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Frequency and intensity of extreme drought in the Delaware Basin, 1600–2002

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[1] The frequency and severity of drought in the Delaware Basin between 1600 and 2002 are examined using the Palmer Drought Severity Index (PDSI) estimated from tree ring data and correlated with reconstructed annual low flows. In the Delaware Basin, the most severe drought in nearly a century occurred during 1995–2002 as the Brandywine River, Delaware's largest surface water supply, ran dry at its mouth and declined to the lowest flow on record since 1912. To evaluate the long-term context of the 1995–2002 droughts given a variable hydroclimate, tree ring and PDSI data were correlated to reconstruct flows along the river to 1600, the beginning of European exploration to the Delaware Bay. Reconstructed PDSI and low flows were fit using general extreme value (GEV) distributions to estimate drought frequency. Some variability is present as reconstructed low flows tend to overestimate recorded streamflow in severe dry years, a finding reported by others. Some uncertainty appears in the correlations as the coefficient of multiple determination (CRSQ) between recorded and estimated PDSI from tree ring data is 0.50–0.54, a level of variance considered to be "quite good," and the coefficient of determination (r^2) between PDSI and low flow is 0.52. Given the uncertainty, PDSI and reconstructed low flow data both agree that the most extreme drought in 400 years occurred during 1635, and the drought of 1995–2000 was historically extreme with differences only in the degree of severity. On the basis of PDSI, the 2002, 1999, and 1995 droughts were the sixth, twelfth, and seventeenth most severe in 400 years with frequencies of once every 50, 33, and 16 years, respectively. Based on low flow, the 2002, 1999, and 1995 droughts were the second, fourth, and ninth most severe since 1600 with frequencies of once every 200, 100, and 50 years, respectively. The record drought of 2002 has a low probability of reoccurring in any given year (2.0% by PDSI and 0.5% by low flow), but droughts nearly as severe have occurred during the 1630s, 1680s, 1820s, 1840s, 1860s, 1930s, 1940s, and 1960s. Increased intensities of drought low flows in Delaware during the late twentieth century through 2002 were coincident with population growth, watershed urbanization, and atmospheric warming although these associations were not correlated and further study is needed. Over 400 years of tree ring, PDSI, and reconstructed streamflow data indicate that the Delaware Basin record drought of 1995–2002 was a historically severe event with important implications for water supply and drought management. Droughts more severe than the record 2002 event have occurred in the past, and droughts may become even more intense should watershed urbanization and atmospheric warming continue in the future.

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1. Introduction

[2] In the Delaware Basin, the most severe drought of record in nearly a century occurred during 1995–2002 on the basis of precipitation measurements dating to 1895 and stream gage data dating to 1912 [*Donnelly et al.*, 2003]. The Delaware Water Supply Coordinating Council (WSCC) reevaluated the historic severity of the 2002 drought since water supply design criteria are based on safe yield for the drought of record. Since precipitation and streamflow records cover only the last 100 years, the objectives of this research were (1) to utilize tree ring width and Palmer Drought Severity Index (PDSI) data to extend the instrumental record and (2) to evaluate the severity of the 1995–2002 drought over a long-term historic context dating to 1600, the beginning of European settlement to the Delaware Bay.

[3] Within the Delaware Basin, the Christina Basin provides drinking water to over 500,000 people in Delaware or 60% of the state's population. The Christina Basin is

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midway between Washington, D. C., and New York City along the East Coast of the United States. The city of Wilmington withdraws up to 35 mgd (132 million liters per day, MLD) of drinking water from the Brandywine River, Delaware's largest surface water supply. The city monitors streamflows at U.S. Geological Survey (USGS) gages along the Brandywine River at Wilmington, Delaware, and Chadds Ford, Pennsylvania (Figure 1).

[4] The National Climatic Data Center reported that 33% of the United States was in severe drought by August 2002. Based on precipitation deficits for the continental United States, January to August 2002 ranked as the fifteenth driest period on record dating to 1895, as more severe droughts were recorded during the early 1910s, mid-1920s, 1930s, and 1950s [*National Climatic Data Center*, 2005].

[5] A convergence of hydroclimatic forces caused severe drought during 2002 in Delaware and along the Atlantic seaboard. During late 2001 and most of 2002, the North Atlantic Oscillation was in a negative pattern, a weak

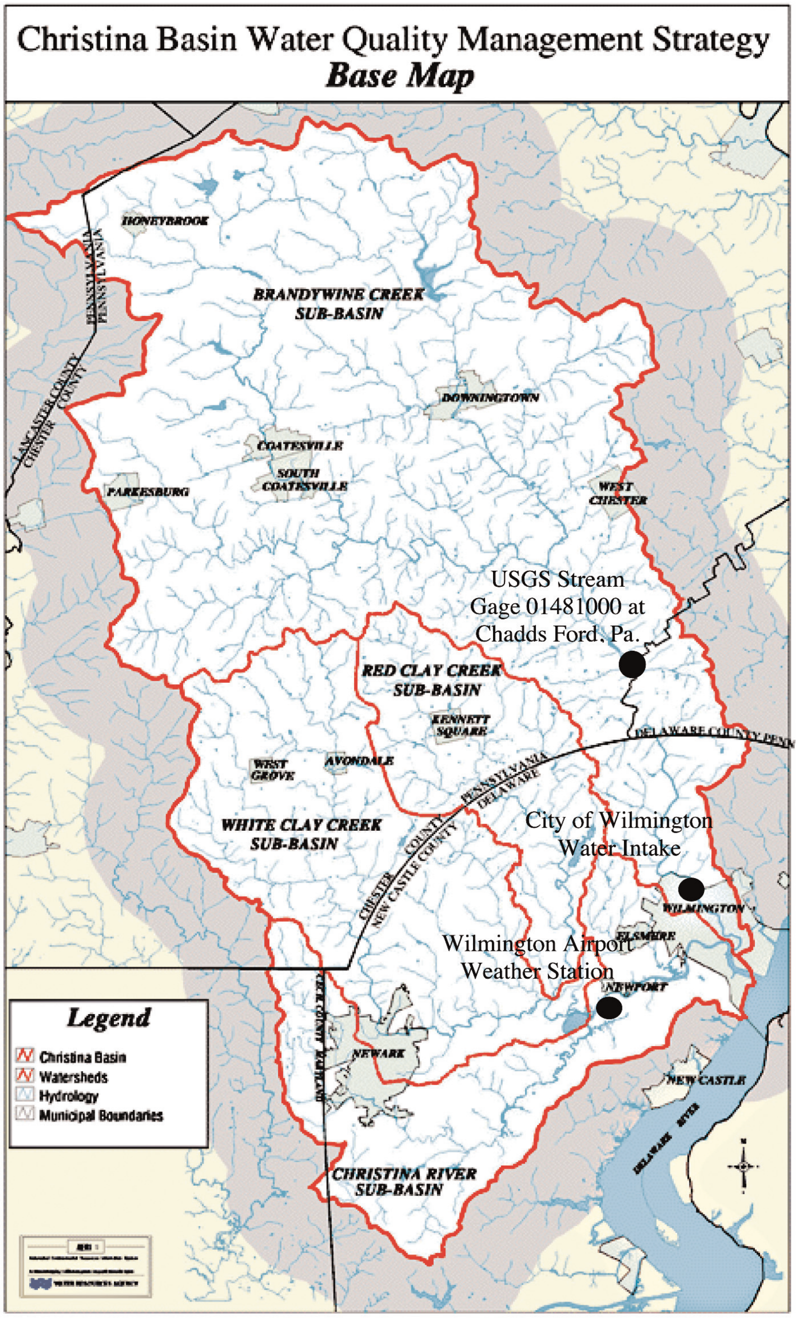


Figure 1. The Christina Basin in Delaware and Pennsylvania depicting U.S. Geological Survey (USGS) stream gage at Chadds Ford, Pennsylvania; Wilmington, Delaware water intake; and Wilmington Airport weather station.

