Stream Low Flows and Regulatory Low Flows Estimation for National Pollutant Discharge Elimination Systems (NPDES) Permitting in Changing Climate

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***Abstract*- The conventional point source discharge permitting decision through the National Pollutant Discharge Elimination System (NPDES) is primarily based on the regulatory low flows such as hydrological (7Q10, 1Q10), biological (4B3, 4B1) and seasonal low-flow conditions. These regulatory low flow conditions are often estimated based on long-term historical flow data and can be expected to meet regulatory water quality protection provided that long-term data are utilized. Since climate change has potential to change the future low flow in the stream, concerns arise regarding the benefit of using long-term data for regulatory low flow estimation. We conducted a study in the Ohio River Basin and some of the selected regions of the Mid-Atlantic and Great Lake to examine the relevance of long-term data for regulatory low estimation. First, we detected the climate change pattern, and then, the study was conducted at various hydro-climatic data network (HCDN) stations to analyze the sensitivity of estimated hydrological/biological conditions on the length of data records. We analyzed the long-term data records for regulatory low flow estimation using various spans of data records. Our analysis indicated that long-term data were not necessarily beneficial for regulatory low flow estimation. The 50th percentile area-normalized 7Q10 indicated that 50 to 60 years of data was sufficient to capture minimum low flows. The average normalized 7Q10 computed using more than 60 years of records started increasing. However, the mean and median 7Q10 computed separately for summer and winter tended to increase for the last 40 years and decreased for the data used beyond 40 years of record. In summary, data of more than 60 years duration in any period over the historical period may not be needed to capture the lowest flow in this climatic region as the lowest flow either increases or remains constant after this period. Our analysis suggests that the large period of records may not be beneficial for regulatory low flow estimation.**

***Keywords*- NPDES permitting, Low Flow, 7Q10, 1Q10, 4B3, 1B3, Hydrologic and Biologic Condition**

I. INTRODUCTION

The conventional point source discharge permitting decision through National Point Discharge Elimination System (NPDES) is primarily based on the hydrological, biological or seasonal low flow (regulatory flow) conditions even though these criteria are not universally accepted (Saunders III et al., 2004; Sharma et al., 2012). These regulatory low flow (7Q10, 1Q10, 4B3, 4B1) conditions are typically estimated based on the long term historical flow data and can be expected to meet regulatory water quality protection provided that long term data are utilized (Saunders III and Lewis Jr, 2003; Saunders III et al., 2004). Since overestimation of low flow is risky for water quality protection, appropriate estimation of low flow conditions is needed (Sharma et al., 2012). Low flows are often estimated using statistical analysis of the long-term observed data without considering potential impacts due to climate change. However, for the last few decades, scientists and researchers have been concerned with climate change and its potential impact on precipitation, temperatures (Angel and Huff, 1997; Field et al., 2014) and hydrological cycles (Bates et al., 2008; Gain et al., 2013). Although there is a discussion for the exact rate and degree of increasing temperature and precipitation trends due to climate change (Michaels and Balling, 2000), there is a general consensus among scientists that global climate change is occurring (Doran and Zimmerman, 2009; Oreskes, 2004, 2007; Walther et al., 2005).

If the climate is changing, the extent to which long-term data is incorporated into regulatory low flow estimation should be reviewed. The exact methods for low flow estimation in a climate-change context have yet to be determined. Some questions that have yet to be answered include: Are the long-term records of more than a 100-year period beneficial, as considered appropriate conventionally, for estimation of 7Q10 if the global climate is truly changing? What consequences will be encountered in terms of pollutant assimilation in the stream? Will additional treatment be needed in waste water treatment facilities in the future? How do we incorporate the global climate change conditions in the point source permitting process? In fact, hydrological conditions and biological conditions of the stream might be affected due to climate change leading to more critical conditions in the future. Therefore, further study related to climate change and its potential impact on regulatory low flow estimation is essential.

Climate change studies are generally conducted using future projected climate data from various Global Circulation Models (GCMs) (Grotch and MacCracken, 1991; Hansen et al., 1983). Since climate models' predictions are based on the input from the Intergovernmental Panel on Climate Change (IPCC) scenarios (which are not deterministic), a degree of uncertainty is

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associated in climate model prediction (Stainforthet al., 2005). Different climate models under various IPCC scenarios may have some variations in future precipitation and temperature projection (Allen et al., 2000) leading to some uncertainty in future hydrological assessments (Maurer, 2007; Wilby and Harris, 2006). As a matter of fact, a climate change study based on the retrospective historical observed data is more relevant due to a relatively lesser degree of uncertainty associated with past records. In other words, studies using the data from the 19th century and its impact in global hydrology will offer an evidence for the potential climate change impact on low flow estimation, and possible consequences in NPDES permitting. Therefore, in this study, observed data for long-term periods are analysed to detect the impact of long-term observed data for regulatory low flow estimation.

In the work presented here, we analyse historical climate patterns and re-analyse the regulatory low flow estimation in numerous ways to detect the stream low flows pattern. Research was conducted based on the long term observed data at the Hydro-Climatic Data Network (HCDN) because minimum anthropogenic influence was expected to be experienced in these stations (Slack and Landwehr, 1992). We chose these regulatory low flow criteria as these were the key basis for NPDES permitting in the USA.

This work differs from past studies in examining climate variability and hydrological or biological low flow estimation (Saunders III et al., 2004) numerous ways: i) it uses a longer period of data; ii) it has analyses the separate low flow criteria for winter and summer; iii) this study detects a flow pattern to suggest the length of past historical record (e.g. 1975 in this study) that should be included for low flow estimation.

During low flow periods, the majority of the streams are significantly affected by point sources such as discharge from the waste water treatment and industrial facilities due to reduced assimilating capacities of the stream. The non-point source contribution during low flow or dry periods is negligible. In fact, water quality problems in the streams are mainly encountered during dry periods (summer) (Van Vliet and Zwolsman, 2008). The release of a point source is based on the criteria (stream low flows) suggested by National Point Discharge Elimination System (NPDES). Therefore, the broad research objectives are to; (i) analyze the climate change and climate variability (e.g. El Niño Southern Oscillation) impact for the estimation of hydrologic and biologic low flows conditions, and ii) detect the climate change effect and prescribe the appropriate period of records needed for the estimation of hydrological and biological low flow conditions without confounding climate change effect.

II. THEORETICAL BACKGROUND

Hydrological and biological conditions are the two major criteria for point source discharge permitting. Since the Clean Water Act (CWA) passed in 1972(Act, 2008), the CWA has defined water quality in terms of scientifically-sound criteria for the protection of aquatic life as well as human health. Various states in the United States use aquatic life criteria (e.g., ammonia, copper) and other water quality concentrations (e.g., dissolved oxygen) in order to develop water quality standards. Based on these water quality standards, the states and the United States Environmental Protection Agency (USEPA) develop Total Maximum Daily Loads (TMDLs) and NPDES permit limits considering critical conditions (e.g. low flows).

III. NPDES PERMITTING

NPDES permitting in the United States has been administered by the USEPA or some authorized states. Permitting has been effective in monitoring point source discharge allowing for significant improvement of water quality. Point source mainly refers for industrial or municipal discharge, which cannot be released directly to the surface water without obtaining NPDES permit.

The severity of water pollution is intensified during low flow periods as the assimilating capacity of the stream is reduced for contaminants released through industrial and waste water facilities. Therefore, waste load allocation, (a portion of TMDL) is allocated to a point source, considering the critical low flow approach (Boner and Furland, 1982). Under this approach, point source permitting is determined to meet numeric water quality criterion for selected low flows. There are two approaches for design flow computations: i) hydrologically-based design flow; ii) biologically-based design flow.

A. Hydrologically-based Design Flow

Originally introduced by the United States Geological Survey (USGS), this approach has been widely used by various states in the USA (Wiley, 2006). This design flow (e.g., 7Q10, 1Q10) is computed first by determining the single lowest flow event from each year of record, then by conducting a statistical analysis using the data from a series of years (Pyrce, 2004). For example, 7Q10 is computed using the minimum consecutive average seven-days low flow of the recurrence interval of 10 years. For this type of low flow analysis, typically a log Pearson III distribution will be fitted once the lowest seven-days flow from each year is plotted using the Weibul plotting position (Riggs, 1972).

B. Biologically-based design flow

This method was originally introduced by the USEPA (Rossman and EPA, 1990). In contrast with hydrologically-based design flow, this method examines entire low flow events within a period of record; that is, several lowest flow events, which are encountered in one year, can be incorporated for statistical analysis to compute a biologically-based design flow (e.g., 4B3, 1B3). Therefore, biologically-based design flow may include numerous low flow records from a single year while no event may

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be included from some years. For example, 4B3 is a four-day average flow event which can be expected once in three years. Since 4B3 may incorporate a number of low flow records from the same year and no record from any other year while examining all low flow events, it is different from 4Q3 because the latter uses only one record from a year.

IV. STUDY AREA

This study was conducted primarily on the Ohio River Basins; however, the study was extended to the few selected stations of the Mid-Atlantic and Great Lakes regions. All stations in the Ohio River Basin that were qualified to meet our criteria were included in this analysis. Since an identical pattern was detected in all the stations, only few a stations were included from the other two regions (Mid-Atlantic and Great Lakes regions) (Slack and Landwehr, 1992), in order to minimize the computational work. Analysis was conducted at 40 stations, as these were the only stations qualified to meet our set criteria, which will be further discussed later in the methodology section.

