation, leading to increased runoff (*Gupta et al., 2015*). The findings that wide spread adoption of soybeans reduced the ratio of annual ET to annual precipitation, leading to increased streamflows, is based on two observations: (1) an empirical relationship relating baseflow to fractional area under soybean production (*Zhang and Schilling, 2006*), and (2) an ET analysis that showed a decrease in the ratio of ET to precipitation. However, Baker et al (2012) showed that ET has remained relatively similiar since the 1960s in the Upper Mississippi River Basin. Gupta et al. (2015) questioned why ET has remained relatively constant over time even though there have been substantial changes in the landscape, including tile drainage, drainage of wetlands, cultivation of prairies, and adoption of different crops in the cropping system? Gupta et al. (2015) tested the assumptions of these papers and concluded, among others, that linear regression models showed no significant shift in the slope and intercept when comparing two periods (before and after 1975) and that added regression coefficients did not add statistical significance, concluding no significant change in the relationship between precipitation and streamflow and that the increases in streamflows are mainly due to increased precipitation, consistent with the principles of higher soil moisture conditions. But it is unknown how Gupta et al. (2015) accounted for the inter-annual dependency of streamflow (e.g. storages such as soil moisture) in their regressions. In addition, it is not surprising that precipitation is the only regression coefficient with statistical significance. Precipitation can be thought of as the only “independent” variable, in a physical sense all other potential variables are dependent on precipitation to generate runoff (e.g. soil moisture relies on the history of precipitation and evapotranspiration).

A common theme of, and a potential common problem with, most studies that have investigated the causes of the increased streamflow, regardless if it is a statistical analysis, developing empirical relationships, or a regression analysis, is the reliance and use of seasonal and annual relationships between precipitation and streamflow. On a large scale (both spatial and temporal), most runoff generation is ultimately driven by precipitation, and all other mechanisms in a watershed just translate precipitation into streamflow. In a sense, precipitation is the only independent variable and all other factors are part of the error in any regression equation. The large natural variation in annual climate and annual streamflow make it difficult to tease out any other potential causes of altered hydrology, leading the current debate on direct causes and lack of consensus in the science. The scientific debate has focused on which of the two leading candidate causes (climate or anthropomorphic changes) of altered hydrology. The science debate should continue to work towards a more rigorous understanding of altered hydrology causes. However, this paper provides a methodology to quantify changes in hydrology and sets mitigation goals without attempting to investigate causes .