Table 1. Lowest 12-Month Precipitation[a]

Rank	Water (years)	Precipitation (in/mm)	Percent of Normal
1	2002	28.4 (721)	66%
2	1965	28.5 (724)	66%
3	1925	29.3 (744)	68%
4	1999	30.1 (765)	70%
5	1909	31.3 (795)	73%
6	1968	31.6 (803)	73%
7	1995	31.6 (803)	73%
8	1963	32.1 (815)	74%
9	1962	32.9 (836)	76%
10	1966	32.9 (836)	76%

[a]Totals taken at Wilmington Airport, Delaware, 1895–2002 [*USNWS*, 2006].

subtropical high pressure and weak Icelandic low, that usually corresponds to low stream flows and drought in the northeast Atlantic states [*Bradbury et al.*, 2002; *Climate Prediction Center*, 2006]. *McCabe et al.* [2004] found the 1999–2002 droughts in the northern United States were associated with North Atlantic warming (positive Atlantic Multidecadal Oscillation) and tropical Pacific cooling (negative Pacific Decadal Oscillation). During the 2002 drought, Bermuda high pressure shifted over the southeastern United States to the west from its usual position over the Atlantic Ocean and stalled for several months, blocking the normal flow of marine moisture from counterclockwise wind patterns. Since the Bermuda high reaches up to the lower troposphere, the sinking flow of air warmed the atmosphere, inhibiting the formation of thunderstorms. Also in 2002, rare summer high pressure formed over the Gulf of Mexico, reducing moisture to the Mid-Atlantic coast thus prolonging the drought [*Weaver*, 2005]. The dry winter of 2001-2002 was also under the influence of La Nina, cooling of eastern Pacific Ocean temperatures, a condition linked to deficit precipitation in Mid-Atlantic states.

[6] In Delaware, the drought of record based on precipitation occurred during 2002 [*U.S. National Weather Service* (*USNWS*), 2006]. During the 2002 water year from October 2001 to September 2002, Wilmington Airport recorded only 28.4 in. (721 mm) of precipitation, or 66% of normal, the lowest on record dating to 1895 (Table 1). The five most severe droughts in Delaware measured by lowest precipitation at Wilmington Airport occurred in 2002, 1965, 1925, 1999, and 1909.

[7] On 23 August 2002, Brandywine River at Chadds Ford, Pennsylvania (just upstream of Delaware), declined to 21 mgd (79 MLD), the lowest flow since the gage was installed in 1912, eclipsing the record of 27 mgd (102 MLD) set in September 1966. The Brandywine River through Wilmington, near its mouth, ran dry for the first time in memory (Figure 2). Based on stream gage records dating to 1912, the 2002 drought was an event with a 1% chance of reoccurring in any given year or a 100 year drought.

[8] Since 1912, the five lowest flows along the Brandywine occurred during the droughts of 2002, 1966, 1999, 1932, and 1995 (Table 2). From the stream gage record dating to 1912, the mean period between severe droughts was 15 years, and the longest period between extended droughts in Delaware occurred during a 30 year interval from the early 1960s to the mid-1990s (Figure 3).

[9] Since instrumental records date back only 100 years, the WSCC reevaluated the severity of the 2002 drought of record over a long-term historic context to determine if water supply facilities would have sufficient storage to meet a repeat of an unrecorded and more severe drought before the installation of the stream gage in 1912 [*Kauffman and Vonck*, 2004]. How often might a drought of the severity of 2002 be expected to reoccur? We utilized linear regression techniques to correlate tree ring width and Palmer Drought Severity Index data to extend the instrumental streamflow record back to 1600, the beginning of European settlement to the Delaware Bay.

Figure 2. Brandywine Creek at Wilmington illustrating the dry streambed, 23 August 2002.

Table 2. Lowest Daily Mean Flows[a]

Rank	Year	Flow[b] (mgd)	Flow[c] (MLD)	Percent Mean Daily Flow
1	2002	21	79	7%
2	1966	27	102	9%
3	1999	30	113	11%
4	1932	31	117	11%
5	1995	32	120	11%
6	1941	34	128	12%
7	1963	35	132	12%
8	1944	36	135	13%
9	1964	38	143	13%
10	1930	39	147	14%

[a] Mean flows are from along the Brandywine Creek at Chadds Ford, Pennsylvania at U.S. Geological Survey stream gage 01481000, 1912–2002.

[b] Here mgd means million gallons per day.

[c] Here MLD means million liters per day.

[10] Tree ring records can be correlated to streamflow data and thus can "extend instrumental records of streamflow and precipitation over periods spanning several centuries" [*Loaiciga*, 2005, p. 949]. Narrow tree rings indicate dry and/or cold years, and wide rings indicate wet and/or warm years. Since water is a limiting factor in tree ring growth, streamflow reconstructions based on tree rings are more accurate for low-flow drought estimates as opposed to high-flow estimates.

2. Literature Review

[11] Tree ring reconstructions have been used to extend drought records in watersheds throughout the United States. Droughts along the Hudson River in New York were more variable prior to 1910 and after 1960 based on a 280-year tree ring record [*Cook and Jacoby*, 1979]. *Cook and Jacoby* [1983, p. 1670] demonstrated the "great potential of annual tree ring chronologies for reconstructing streamflow data in eastern North America." Tree ring records for July–September along the Potomac River at Point of Rocks, Maryland, indicated that the early 1960s drought was the most severe event since 1730. Tree ring records dating to 1700 indicated that the 1986 drought in the southeastern United States was rare with a recurrence interval of 287 years [*Cook et al.*, 1988].

[12] A 1053 year tree ring reconstruction of spring rainfall in North Carolina through Georgia suggested that very dry conditions persisted at the end of the twelfth century and in the mideighteenth century [*Stahle and Cleaveland*, 1994]. Meteorological records extended by a 425-tree grid from 1700 to 1978 in the continental United States indicated that the Dust Bowl megadrought of the 1930s was the most severe drought to occur in America since 1700 [*Cook et al.*, 1999]. Comparisons of PDSI and precipitation deficits in the New York City area indicated that 1995 had the second most severe drought since 1945, second to the mid-1960s drought [*DeGaetano*, 1999].