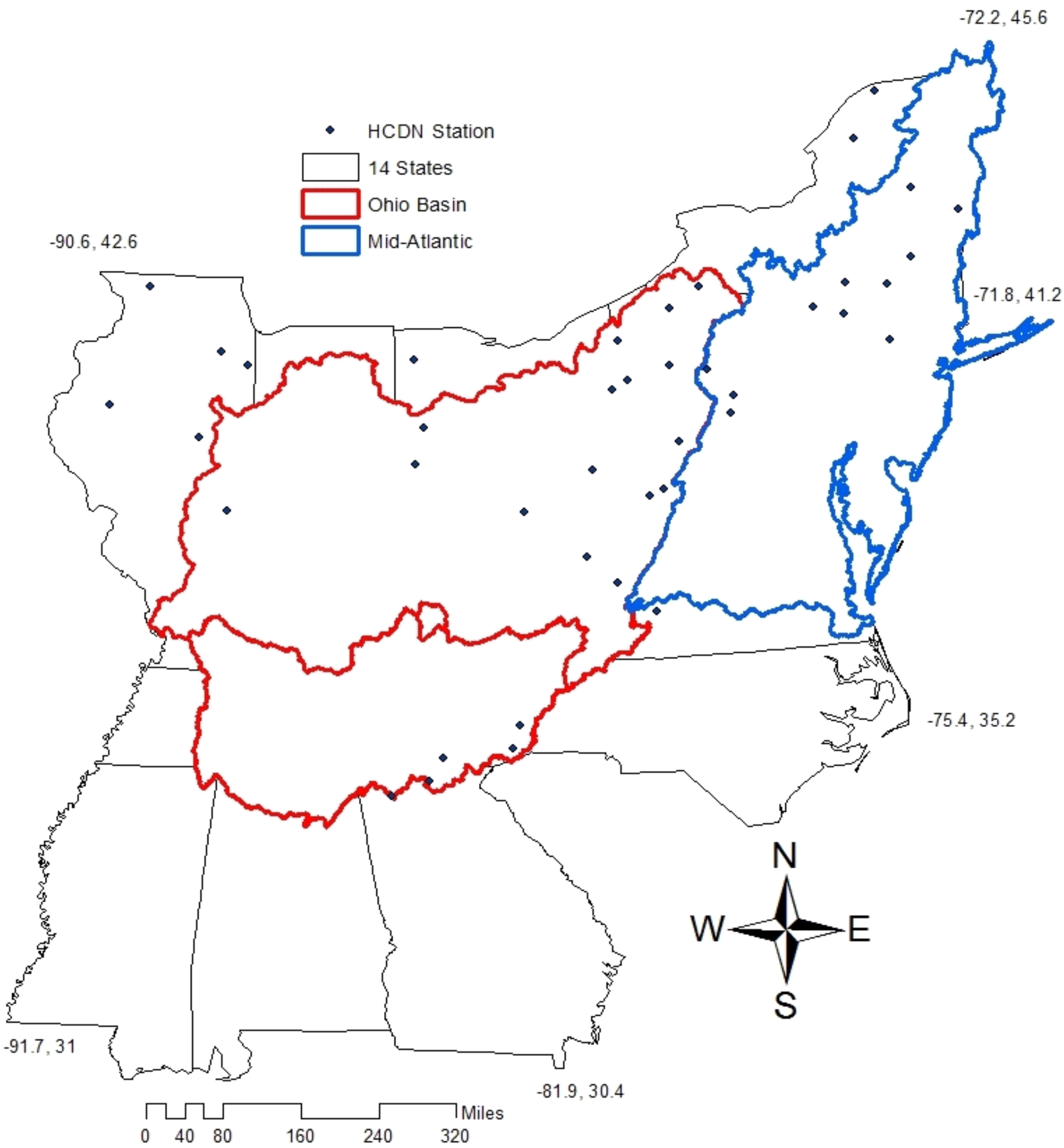


Figure 1.Study area with hydro-climatic data network (HDCN) stations, which furnishes data for than 90 years period of record. The number in the outer edge indicates the latitude and longitude

The Ohio River Basin is one of the largest river basins in the USA. The Ohio River Basin covers 204000 square miles, including portions of 14 states and is a significant contributor to the Mississippi River Basin. Though the Ohio River Basin is one of the the largest basins in the continental United States, limited studies have been conducted on this basin.

The basin lies between 340N and 410N latitude and 770W and 890W. It drains a major portion of eight states and some portion of six additional states. Indiana, Ohio and Pennsylvania are situated on the right bank, and are the major contributors for the River, whereas Kentucky and West Virginia are the principal states located on the left bank. The Ohio River Basin begins in Pittsburgh, PA at the confluence of the Allegheny and Monongahela Rivers, and after flowing 1579 km up to south west Cairo in Illinois, it eventually drains into the Mississippi River with substantial streamflow contributions due to uniformly distributed high precipitation across this region. This basin is one of the large contributors to the Mississippi River Basin (Turner and Rabalais, 2004). Although the Ohio River represents only 18% of the drainage area of the entire Mississippi River, it contributes 60% of the total flow in the Mississippi River Basin (Drum and Frevert, 2010). The basin is characterized with warm and humid summers and a mixed winter ranging from severely snowy cold in the Northeast to moderate and occasional snowy winters in the South. The average annual precipitation varies significantly, from 2024 mm in the Eastern region to 506 mm in the Northwest. The basin consists of 46.3% agricultural land, 42% pasture and range land, and 8% woodlands (Moore, 1989).

Of the two other regions (Great Lake Regions and Mid-Atlantic Region), the Great Lakes Region (Region 4) ultimately discharges into the Great Lakes system, including the lake surfaces, bays and islands, and St. Lawrence River. Similarly, the Mid-Atlantic Region (Region 2) ultimately discharges into the Atlantic Ocean within and between the states of New York and Virginia.

V. CLIMATE VARIABILITY AND CLIMATE CHANGE IN STUDY AREA

The severity of water pollution is intensified during low flow periods as the assimilating capacity of the stream is reduced for contaminants released through industrial and waste water facilities. Therefore, waste load allocation, (a portion of TMDL) is allocated to a point source, considering the critical low flow approach (Boner and Furland, 1982). Under this approach, point source permitting is determined to meet numeric water quality criterion for selected low flows. There are two approaches for design flow computations: i) hydrologically-based design flow; ii) biologically-based design flow.

A. *Climate variability*

Climate variability in the Ohio River Basin and nearby regions has been reported in several studies (Kunkel and Angel, 1999). For example, Kunkel and Angel (1999) reported the El Niño Southern Oscillation (ENSO) effect on snowfall in the Basin. Likewise, Brolley (Brolley, 2007) studied the impact of large scale climate patterns, including the ENSO, North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO), that brought significant changes to the climate variability of this region.

B. *Climate Change*

The future climate model projection, over the 21st century, indicates the consistent increasing trend of precipitation in higher latitudes (Field et al., 2014). Similarly, there are several indications of impact of climate change of on the Ohio River Basin, the Mid-Atlantic Region (Najjaret al., 2000; Neff et al., 2000; Rogers and McCarty, 2000), and the Great Lake Regions (Lofgren et al., 2002). The global trend of climate change is consistent with the climate change trend in the Ohio River Basin (USACE, 2015). For example, several indicate a trend of increasing precipitation in Northern America (Karl and Knight, 1998; Kunkel, 2003; Peterson et al., 2008; Pryoret al., 2008), particularly, from September to November. Similarly, the increased trend in streamflow was observed in this region during the 20th century (Karl and Knight, 1998; Lettenmaieret al., 1994; Olsen et al., 1999; Tomer and Schilling, 2009). The recent findings of the "Ohio River Basin Climate Change Pilot Study" are somewhat consistent with these earlier studies. The "Ohio River Basin Climate Change Pilot Study" suggests that the climate of the region from 1976 to 2040 will remain more or less the same, but high flow will start increasing and low flow will start decreasing after 2040. In the context of these findings, it is important to evaluate the relevancy of using long-term historical climate data in the low flow estimation for point source discharge permitting. Also, it is essential to determine the optimal number of years needed to compute 7Q10, which ensures the necessary treatment for the sufficient assimilation of the pollutant in a climate change context.

VI. METHODOLOGY

There are two approaches for design flow computations: i) hydrologically-based design flow; ii) biologically-based design flow. The analysis was conducted at HDCN stations based on the long-term historical records to estimate the exact period of data record needed for stream water quality protection. Therefore, extensive analysis was conducted to evaluate the benefit of incorporating long term data for regulatory low flow estimation. For this, USEPA's Dflow program (Rossman and EPA, 1990) was utilized, and low flows estimated at various lengths of data records were analysed.

A. *Methodology for Objective I*

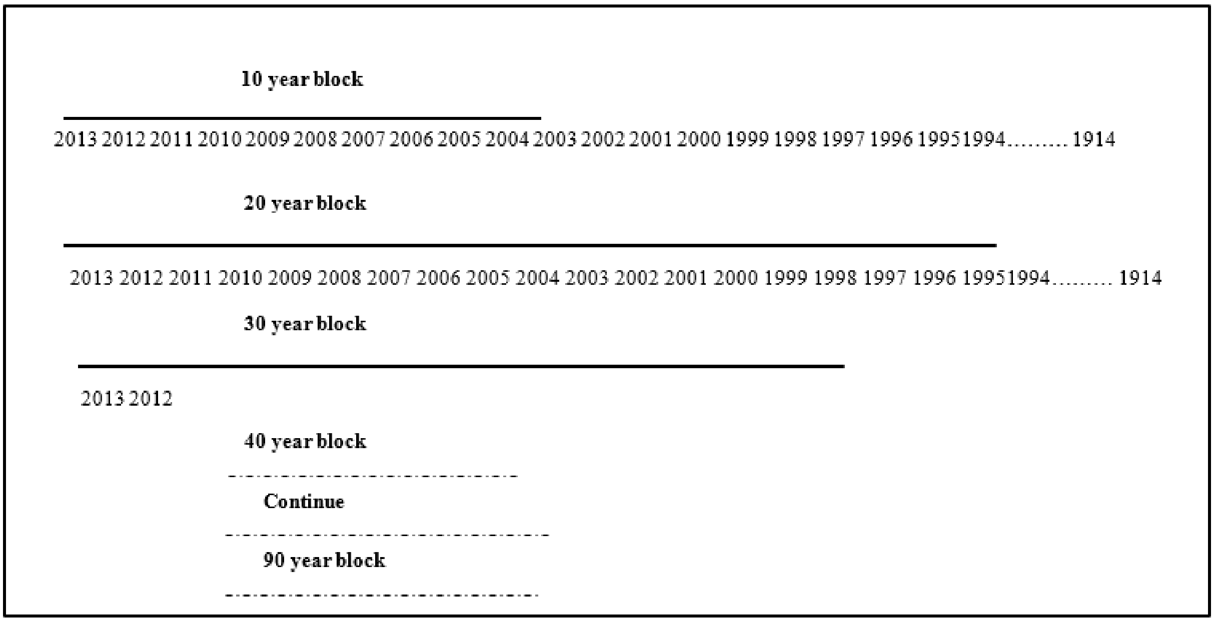
The analysis was limited to the HDCN stations expecting very little or no anthropogenic influence in these stations (Slack and Landwehr, 1992). Stations with data gaps were eliminated for consideration in analysis. Additional criteria were used for station selections such as the station should furnish daily data with non-zero flow at any time, and the station should also offer more than 90 years of observed data.