[13] Tree ring data indicated that a megadrought of continental proportions occurred from 1576 to 1585 with epicenters in the southwestern and Mid-Atlantic United States [*Stahle et al.*, 2000]. The worst drought in Virginia occurred from 1606 to 1612 and may have accounted for the failure of the Jamestown colony, circa 1606, in which 80% of the colonists perished from famine [*Blanton*, 2000; *Nash*, 2002]. A network of 32 tree rings dating to 1750 shows that Columbia River low flows at Dalles, Oregon, during the 1840s were the lowest in 250 years and drought flows during the 1930s were almost as extreme [*Gedalof et al.*, 2004].

[14] In the Mid-Atlantic United States, growing season moisture conditions during the twentieth century were within the range of natural climate variability when compared to the tree ring record dating to 1185 [*Quiring*, 2004]. A 500 year tree ring reconstruction of PDSI in southeastern New York State indicated severe droughts occurred during the 1560s, 1620s, 1680s, 1750s, 1790s, 1820s, 1870s, 1910, and early 1960s [*Lyon et al.*, 2005].

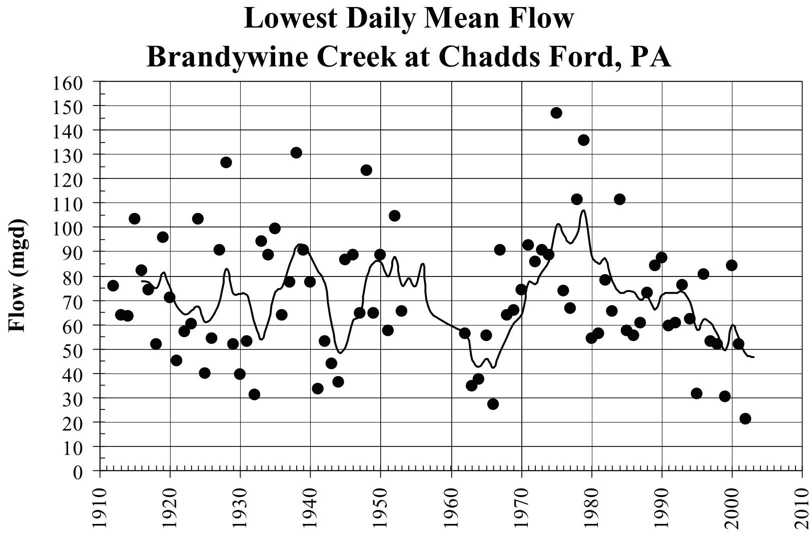


Figure 3. Lowest daily mean flows along the Brandywine Creek at Chadds Ford, Pennsylvania, USGS stream gage 01481000. The smoothed line is a 5 year moving average illustrating extended droughts during the 1920s, 1930s, 1940s, 1960s, and 1995–2002 (USGS).

3. Methods

[15] Lowest daily flows in each year were plotted for the USGS stream gage 01481000 along the Brandywine River at Chadds Ford, Pennsylvania, from 1912 through 2002. The Brandywine is used to define the drought of record, as the river is the largest surface water supply source in Delaware. This gage has the longest period of record of any stream flowing through Delaware and Pennsylvania (a few miles upstream from the state line), is used for water supply planning in Delaware.

[16] PDSI values were plotted and correlated with recorded low flows along the Brandywine River. The PDSI measures dryness based on precipitation and temperature inputs on a scale ranging from extreme wetness (+4), severe wetness (+3), moderate wetness (+2), normal conditions (0), moderate drought (−2), severe drought (−3), to extreme drought (−4) [*Drought Information Center*, 2006].

[17] *Cook and Krusic* [2004] established a national network of reconstructed annual PDSI for 286 regions across North America from the analyses of 835 tree ring chronologies over 2000 years. Reconstructed PDSI values for point 262 near the Brandywine River watershed were excerpted for a tree ring record from 1600 to 2002. Cook and Krusic found that the tree ring network used the calibration R-squared (CRSQ) or "coefficient of multiple determination" statistic to measure the variance between the actual and estimated PDSI at each tree grid point. CRSQ ranges from 0 to 1.0 (perfect agreement between instrumental PDSI and tree ring estimates). The median CRSQ of the 286 grid points in North America is 0.51. Cook and Krusic concluded that 50% of the PDSI variance is in line with tree ring widths over the 286 grid points, a level of calibrated variance that is considered "quite good." The CRSQ of point 262, the tree ring chronology that we utilized near the Brandywine watershed, ranges from 0.50 to 0.54 from 1600 to 2002, which is a calibration variance that is also quite good.

[18] Linear regression (Figure 4) and statistical significance tests were conducted to correlate annual low flows recorded along the Brandywine Creek (1912–2002) with PDSI values. Statistical tests indicate reasonable correlations between recorded low flow and PDSI as the coefficient of determination (r^2) is 0.52 and the Pearson correlation coefficient (r) is 0.67, significant at $\alpha = 0.01$. An r^2 or r equal to 1.0 would indicate a perfect linear relationship between PDSI and recorded streamflow.

[19] PDSI values were input to a linear regression equation to estimate low flows in years before the instrumental record. With Brandywine River low flow (BC) as the dependent variable and PDSI as the independent variable, the linear trend equation is

$$BC = 12.18 \times PDSI + 73.06.$$

[20] Recorded Brandywine River low flows (1912–2002) were plotted against estimated flows computed from PDSI from the linear egression equation to visually check for accuracy (Figure 5). Estimated low flows tend to reasonably simulate recorded flows except in extremely dry years such as 1930, 1966, 1995, 1999, and 2002. *Brockway and Bradley* [1995] also observed that tree ring reconstructed flows tend to overestimate observed extreme low stream flows during severe droughts.

[21] The coefficient of determination (r^2) from the linear regression between PDSI and reconstructed low flow captures about 50% of the variance. To address the robustness of the regression for goodness of fit, we performed a cross-validation analysis between the PDSI and recorded low flow values. To perform the cross-validation test, the sample from 1912–2002 was split into two samples using a random number generator. The linear regression equation was determined for the first sample, and an original r^2 was calculated. The first equation was used to predict annual low flows using PDSI values from the second sample. The predicted low flow values were correlated with the observed low flow values, and a second r_{y^2} (the cross-validity coefficient) was calculated. The difference between the original r^2 and the

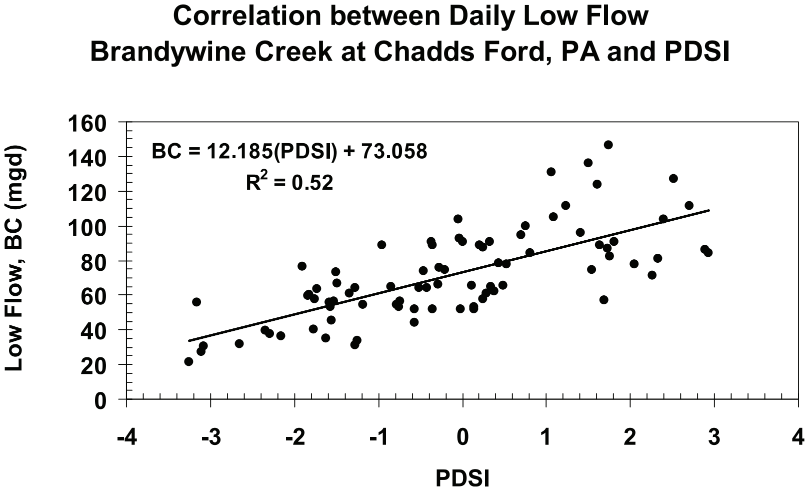
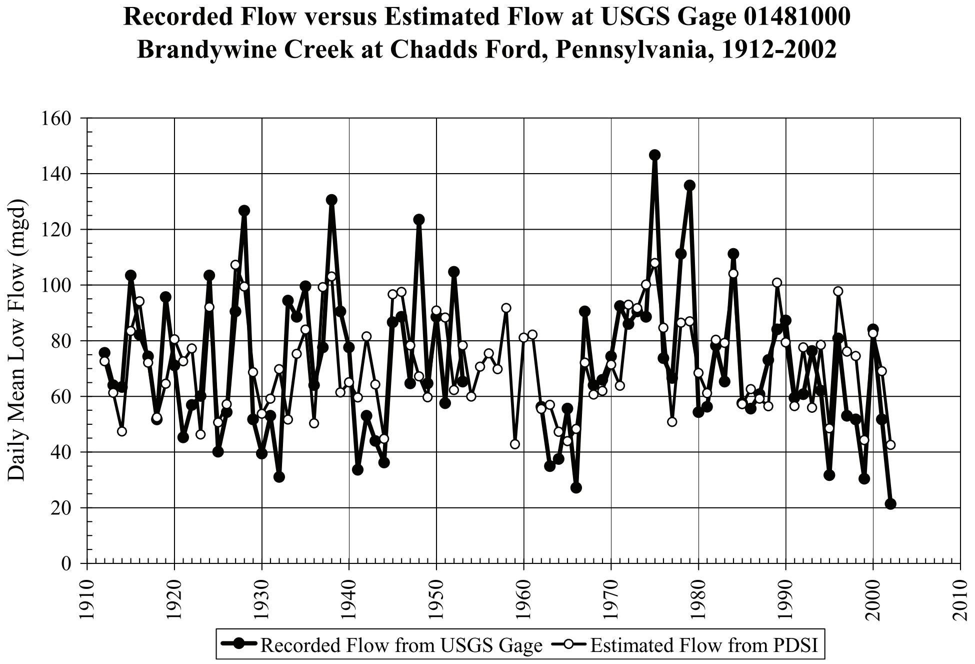


Figure 4. Correlation between annual low flow recorded at USGS gage 01481000, Brandywine Creek at Chadds Ford, Pennsylvania (1912–2002) and PDSI values obtained from tree ring records developed by *Cook and Krusic* [2004].



Recorded Flow versus Estimated Flow at USGS Gage 01481000
Brandywine Creek at Chadds Ford, Pennsylvania, 1912-2002

Figure 5. Recorded annual daily low flow versus estimated flow from reconstructed PDSI values at USGS gage 01481000, Brandywine Creek at Chadds Ford, Pennsylvania, 1912–2002.

second r_{y^2} is known as shrinkage. While uncertainty is still present, if shrinkage is lower, there is greater confidence in the linear regression technique in application of the equation to estimate low flows back to 1600 using PDSI values.

[22] The cross-validation analysis indicates that shrinkage is low and hence reasonable confidence in the linear regression technique. For the first random sample, original $r^2 = 0.54$, and the linear trend line is BC $= 11.36 \times$ PDSI $+ 70.34$. For the second random sample, $r_{y^2} = 0.46$, and the second linear trend line is BC $= 0.43 \times$ PDSI $+ 39.29$. Given the original $r^2 = 0.54$ and the second $r_{y^2} = 0.46$, shrinkage is 8%, a relatively good outcome indicating reasonable confidence in use of the PDSI to predict annual low flows prior to the beginning of the instrumental record.

[23] Although there is some uncertainty given $r^2 = 0.52$, the linear regression equation reasonably estimates low flows correlated with PDSI along the Brandywine River over the period of record (1912–2002). We applied the equation to the reconstruction of low flows back to the year 1600 using PDSI values obtained from the tree ring width record. The reconstructed low flows are plotted on time series scatterplots to visually examine for statistical patterns and to examine the severity of modern droughts over a long-term historic context.

[24] Last, we estimated the probability and frequency of droughts as measured by PDSI and annual low flows using the cumulative distribution function from the general extreme value (GEV) analyses. The GEV is a probability function used in hydrology and climatology to model rare and extreme events such as droughts or floods. We plotted two GEV cumulative distribution curves: the first relating PDSI to probability $F(x)$ and the second relating annual low flow to probability. We then determined a reasonable goodness of fit for the GEV analyses using the Kolmogorov-Smirnov test statistics as both distributions are less than a critical value defined by a significance level ($\alpha \leq 0.10$). Both distributions are slightly and positively skewed (mass concentrated to the left with a longer tail to the right) and nearly normally distributed as skewness values are less than 1.00 (0.07 and 0.31). Both distributions have relatively low and positive excess kurtosis (0.42 and 0.34) which indicates less variance due to extreme, infrequent events and a rounded peak and shorter tails on the probability curves.

4. Results

4.1. Palmer Drought Severity Index

[25] Based on Palmer Drought Severity Index (PDSI), the most severe drought in 400 years occurred during 1635 (PDSI $= -4.71$). The droughts of 2002 (-4.71), 1999 (-3.08), and 1995 (-2.66) were the 6th, 12th, and 17th most extreme since 1600 (Figure 6). The drought of 1965 was the 8th most severe (-3.16) and the Dust Bowl year of 1930 was the 36th lowest PDSI (-2.34). In chronological order, the most severe droughts defined by PDSI ≤ -3.0 occurred during 1635, 1685, 1686, 1748, 1791, 1819, 1838, 1864, 1872, 1965, 1966, 1999, and 2002 (Table 3).