The HCDN data for more than 90 years of record are available in the USGS website (http://pubs.usgs.gov/wri/wri934076/region05.html). First, we analysed the long-term streamflow data monitored through HCDN in all qualified stations of the Ohio River Basin. Next, we selected some of the stations of the Mid-Atlantic and Great Lake Regions. Analysis of the two additional regions was particularly essential for two reasons: i) firstly, low flow estimation based on the short term data may not capture the lowest flows, and risky for adequate protection of fish and aquatic life, ii) and secondly, incorporating long-term data for regulatory low flow estimation may not be appropriate because climate change may have a different trend over a century leading to the new hydrological conditions. In order to address such issues, and also to ensure climate variability for regulatory low flow estimation, optimal lengths of data records are needed to estimate regulatory low flow criteria.

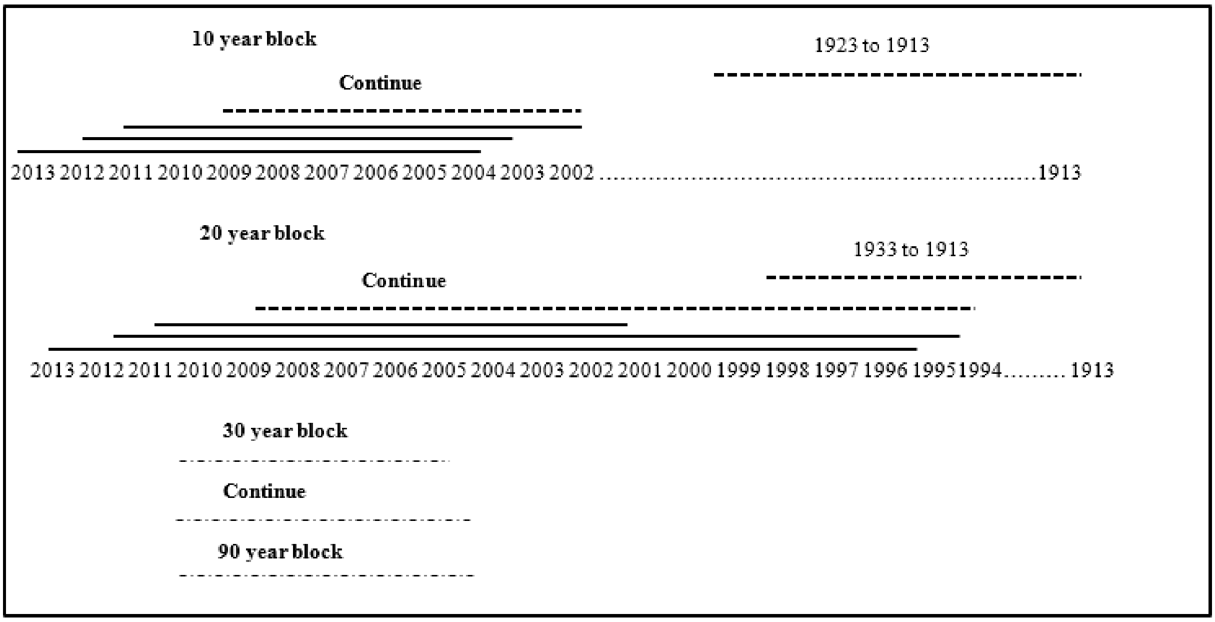
We analysed for the optimal period of data record needed to estimate low flow conditions using two different time frames: i) first, in a 10-year block; ii) and second, with a one-year lag. The second approach was similar to the approach discussed in the Saunders III et al. (2004). The outline of the methodology is briefly sketched in Figure 2. For the analysis using the first approach (Figure 2a), we used data of various lengths of records such as 10 years, 20 years, 30 years, and so on, up to 90 years, starting from 2013 to the retrospective year of 1913. That said, we calculated 7Q10 for each 10-year, 20-year, 30-year, 40-year and up to 90-year block from the current year (2013) at each stations (40 altogether). For example, first 7Q10 was computed using 10 years data, the next value was based on 20 years of data and the 9th value was computed using 90 years of data. This approach was essential in revealing the climate variability that was experienced over the historical period. The computation of low flows was accomplished in two ways using: (i) separate summer and winter regulatory low flow criteria; (ii) single regulatory low flow criteria for an entire year. Many states have adopted summer and winter regulatory low flow criteria to develop NPDES permitting for various pollutants.

For the second approach, we created a data block that was lagged by a year (Figure 2b). For example, 90 blocks of 10 years data was created using data from 2013 to 1913, with each block lagged by one year. We calculated various 7Q10 using 10-, 20-, and 30year data blocks and repeated this up to 100 years of data. Ninety different values of 7Q10 were computed using 10-year data in a single station that used a 10-year block. Each block was lagged by a year for the 100-year period of record. Likewise, 80 different values of 7Q10 were computed for the same station using 20 years of data. In this way, 3600 different values of 7Q10 were computed using different lengths of data records for 40 stations just by using the 10 years of data record. Similarly, 2880 and 2520 numbers of 7Q10 were computed using 20 years and 30 years of data block, respectively. This entire process is repeated for 1Q10, 4B3 and 1B3. We normalized the regulatory low flow criteria (7Q10, 1Q10, 4B3, 1B3 flow divided by respective basin area) computed from the second approach to detect the sufficient period of data needed for low flow computation. The normalization of data made it easy to analyse the data from various sizes of basins in a common platform to identify the minimum period of data records needed to incorporate sufficient climate variability

Analysing the low flow criteria was useful in determining the period of data records needed to sufficiently capture the extreme low flow conditions in this particular climate region. Also, it was useful to determine the farthest period of record in the historical period that should be incorporated for hydrologic and biologic low flow estimations.



(a) First approach



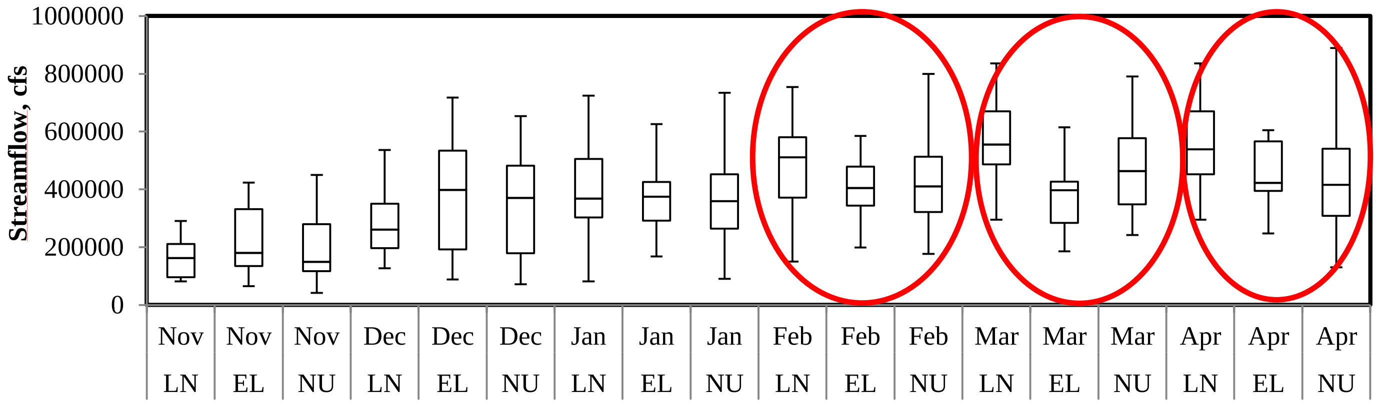
(b) Second approach

Figure 2. Methodology for two approaches showing the different period of data period used for 7Q10 computation

VII. RESULT AND DISCUSSION

A. Climate Variability

We analysed the streamflow during the growing and non-growing seasons at different months, over various phases of ENSO to detect if the basin experienced any teleconnection of streamflow with ENSO phases. The streamflow analysis was important to detect an ENSO signature with stream low flows so that hyrdological or biological low flow conditions could be correlated with these predictable climate forcing functions. Results of the analysis indicated that ENSO had better signature with streamflow, especially in February, March and April of the non-growing season, and also in September and October of the growing season (Figure 3). However, ENSO did not depict any significant impact on streamflow variation, except for a few months (Figure 3). This led a conclusion that a basin might encounter precipitation and streamflow variation only in some months due to a number of oceanic and atmospheric phenomenon including NAO and PDO, but not for the entire season.



(a)

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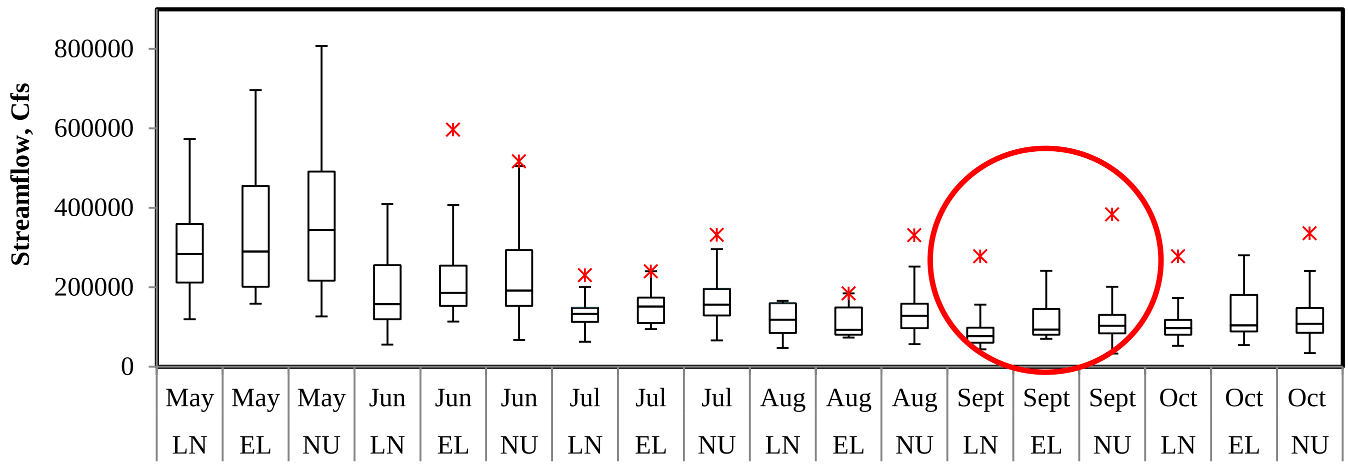
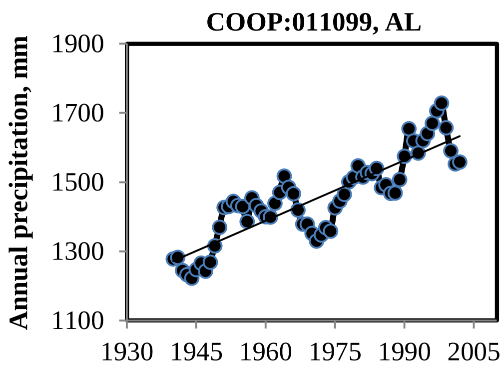