[26] Table 4 summarizes 10, 50, and 100 year PDSI values dating to 1600. The 2002 drought PDSI (-3.26) has a 2% probability $F(x)$ of reoccurring in any given year or once every 50 years. The 1999 PDSI (-3.08) has a 3% probability or once every 33 years. The 1995 PDSI (-2.66) has a 6% probability or a frequency of once every 16 years. The 100 year drought PDSI (-3.50) has a 1% chance of occurring in any given year. Based on PDSI, the 100 year drought occurred within intervals ranging from 8 years (1864–1872) to 156 years (1635–1791). The last 100 year drought prior to 2002 occurred in 1872. The frequency of

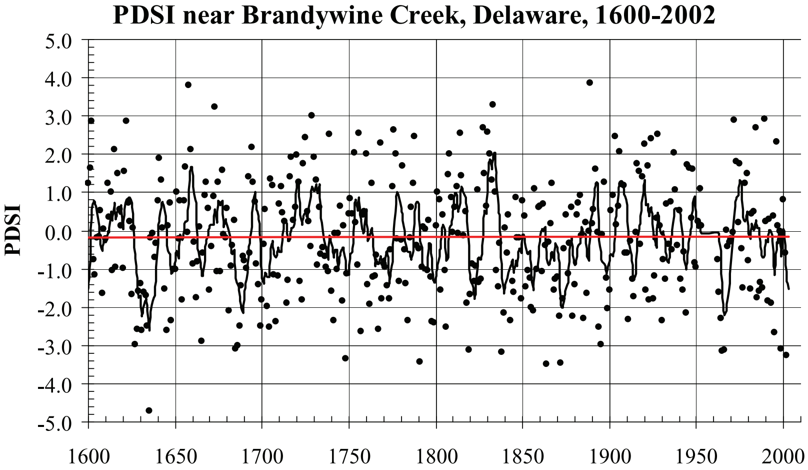


Figure 6. Reconstructed PDSI in the vicinity of Brandywine Creek, Delaware, 1600–2002. The smoothed line is a 5-year moving average. The linear trend line is depicted in red.

droughts (PDSI ≤ -2.0) varied slightly and droughts occurred in 13 years in the seventeenth century, 10 years in the eighteenth century, 14 years in the nineteenth century, and 10 years in the twentieth century. Table 5 summarizes cumulative distribution statistics for Brandywine Creek PDSI values, 1600-2002.

4.2. Streamflow

[27] Based on a smoothed line defined by a 5 year moving average of low flows along Brandywine Creek from 1600–2002, extended droughts occurred during the 1630s, 1680s, 1820s, 1840s, 1860s, 1870s, 1930s, 1940s, 1960s, and 1995–2002 (Figure 7). Over 400 years, the interval between droughts with a 10% probability of reoccurring ranged from 1 to 33 years. One of the longest cycles between droughts occurred between the mid-1960s and late 1990s, over 30 years.

[28] Low flows with a 10% probability ($\leq$45 mgd or 169 MLD) occurred in greater frequency and severity during the twentieth century compared to earlier centuries. The droughts of 2002, 1966, 1999, 1932, and 1995 recorded the second, third, fourth, fifth, and ninth lowest flows, respectively, since 1600 (Table 6). The worst drought in the last 400 years occurred in 1635. Low flows ($\leq$45 mgd) occurred during 12 years in the seventeenth century, 10 years in the eighteenth century, 8 years in the nineteenth century, and 15 years in the seventeenth century (Figure 8). Drought years, in which the number of days with low flows are $\leq$50 mgd (188 MLD), have increased during the twentieth century (Figure 9).

Table 3. Most Severe Droughts[a]

Rank	Year	PDSI
1	1635	−4.71
2	1864	−3.50
3	1872	−3.47
4	1791	−3.43
5	1748	−3.33
6	2002	−3.26
7	1819	−3.19
8	1838	−3.18
9	1965	−3.16
10	1966	−3.11
11	1685	−3.09
12	1999	−3.08
13	1686	−3.00

[a] Data based on PDSI in the vicinity of Brandywine Creek, Delaware, 1600–2002.

[29] Table 7 summarizes estimated probabilities of drought low flows from the reconstructed record dating to 1600. The 2002 low flow (21 mgd or 79 MLD) has a 0.5% probability of reoccurring or a frequency of once every 200 years. The 1999 low flow (30 mgd/113 MLD) has a 1.0% probability or once every 100 years. The drought of 1995 low flow (32 mgd/120 MLD) has a 2.0% probability or a frequency of once every 50 years.

[30] The 100 year drought low flow of 30 mgd (113 MLD) has a 1% chance of reoccurring in any given year. The reconstructed low flow record over 400 years indicates the 100 year drought has occurred within intervals ranging from 3 years (from 1999 to 2002) to 331 years (from 1635 to 1966). Table 8 summarizes cumulative distribution statistics for Brandywine Creek Low Flow, 1600-2002.

5. Discussion

5.1. Published Accounts

[31] Popular accounts corroborate findings that severe nineteenth century droughts occurred before the beginning of instrumental precipitation and stream gage records. In

Table 4. Probability of PDSI in Vicinity of Brandywine Creek, 1600–2002

Frequency	10 Year	50 Year	100 Year
Probability of occurring in any year	10%	2%	1%
Rank	42nd lowest PDSI	13th lowest PDSI	2nd lowest PDSI
PDSI	−2.2	−3.0	−3.5
Minimum interval (years)	1	1	8
Maximum interval (years)	33	70	156
Range (years)	1708–1741	1895–1965	1635–1791

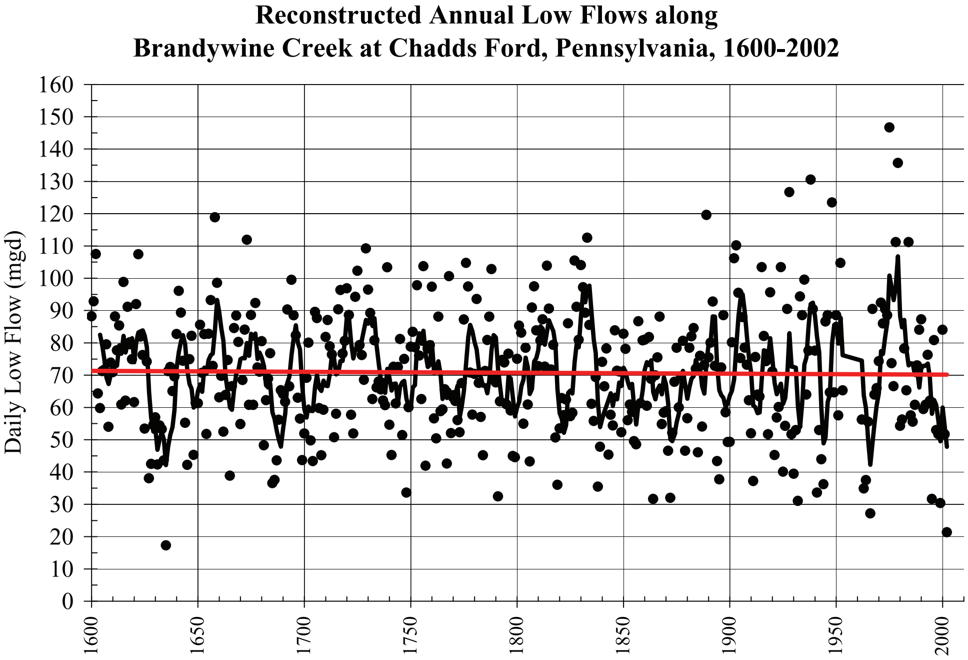


Figure 7. Reconstructed annual low flows along Brandywine Creek at Chadds Ford, Pennsylvania, 1600–2002. The smoothed line is a 5-year moving average. The linear trend line is depicted in red.

1819, James Madison, fourth President of the United States, wrote of a severe drought in Virginia that threatened famine [*Madison*, 1908]. In 1838, a "memorable drought" occurred along the Ohio River in West Virginia [*Frazer*, 1857]. That year in Philadelphia, Franklin Institute meteorologist James Espy was concerned about the drought and proposed to artificially create rain by "setting fires to the woodlands" [*Gelber*, 2002]. During the summer of 1838, the Secretary of the Chesapeake and Delaware Canal reported that pumps kept the canal supplied with water during the "unusual drought" [*Hazard*, 1840].

[32] The 1864 drought during the American Civil War was so notable that *Harpers Weekly* [1864] in New York City published a drought poem with the verse: "... the shallow rivers scarcely run, the streamlet's bed is dry." During the summer of 1864, the *New York Times* [1864] published headlines about drought and smoky days in central New York. The 1864 drought during the Civil War Shenandoah Valley campaign in Virginia reportedly caused more casualties than inflicted by the other side's troops [*Gallagher*, 2006]. In August 1869, the Philadelphia Water Works log recorded a severe drought that later resulted in the construction of a Fairmount Park reservoir [*Baker*, 1888].

5.2. Human Impacts

[33] Drought low flows along the Brandywine Creek have decreased yet occurred more frequently and variably during the twentieth century. The slope of the linear trend line for the low flow sample is negative, indicating slight decreases in low flows since 1600. Oscillations between the lowest low flows ($\leq$50 mgd or 188 MLD) and the highest low flows ($\geq$120 mgd or 450 MLD) are more noticeable during the twentieth century than in previous centuries, indications of greater streamflow variability that would be characteristic of watershed urbanization and atmospheric warming impacts.

[34] Increased frequency and intensity of drought low flows during the twentieth century are coincident with

Table 5. Cumulative Distribution Statistics for Brandywine Creek PDSI Values, 1600–2002

Statistic	Value (PDSI)	Percentile	Value (PDSI)
Sample	403 years	Min	−4.71
Range	8.6	5%	−2.61
Mean	−0.2	10%	−2.25
Variance	2.3	25%	−1.32
SD	1.5	50% (Median)	−0.19
CV[a]	−7.3	75%	0.80
SE	0.07	90%	1.79
Skewness	0.07	95%	2.46
Excess kurtosis	0.42	Max	3.87

[a] CV, coefficient of variation.

Table 6. Most Severe Droughts[a]

Rank	Year	Low Flow[b] (mgd)	Low Flow[c] (MLD)
1	1635	17	64
2	2002	21	79
3	1966	27	101
4	1999	30	113
5	1932	31	117
6	1791	32	120
7	1864	32	120
8	1872	32	120
9	1995	32	120
10	1748	34	128
11	1941	34	128

[a] Data based on reconstructed annual daily low flows along the Brandywine Creek at Chadds Ford, Pennsylvania, 1600–2002.
[b] Here mgd means million gallons per day.
[c] Here MLD means million liters per day.

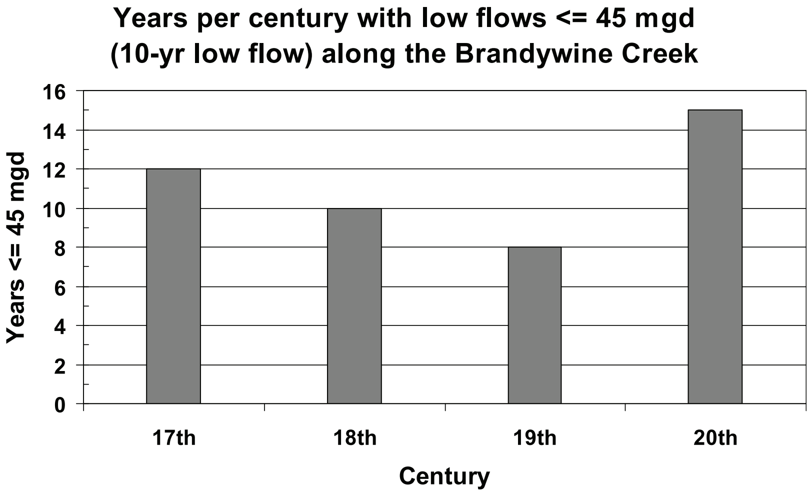


Figure 8. Years per century with low flows ≤45 mgd along the Brandywine Creek.

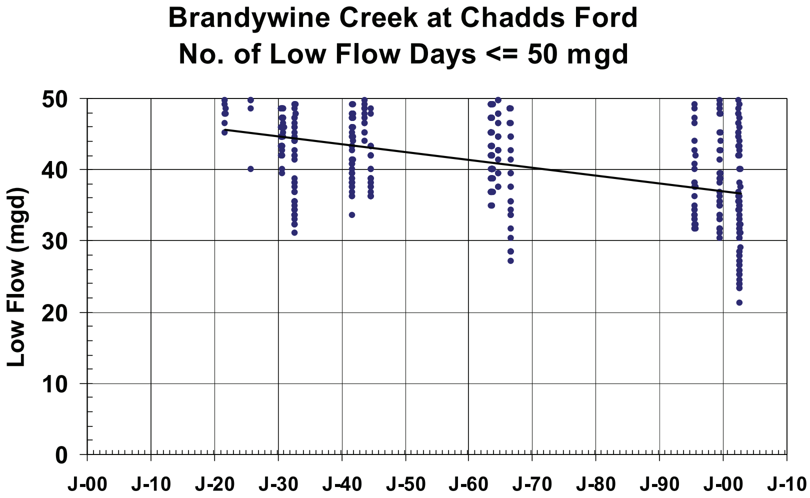


Figure 9. Number of low flow days ≤50 mgd along Brandywine Creek. Negative slope of the linear trend line depicts increased frequency of drought low flows during the 20th century.

Table 7. Probability of Reconstructed Low Flows[a]

Frequency	10 Year	50 Year	100 Year
Probability of occurring in any year	10%	2%	1%
Rank	37th lowest flow	6th lowest flow	4th lowest flow
Low Flow	45 mgd[b] (69 MLD)[c]	32 mgd (120 MLD)	30 mgd (113 MLD)
Minimum interval (years)	1	3	3
Maximum interval (years)	33	156	331
Range (years)	1708–1741	1635–1791	1635–1966

[a] Data specific to Brandywine Creek at Chadds Ford, Pennsylvania, 1600–2002.

[b] Here mgd means million gallons per day.

[c] Here MLD means million liters per day.