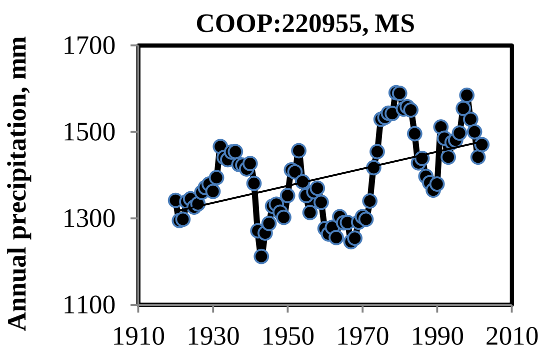
(b)

Figure 3 Streamflow (USGS 3611500) with ENSO phases during a) non-growing season, and b) growing season. LN, EL and NU refer for La Niña, El Niño, and Neutral, respectively

B. Climate Change

Ten years of running averages of precipitation levels were plotted for 14 pre-selected stations from each state (Figure 4a and Figure 4b). The stations in each state were selected based on two criteria: i) first, the station should be within the watershed boundary; ii) and second, the station should furnish a continuous length of data records for long periods. Overall, there were no substantial differences in plotting from one state to another except for Ohio, Pennsylvania and Kentucky (Figure 4b). Station selected in Kentucky did not show a clear trend of increasing annual precipitation over the last century when using Mann-Kendall test (p-value=0.87). All other stations showed significant increasing trend with p-value<0.05 (Table 1). On the other hand, some of the stations (e.g., West Virginia, Tennessee, Virginia, Mississippi and Alabama) showed sharp increase in a precipitation trend (p-value < 0.002). The rest of the states showed moderate increase in annual precipitation. In order to further confirm the climate change pattern, we plotted the long-term records of streamflow at the outlet of the Ohio River Basin (USGS gage 3611500) in Illinois (Figure 5). The increasing pattern of streamflow records was consistent with the increasing precipitation records of the region (Figure 4). In fact, all of the aforementioned states eventually contributed to the streamflow in the Ohio River Basin. We further analyzed the annual flow using Mann-Kendall test and the distinct pattern of increasing trend (p-value <0.05) in annual flow was detected for two USGS stations (Table 2). Next, we evaluated consecutive seven-day low flows (minimum) of each year from 1929 to 2013. Interestingly, we detected different patterns in minimum seven-day low flows before and after 1975 (Figure 6). While our analysis indicated an increased rate of annual streamflow, minimum consecutive seven-day low flows were found increasing until 1975, and decreasing after this period. The same trend was detected for two USGS stations while using Mann-Kendell test (Table 2). The increasing trend was not realized in USGS 1570500 while decreasing trend after 1974 was distinct (p-value <0.1) We should mention that seven-day low flows varied from 1975 for all three major River Basins of this region. Since the low flow pattern before and after 1975 were distinctly different (Figure 6), we analyzed the regulatory low flow estimations for various lengths of data record in order to further confirm whether historical data beyond 1975 are needed for the 7Q10 computation.





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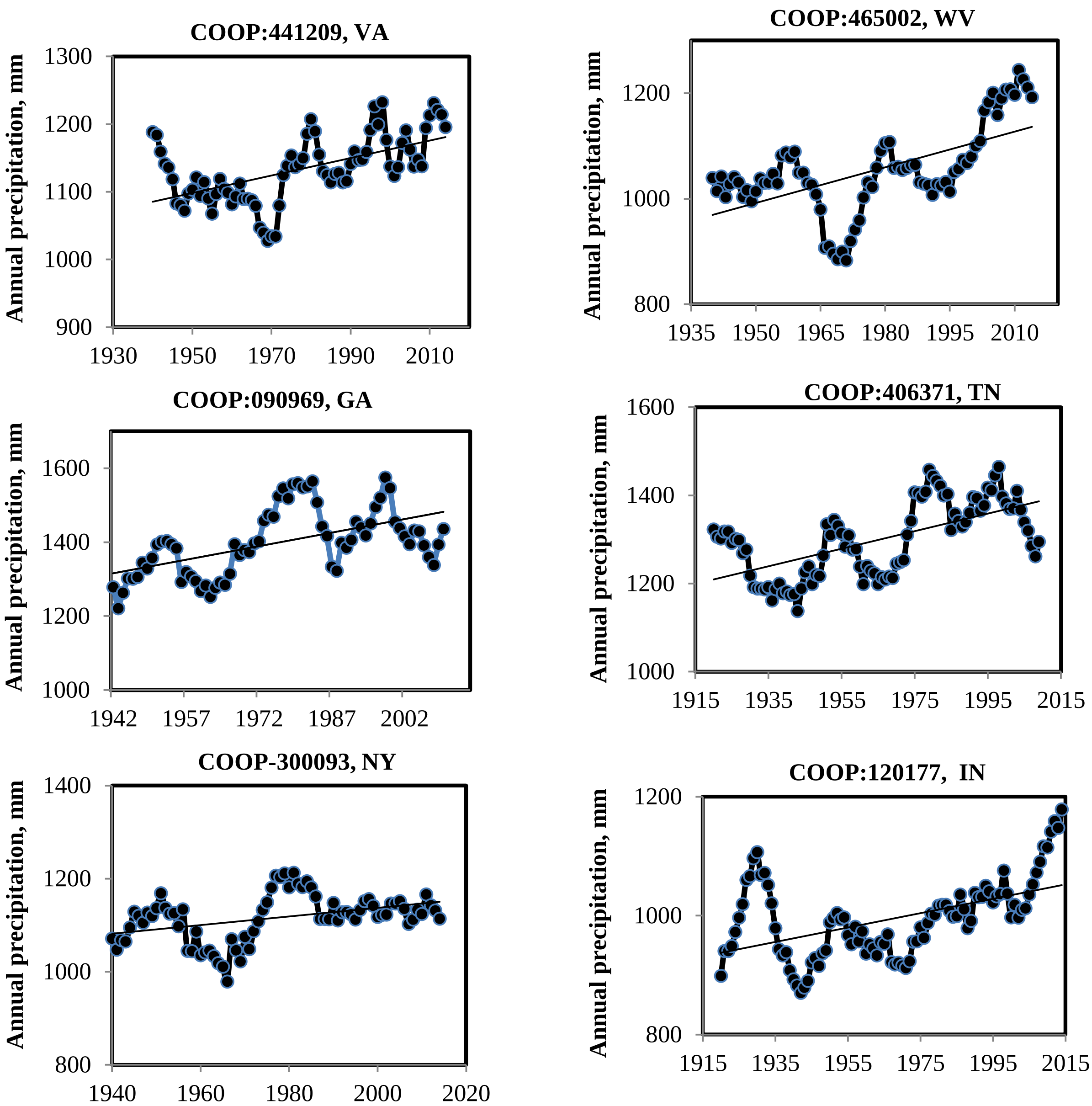
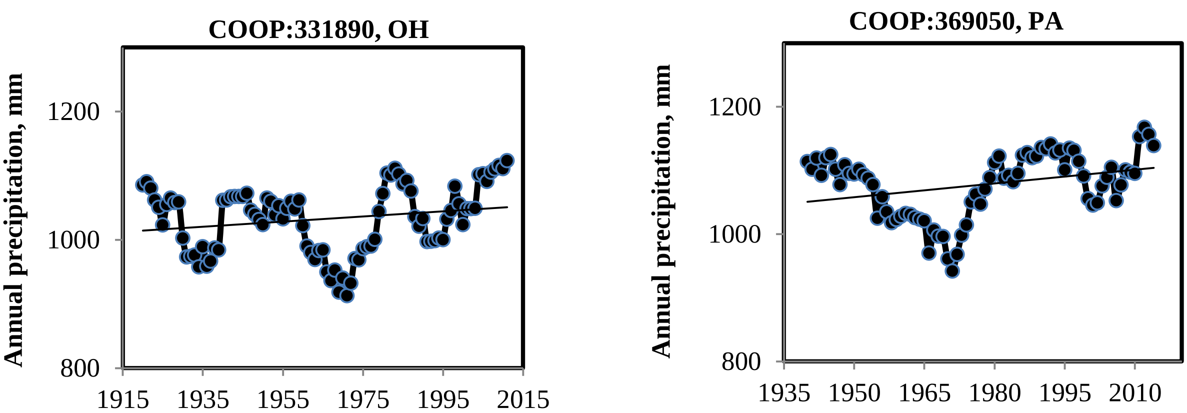


Figure 4a.10 year average annual precipitation at selected climate stations of Alabama (AL), Mississippi (MS), Virginia (VA), West Virginia (WV), Georgia (GA), Tennessee (TN), New York (NY) and Indiana (IN)