Table 8. Cumulative Distribution Statistics for Brandywine Creek Low Flow, 1600–2002

Statistic	Value[a] (mgd)	Percentile	Value (mgd)
Sample	395 years	Min	17
Range	130	5%	38
Mean	71	10%	45
Variance	405	25%	57
SD	20	50% (Median)	71
CV[b]	0.28	75%	84
SE	1.01	90%	96
Skewness	0.31	95%	104
Excess kurtosis	0.34	Max	147

[a] mgd, millon gallons per day.
[b] CV, coefficient of variation.

human impacts from increased population, watershed urbanization, and increased water withdrawals. The population in the Brandywine River watershed grew from a few hundred people during the early seventeenth century when Dutch and Swedish settlers first came to Delaware, to 50,000 by the Industrial Revolution in the late 1800s, to 120,000 by 1950, and doubled to a quarter million people by 2010 (Figure 10). Drought low flows have declined with increased Brandywine Creek allocations as 12 companies hold permits to withdraw water supplies (8 mgd/30 MLD) from the creek. The observed decline in low flows in an urbanizing Brandywine watershed are consistent with findings of *Zhu and Day* [2005] at 47 stream gages in Pennsylvania from 1971 to 2000, in which 87% of the streams had downward trends in total stream and base flow, a finding the researchers attributed to urbanization. Water diversions in urbanized watersheds also artificially decrease low flows during drought [*Claessens et al.*, 2006].

[35] It is unlikely that decreased precipitation alone accounts for declining low flows. A double-mass curve indicates cumulative precipitation at Wilmington Airport increases at a slope similar to and parallel to cumulative low flow along Brandywine Creek at Chadds Ford (Figure 11). Both double-mass curves increase with the line of unity with little change in slope except for a barely discernable yet slight decrease in slope during the droughts of the early 1960s.

[36] Atmospheric warming may have contributed to increased frequency and severity of low flows along the Brandywine Creek during the twentieth century. The U.S. Global Change Research Program [*Karl et al.*, 2009, p. 41] reported with warming of the atmosphere, "droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change" and streamflows will become more variable. Mean annual temperatures in northern Delaware increased after the 1970s from 54.0°F (12.2°C) during 1895–1970 to 54.6°F (12.6°C) during 1971–2002 (Figure 12), a warming trend that would lead to increased evapotranspiration and lower stream base flows.

[37] The droughts of 1995–2002 in Delaware have higher probabilities of reoccurring when estimated by PDSI than by reconstructed low flow (Table 9). Based on 400 years of tree ring data, the drought of 2002 has a 2.0% probability (once every 50 years) measured by PDSI compared to 0.5% (once every 200 years) measured by streamflow. The PDSI is a measurement of dryness based on temperature and precipitation and does not include streamflow, which is a parameter influenced by watershed urbanization and population growth. The 1995–2002 droughts defined by PDSI are less severe and have higher probabilities of reoccurring compared to streamflow because PDSI includes only the effects of temperature and precipitation, which are influenced by climatic patterns. Droughts measured by streamflow are estimated as more severe than those defined by PDSI and have a lower probability of reoccurring because of the effects of artificially reduced river flows from watershed urbanization, population growth, and increased water withdrawals in addition to temperature and precipitation impacts.

[38] PDSI correlates with low flows ($r^2 = 0.52$) but with some scatter, as reconstructed low flows from PDSI tend to overestimate recorded flows during severe drought years, a

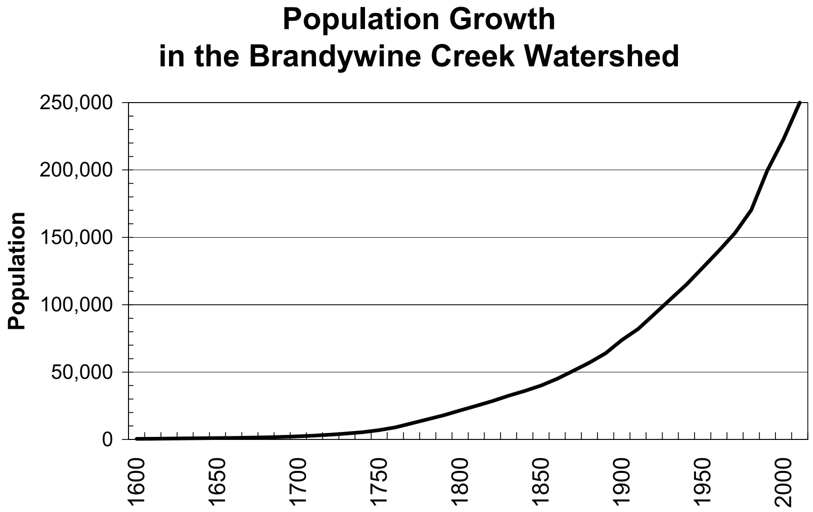


Figure 10. Population growth in the Brandywine Creek watershed. Population after 1900 derived from U.S. Census Bureau, 1995.

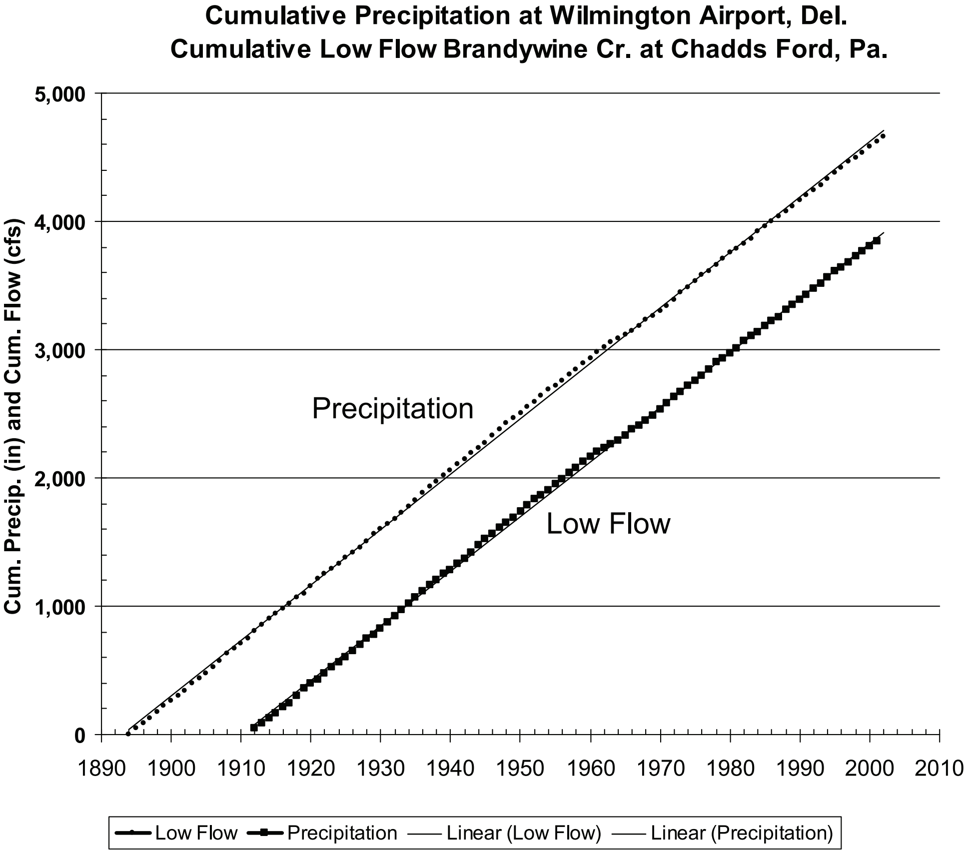


Figure 11. Double-mass curve depicting cumulative precipitation at Wilmington Airport, Delaware and cumulative low flow along Brandywine Creek at Chadds Ford, Pennsylvania.