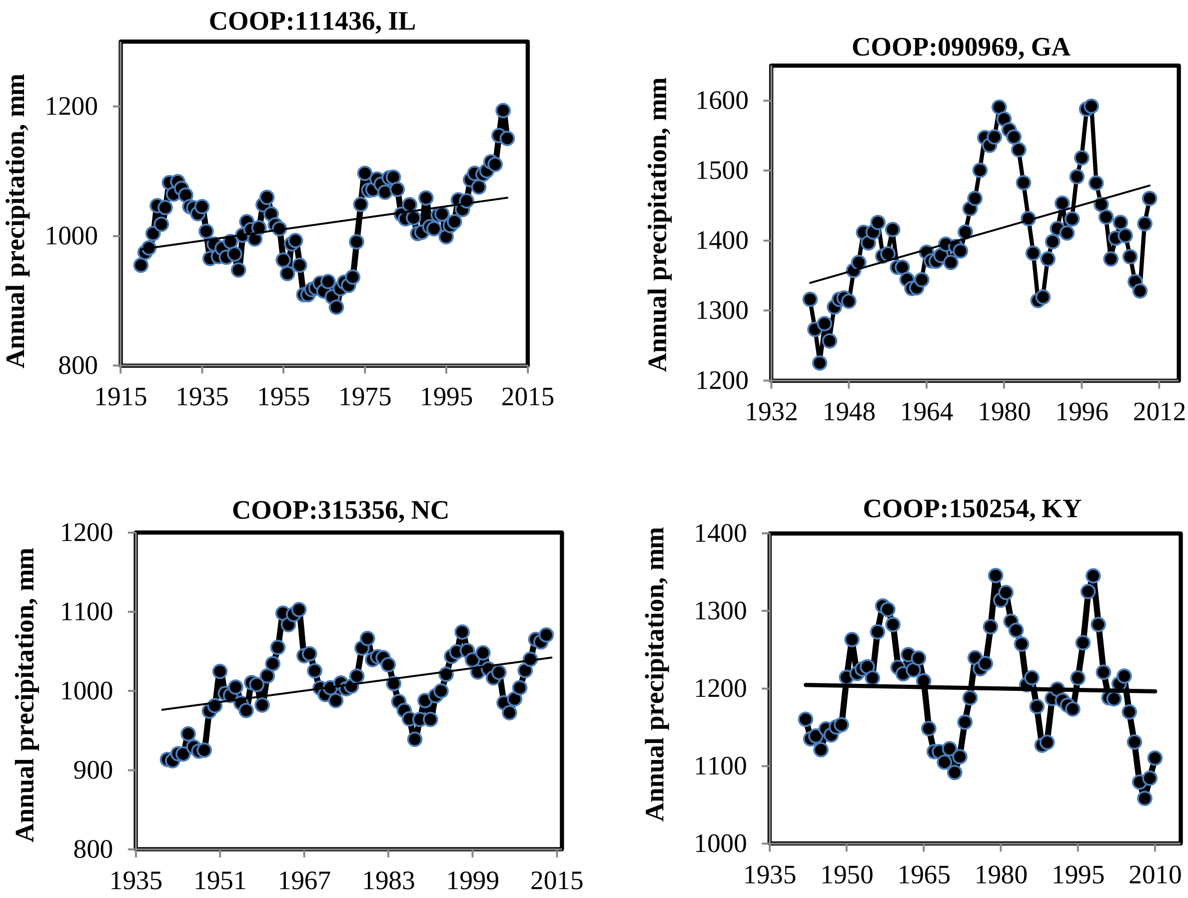


Figure 4b.10 year average annual precipitation at selected climate stations of Ohio (OH), Pennsylvania (PA), Illinois (IL), Georgia (GA), North Carolina (NC) and Kentucky (KY).

TABLE I MAN-KENDALL TEST TO DETECT THE TREND OF ANNUAL PRECIPITATION OF 14 STATES WITHIN OHIO RIVER BASIN

Trend Detection for Annual Precipitation of 14 States within Ohio River Basin							
Stations	Mean, mm	Mean Absolute Deviation (MAD), mm	Standard Deviation (SD), mm	Mann-Kendall S value	Mann-Kendall Z value	Mann-Kendall P value	Trend
COOP:011099, Alabama (AL)	1450	71	117	1212	5.8	0.000	Increasing
COOP:220955, Mississippi (MS)	1405	75	95	1411	4.8	0.000	Increasing
COOP:441209, Virginia (VA)	1133	37	49	1113	5.1	0.000	Increasing
COOP:465002, West Virginia (WV)	1042	22	44	467	3.0	0.002	Increasing
COOP:090969, Georgia (GA)	1409	52	84	941	4.7	0.000	Increasing
COOP:406371, Tennessee (TN)	1298	76	84	1599	5.6	0.000	Increasing
COOP-300093, New York (NY)	1120	24	46	584	2.8	0.005	Increasing
COOP:369050, Pennsylvania (PA)	1079	33	48	521	2.4	0.015	Increasing
COOP:331890, Ohio (OH)	1032	42	51	572	1.9	0.050	Increasing
COOP:120177, Indiana (IN)	993	44	64	1693	5.5	0.000	Increasing
COOP:111436, Illinois (IL)	1017	44	60	893	3.0	0.002	Increasing
COOP:315356, North Carolina (NC)	1009	30	45	738	3.5	0.000	Increasing
COOP:150254, Kentucky (KY)	1201	51	68	-33	-0.2	0.870	Neutral

When 7Q10 was computed using more than 50 or 60 years of data from 2010 in a retrospective period (historical period), 7Q10 was almost constant (Figure 7). This result is not surprising, but rather consistent with our earlier plotting (Figure 6) because the earlier plotting of minimum seven-day low flows showed the increasing trend up to 1975 from the beginning, and then a decreasing trend (Figure 6). In fact, this is also manifested in Figure 7. The 7Q10 in Figure 7 is based on computed 7Q10 beginning from 2010 back to the 100 years of the retrospective period (e.g 1910). This analysis indicated that retrospective data beyond 50 or 60 years were not needed for 7Q10 computation because of the fact that low flow had a different trend on low flows from 1975. This analysis was conducted for only hydrological conditions including separate summer and winter low flows (Figure 7) over the selected stations. Various states in the USA adopt summer and winter 7Q10, separately. Since some pollutants (e.g. ammonia) are released based on the different threshold of regulatory criteria for summer and winter, we first divided the low flows for summer and winter. Then, 7Q10 and 1Q10 were analyzed separately for summer, winter. Mean and median 7Q10/1Q10 for the entire year has been plotted in Figure 7a, whereas the mean and median 7Q10/1Q10 analyzed for summer and winter has been plotted in Figure 7b and Figure 8, respectively.

Overall, mean or median 7Q10/1Q10 was in a slightly increasing trend up to the historical 40 or 50 years and somewhat decreasing or constant trend beyond 50 years. This indicates that historical data beyond 50 years are not necessarily useful for 7Q10 or 1Q10 computation as the trend is almost constant. By analysing the data with a 10-year block without overlapping the data period enabled us to further confirm the different trend of a low flow pattern, which was experienced on low flows estimation.

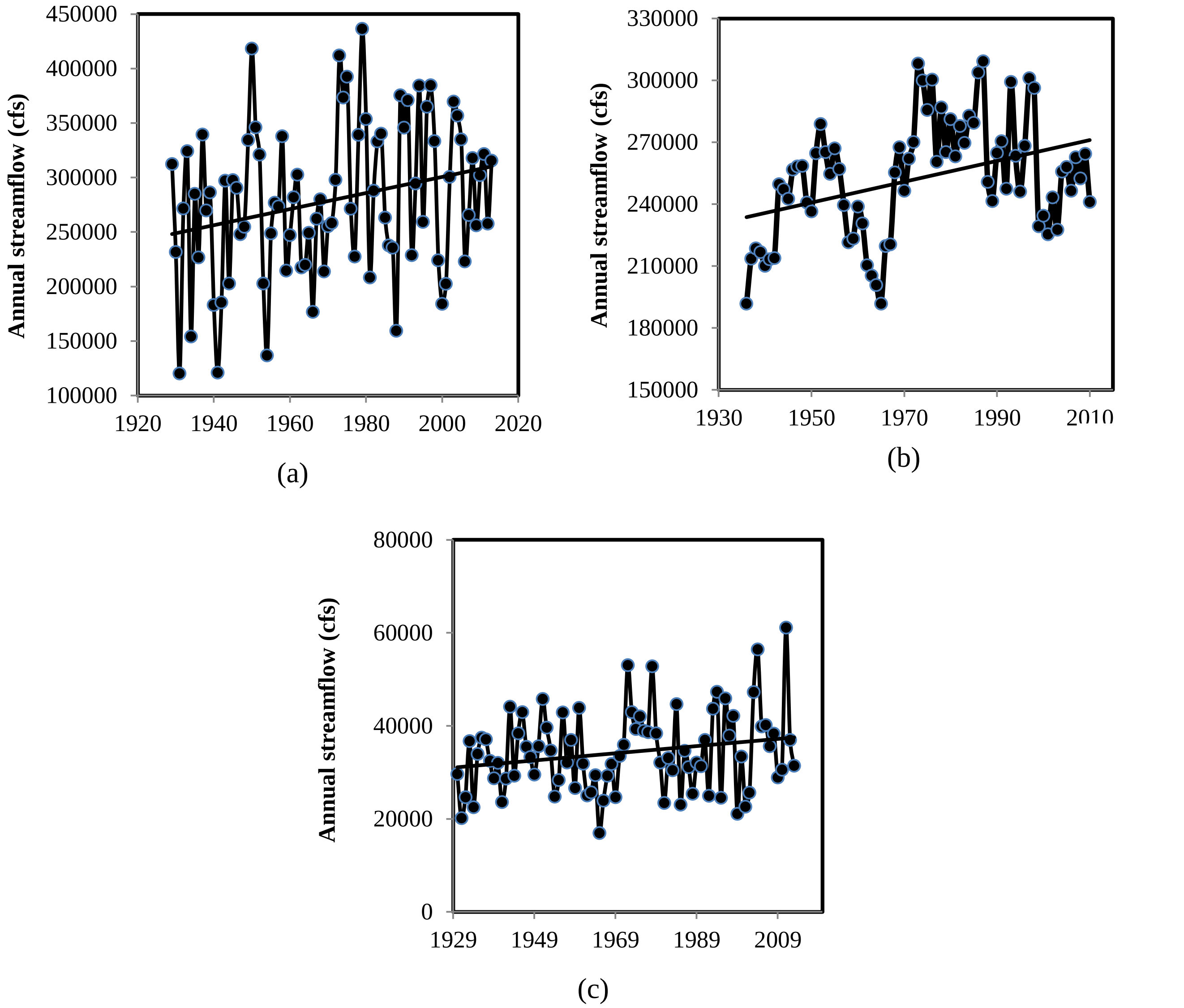


Figure 5. Increased trend of annual streamflow in major river basins of study area; a) USGS 3611500, b) USGS 4264331, c) USGS 1570500

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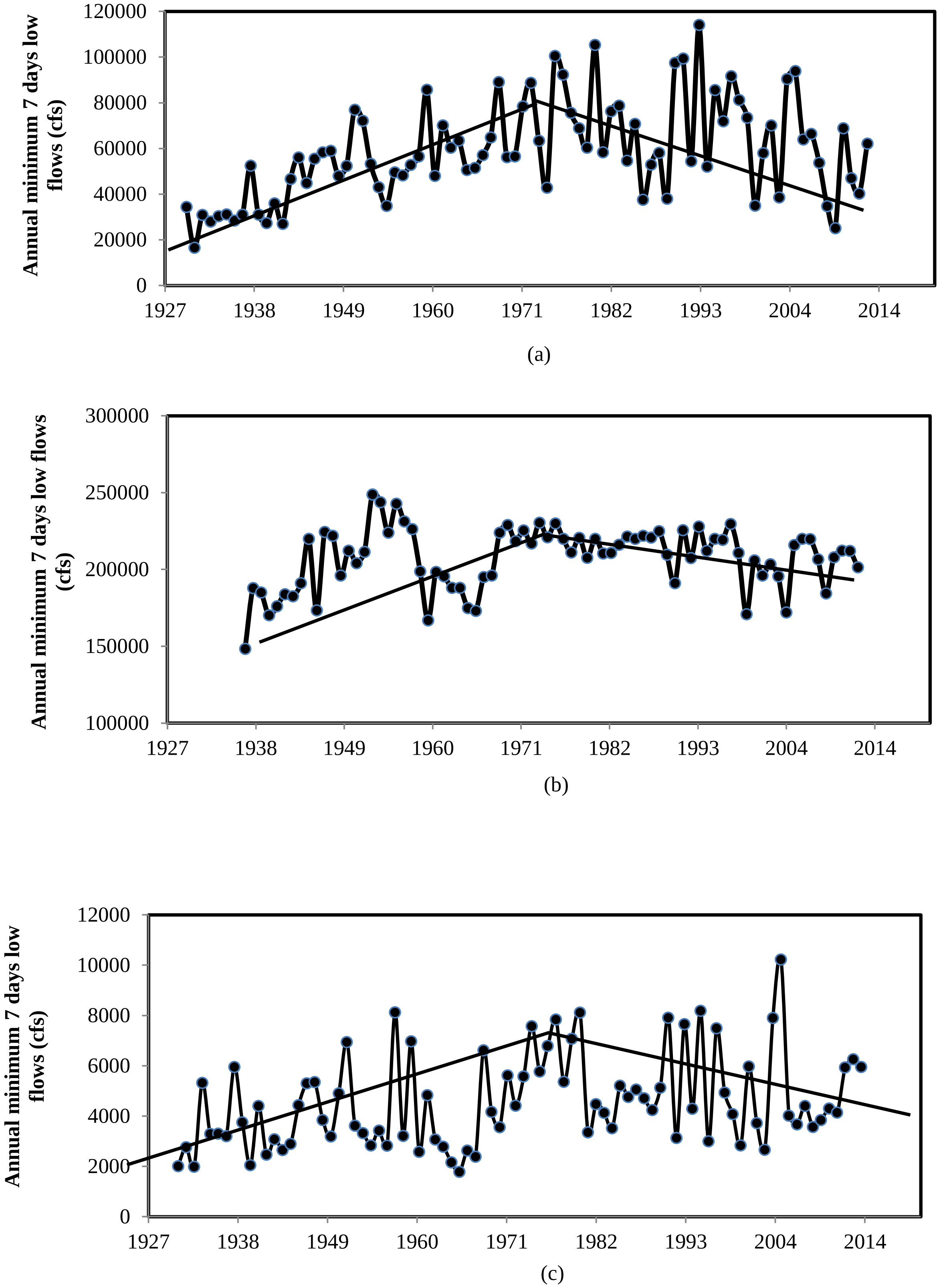

Figure 6. Consecutive average 7 days lows flows at: a) USGS 3611500, b) USGS 4264331 and c) USGS 1570500

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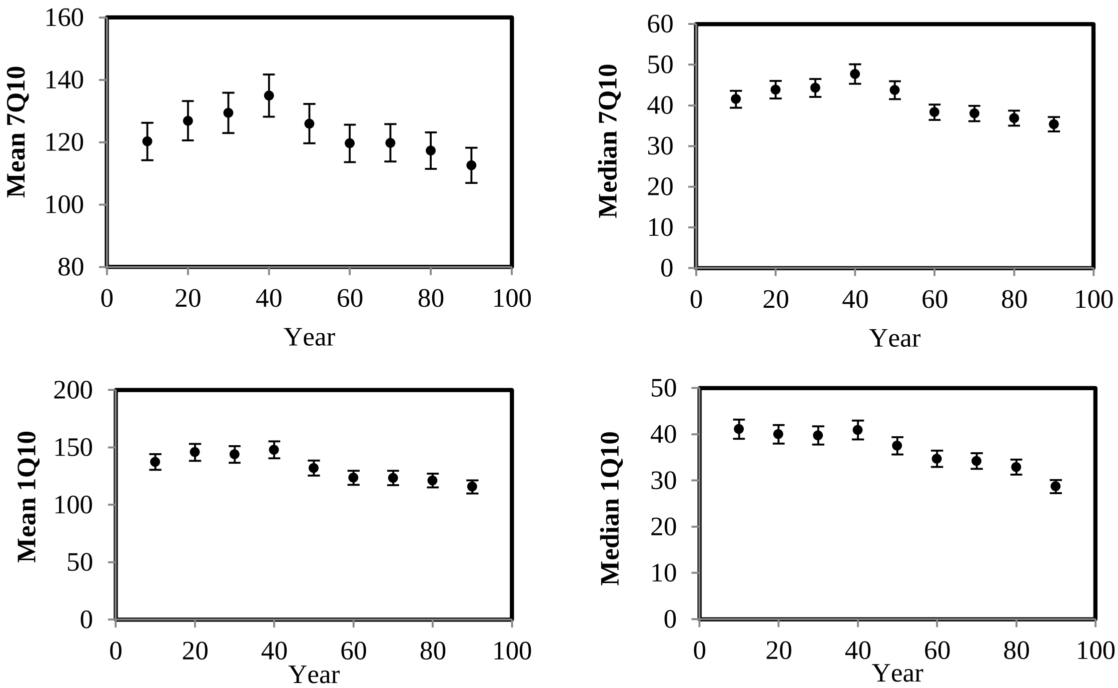
TABLE II MAN-KENDALL TEST TO DETECT THE TREND OF ANNUAL STREAMFLOW IN THE SELECTED USGS STATIONS OF THE OHIO RIVER BASIN, MID-ATLANTIC REGION AND THE GREAT LAKE REGION

Stations	Mean flow, cfs	Mean Absolute Deviation (MAD), cfs	Standard Deviation (SD), cfs	Mann-Kendall S value	Mann-Kendall Z value	Mann-Kendall P value	Trend
Trend Detection for Annual flow and Seven Days Low Flows							
USGS-3611500	279121	50400	69245	574	2.2	0.03	Increasing
USGS 4264331	254045	15000	26963	578	2.7	0.006	Increasing
USGS 1570500	33677	5310	7707	279	1	0.27	Neutral
Trend Detection for Seven Days Low Flows							
USGS-3611500 (Up to 1974)	50737	10229	17613	529	5.3	0	Increasing
USGS-3611500 (After 1974)	67239	14343	21826	-199	-2.1	0.004	Decreasing
USGS 4264331 (Up to 1975)	204361	20000	24300	213	2.5	0.014	Increasing
USGS 4264331 (After 1975)	213235	7571	10585	-177	-2.3	0.021	Decreasing
USGS 1570500 (Up to 1974)	3601	711	1226	68	0.8	0.45	Neutral
USGS 1570500 (After 1974)	5197	1176	1664	-148	-1.7	0.09	Decreasing



(a) Hydrological conditions in cfs

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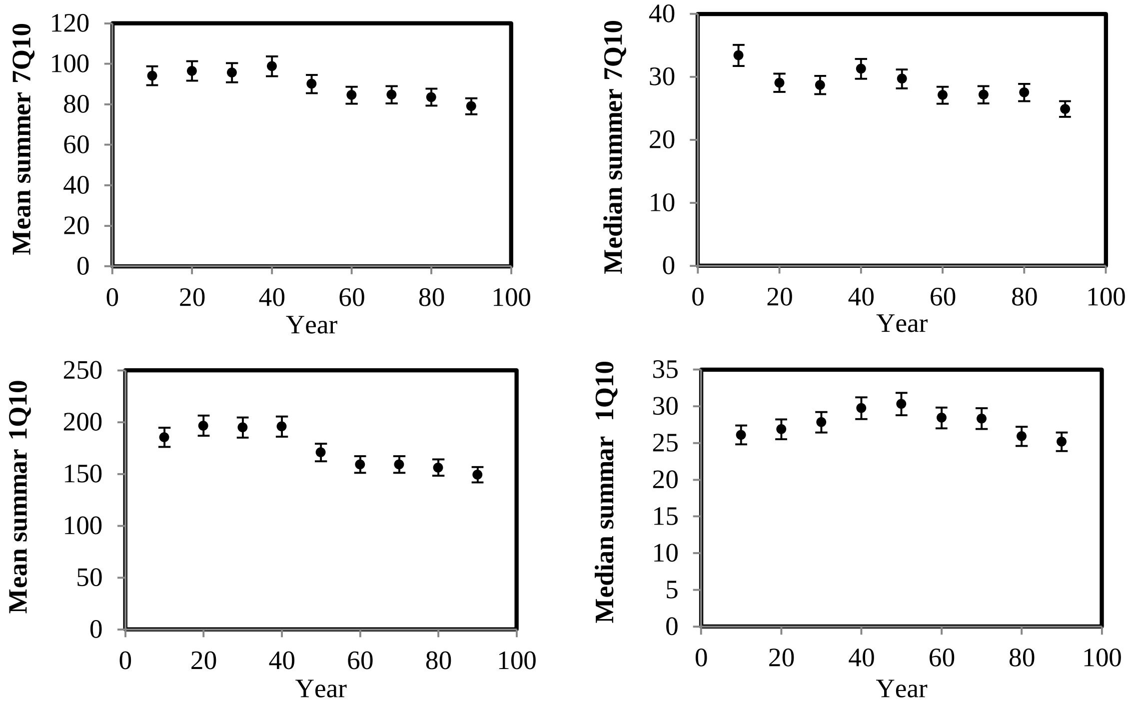