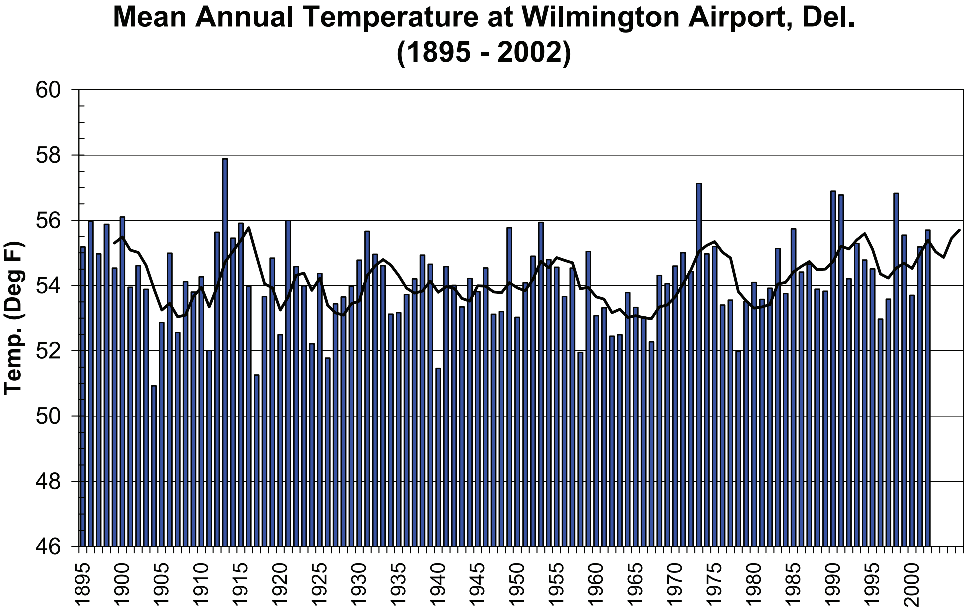


Figure 12. Mean annual temperature at Wilmington Airport, Delaware. The solid line is a 5-year moving average indicating warming since the 1970s. The mean temperature increased from 54°F during 1895–1970 to 54.6°F during 1971–2002 [*USNWS*, 2006].

Table 9. Probability of 1995, 1999, and 2002 Droughts[a]

	1995 Drought		1999 Drought		2002 Drought	
Parameter	Low Flow	PDSI	Low Flow	PDSI	Low Flow	PDSI
Low flow or PDSI	32 mgd	−2.66	30 mgd	−3.08	21 mgd	−3.26
Probability	2.0%	6.0%	1.0%	3.0%	0.5%	2.0%
Frequency	50 years	16 years	100 years	33 years	200 years	50 years
Drought rank	Ninth	Seventeenth	Fourth	Twelfth	Second	Sixth

[a]Data based on PDSI and Brandywine Creek low flow.

finding noticed by other researchers. PDSI is based on a weighted average of precipitation for the entire year while low flow represents the base flow recession during a season, usually late summer, with a different response to precipitation and temperature deficits. This difference in response to temperature and precipitation deficits leads to the high scatter while correlation between PDSI and low flow is in the same direction.

[39] Uncertainty is inherently present in the correlation between tree ring width data, PDSI, and reconstructed low flows. The coefficient of multiple determination is 0.51 for PDSI, a level of calibrated variance that scientists from the Lamont-Doherty Tree-Ring Lab considered to be "quite good" for dendrochronology reconstructions. The coefficient of determination (r^2) is 0.52 for the correlation between PDSI and reconstructed low flow.

[40] While variance is present, the analysis of drought over 400 years using two parameters, PDSI and low flow, indicates that the droughts of 1995–2002 in the Delaware Basin are historically extreme with differences only in the magnitude of severity. Given that tree ring width data are used to estimate conditional means of PDSI and that uncertainty is associated with individual values of PDSI, the 2002 drought was the sixth worst drought based on PDSI and the second worst drought based on low flow since 1600. The 1999 drought was the twelfth worst drought by PDSI and the fourth worst drought by low flow. Both methods (PDSI and low flow) agree that the 1635 drought was the most severe event since 1600.

6. Conclusions

[41] This paper examines the frequency and severity of drought in the Delaware Basin using the Palmer Drought Severity Index (PDSI) from Lamont-Doherty tree ring data (1600–2002) correlated with reconstructed low flows along the Brandywine River. In the Delaware Basin, the most severe drought in a century occurred during 2002 as the Brandywine River, Delaware's largest surface water supply, declined to 21 mgd (79 MLD), the lowest flow on record since the gage was installed in 1912. To evaluate the 1995–2002 drought over a long term given a variable hydroclimate, tree ring and PDSI were correlated to reconstruct flows along Brandywine Creek to 1600 ($r^2 = 0.52$).

[42] While variance and uncertainty are present in the correlation between tree ring width, PDSI, and reconstructed low flows, in which the coefficient of multiple determination is 0.51 and coefficient of determination is 0.52, probability analyses of PDSI and low flows both agree that the most extreme drought in 400 years occurred during 1635. Based on PDSI the 2002, 1999, and 1995 droughts were the sixth, twelfth, and seventeenth most severe in 400 years with frequencies of once every 50, 33, and 16 years, respectively. Based on low flow, the 2002, 1999, and 1995 droughts were the second, fourth, and ninth most severe since 1600 with frequencies of once every 200, 100, and 50 years, respectively. The instrumental record drought of 2002 has a low probability of reoccurring in any given year (2.0% by PDSI and 0.5% by low flow), but droughts nearly as severe have occurred during the 1630s, 1680s, 1820s, 1840s, 1860s, 1930s, 1940s, and 1960s. Increased frequency and severity of drought low flows in Delaware during the late twentieth century through 2002 were coincident with population growth, watershed urbanization, and atmospheric warming although these associations were not correlated and deserve further study.

[43] Over 400 years of tree ring, PDSI, and reconstructed low flow data indicate that the Delaware Basin drought of 1995–2002 was a historically significant event (whether measured by PDSI or low flow) with important implications for water supply planning and drought management. Water supply and drought managers are appropriately conservative in specifying the extreme 2002 drought of record for water supply design as even more severe droughts have occurred since 1600. If population growth, watershed urbanization, and atmospheric warming continue, drought low flows in the future may become more frequent, intense, and variable.

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