(b) Hydrological conditions in cfs for summer period

Figure 7 Mean and median 7Q10/1Q10 (cfs) for entire year (a), and summer period (b) using first approach

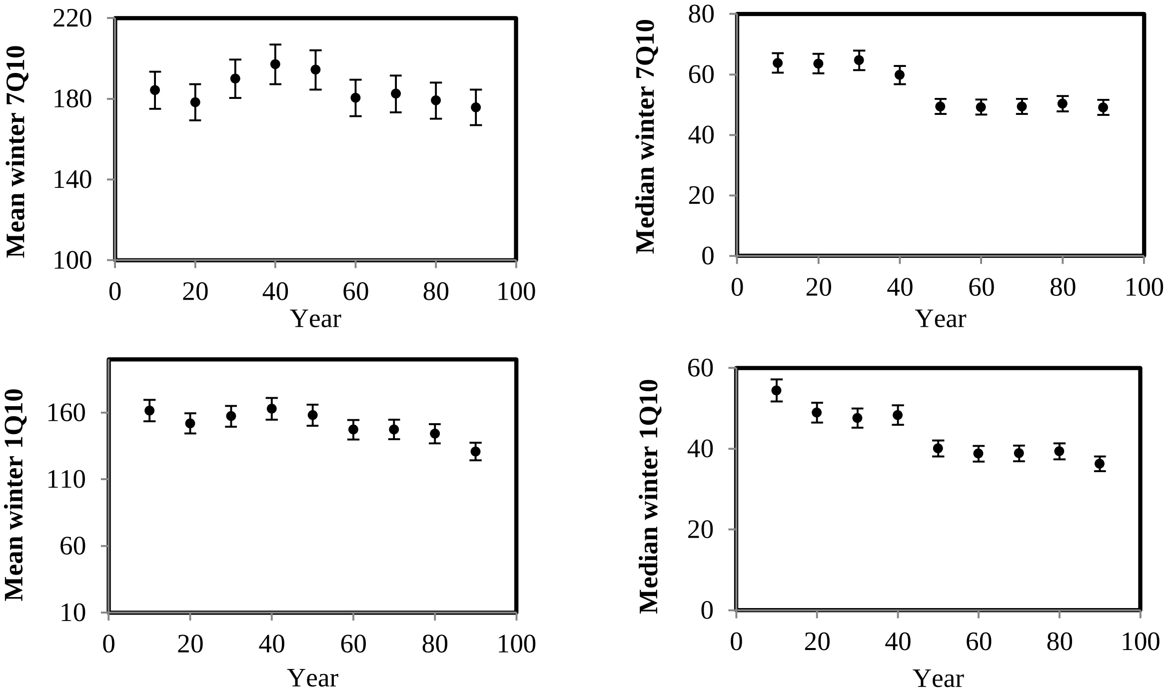


Figure 8 Mean and median 7Q10/1Q10 (cfs) for winter lowflows computed using first approach

One major research question is how many years of data are sufficient to capture the lowest flows. To answer this question, we analyzed the regulatory low flow estimations at different bands of 10 years to 100 years at one-year lagged interval (second approach). This analysis provided some evidence of the flow pattern. Figure 7 shows the 7Q10 computed using 10 years to 90 years of data. However, as mentioned earlier, 10-year to 90-year periods of data were constructed with one-year lag time resulting in ninety 7Q10 at a single station. It is worthwhile to note that 10 years of data shows significant variability in 7Q10 estimation. For example, the estimated 7Q10 could remain anywhere from 275 cfs to 475 cfs if 10 years of data were used depending upon the period of record (left panel of Figure 9a). However, estimated 7Q10 remained within the range of 360 cfs to 350 cfs while using 90 years of data. This indicates that less uncertainty and variation exists when longer periods of record are used in 7Q10 computations. Even though the left panel of Figure 9a was based on the analysis at selected station (USGS 2387500), identical results were obtained in several other stations. Figure 9a (right panel) indicates the percentile 7Q10 generated using entire data sets for all stations; each circle represents the percentile varying from 10 (bottom circle) to 100 (top most circle). The figure indicates that data records of more than 60 years do not show much variability. A similar trend was obtained while analyzing 1Q10 for a selected station (left panel of Figure 9b) and using the entire data sets (right panel of Figure 9b).Figure 10 indicates the normalized regulatory low flows estimated for various lengths of data records from 10 to 90 years.

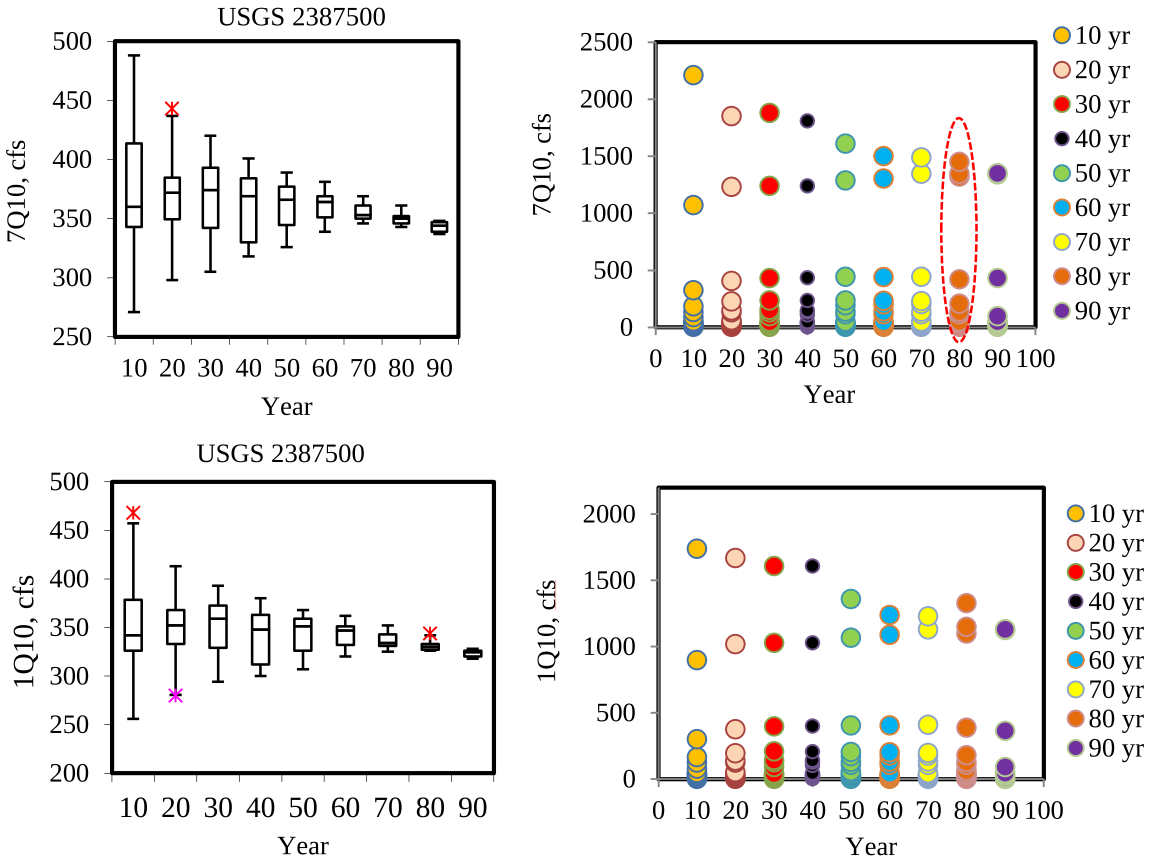
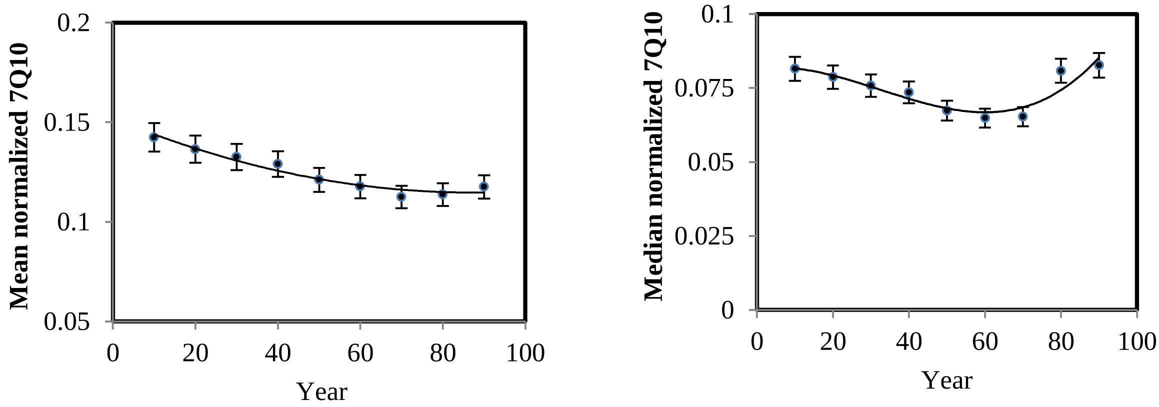


Figure 9. Top left panel shows the 7Q10 computed at selected station (USGS 2387500), and top right panel shows the 7Q10 computed at various percentiles from bottom (10 percentile) to top (100 percentile) for entire datasets (a); bottom left panel shows the 1Q10 at selected station (USGS 2387500), and bottom right panel shows the 1Q10 computed at various percentiles (10 to 100 percentile) from bottom to top for entire datasets (b)



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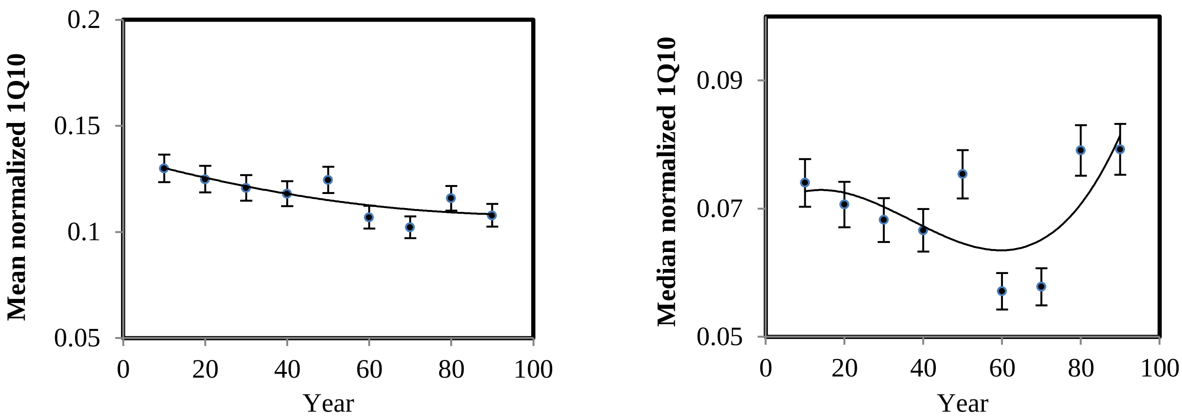

Figure 10. Top panel shows mean and median 7Q10 (normalized with area) and bottom panel shows mean and median 1Q10 (normalized with area).

The low flows after normalization (7Q10/Area) from various stations were plotted throughout the study area (Figure10). The top panel of Figure 10 shows the mean and median normalized 7Q10, while the bottom panel shows the mean and median normalized 1Q10. We found decreasing trends up to 60 years, especially for the median values. Similarly, normalized 1Q10 was also found to be decreasing when an increased period of data records was used in the computations. Furthermore, the median (50th percentile) data showed that, normalized 7Q10 and 1Q10 decreased up to 60 years and then started increasing. Please note that slightly different pattern and outcome was obtained from this approach; this was expected because both approaches used different methodology. It is worth noting that incorporating the data records of beyond 60 years may not lead to the estimation of lowest flows; rather, flows computed using data more than 60 years may overestimate 7Q10. This suggests that merely increasing the number of years does not necessarily capture the lowest flow for NPDES permitting to protect water quality. We found a consistently decreasing pattern and sharp decrease in 7Q10, while we plotted the maximum 7Q10 corresponding to the respective period of data records from 10 to 90 years (not shown). Essentially, the 100th percentile data represented the maximum possible 7Q10/1Q10 that corresponded to each period of records. A Few inferences can be drawn from this analysis: 7Q10 computed from 10 years of records can result in possibly higher low flow estimations; however, long term records may not necessarily result in the lowest flow as indicated by the 50th-percentile data sets. Also, normalized 7Q10 for higher (100th percentile) flow tends to decrease sharply with the increased number of years (not shown).

Interestingly, normalized 7Q10 showed a decreasing pattern up to a 50- or 60-year back to the historical period (literally, it includes the past 50 to 60 years of data from 2013). The mean and median Normalized 1Q10 from all aforementioned (40) stations that were computed using various periods of data records were plotted as shown in Figure 10. This is consistent with our analysis that a minimum of seven-day low flows start decreasing after 1975 (Figure 6). The normalized 7Q10 computed from the second approach was first in a decreasing trend and then in an increasing trend. This is mainly because we computed 7Q10 using data of historical periods in a backward direction (Figure 2) even for the second approach. However, while computing low flows and seven day low flows, we used the data from the beginning of 19th century. Also, the trend is different than that of the first approach because the second approach used data records at a one year lagged interval.

Similarly, we analyzed for normalized 4B3 and normalized 1B3 (Figure 11). Even though 4B3 and 1B3 does not need a longer period of data records as needed for 7Q10, we utilized the same period of data sets and computed all regulatory low flow criteria at a single stretch in order to save the computational time. The 4B3 was also found to be in a decreasing trend; however, this was not the case for 1B3 as it decreased for the first 40 years and inclined to increase after 40 years. For the median, a sharp decreasing trend was observed up to 60 years for both 4B3 and 1B3; the decreasing trend was especially prominent for 1B3. Beyond the 60-year periods of data, we found an increased trend.

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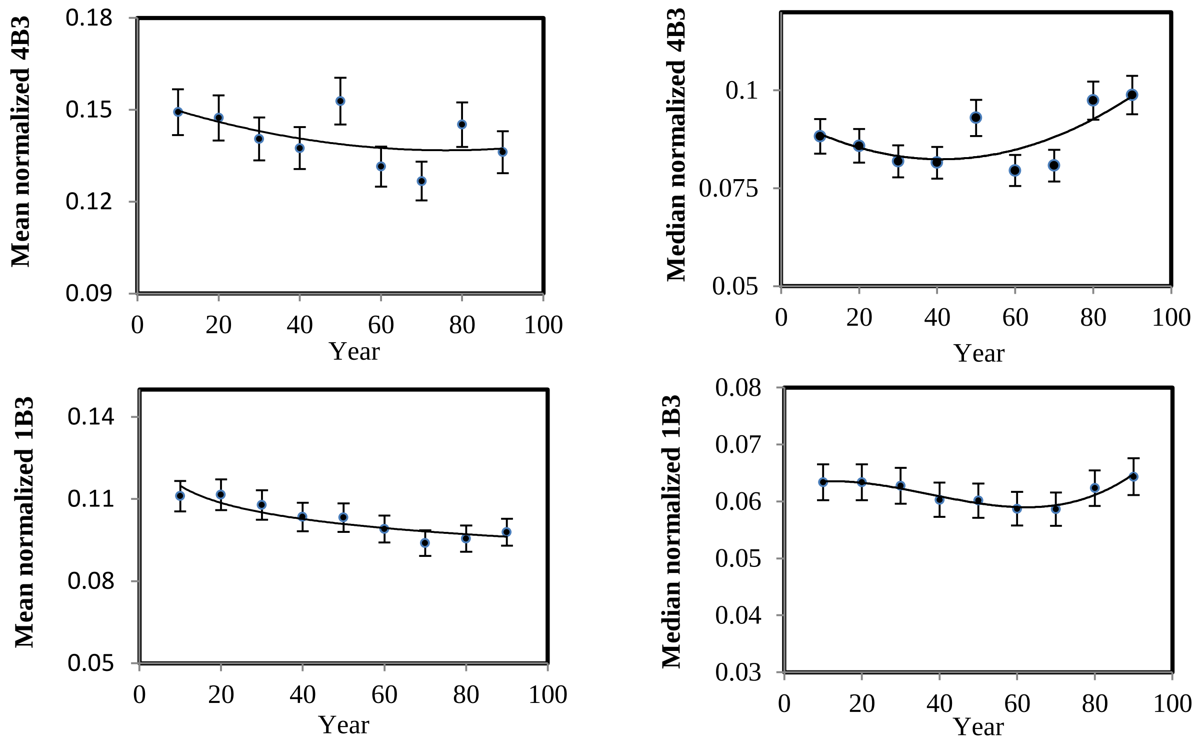

Figure 11 Top panel shows mean and median 4B3 (normalized with area), and bottom panel shows mean and median 1B3 (normalized with area).

Even though a decreasing trend of regulatory low flow was detected with the use of an increased period of records, it is worth mentioning that utilizing data of many years in the computations may not necessarily capture the lowest flow as suggested by the 50th-percentile (median) graph (Figure 10 and Figure 11). However, in all cases, we found that the regulatory low flow estimation was in a decreasing pattern for a data length considered up to 60 years of the historical period.

VIII. SUMMARY AND CONCLUSION

We investigated the general trend of precipitation pattern over the selected stations of 14 states within the Ohio River Basin. In most of the stations, an increasing trend of precipitation was observed. Also, the annual streamflow was analyzed at the outlet of the Ohio River Basin and selected Basins of two other regions: the Great Lakes Region; and the Mid-Atlantic Region. The average annual streamflow shows the increased trend of streamflow over the basins while seven-day low flows for each year does not reveal a continuous increasing trend, rather a decreasing trend after 1975. After investigating the climate change and climate variability of the basins, the regulatory low flow criteria was analyzed in two different ways: i) first analysis was conducted to compute 7Q10 using 10-year to 90-year blocks; ii) second analysis was conducted using 10 to 90 years of data at one-year lagged intervals. Analyses using the first approach indicated a distinct pattern of low flows before and after 1975.The analyses also indicated that data beyond 50 years in the historical period may not be needed for regulatory low flow estimation. Analyses using the second approach indicated that more than 60-year periods of data records may not be needed to capture the lowest flows for regulatory low flow estimation. A similar trend was detected while replicating the same experiment with 1Q10, 4B3 and 1B3, which indicates that incorporating long term data sets are not necessarily beneficial for regulatory low flow estimation because of the different low flow patterns since the late 19th century. This analysis is useful in order to estimate appropriate future regulatory low flow criteria, as the regulatory low flow criteria based on historical data sets may not truly represent the same in the future. Overall, the findings of the analysis can be summarized as follows:

- Precipitation and streamflow were found to consistently increase, however low flows were found to decrease somewhere after 1975.
- Consideration of shorter periods of data will increase the degree of uncertainty.
- Long-term data is needed for regulatory low flow estimation even though 7Q10 can be estimated using 10 years of data.
- Longer periods of record will decrease the variability and uncertainty but may not necessarily capture the lowest flows.
- Data of 60 years in any historical period is sufficient to capture the lowest flows for stream water quality protection as more than 60 years periods of record either tends to increase or remains constant.

Global climate change and climate variability over the last several decades indicate the increasing trend of temperature variability and changes in precipitation patterns. These global changes may affect the large scale hydrological cycle (Risleyet al., 2011). As such, the conventional point source discharge permitting based on the historical climate data may not be sufficient to protect fish and aquatic life in the future. Increased temperatures due to climate change may decrease the assimilation capacity of the stream. In such cases, fish and aquatic life may experience additional stresses due to confounding variables that include: i) decreases in the assimilative capacity of the stream and a decrease in the dissolved oxygen (DO) level due to the increased water temperature; ii) decreases in the stream low flows leading to the decrease in reaeration and dissolved oxygen; iii) increases in stream temperature and pH.

Since certain types of fish and aquatic life are sensitive to the increased temperatures and pH, point source permitting criteria, which are mostly based on hydrological and biological low flow conditions, should be re-examined for future use. Also, it is essential to adequately address the climate variability of the region, while estimating regulatory low flow criteria, to ensure sufficient assimilation of the pollutants because the estimation of low flows has potential implications in the assimilation capacity of the stream that is required to dilute pollutants, and also for the treatment needed in waste water treatment plants.

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