Analysis of Observed Hydrological and Meteorological Data to Identify and Model Trends Due to Climate Change

J.Y. Diiwu, A.G. Bobba and R.P. Rudra

NWRI Contribution No. 00-126
Management Perspective

Simple statistical tests for equality of means and variances, and Box-Jenkins univariates and input-output models are shown to be tools to detect hydrologic changes. The structural decomposition of daily runoff series into periodic and stochastic components and the step response function of daily runoff processes in relation to daily rainfall processes provide parameters that form a basis for evaluating the changes in the hydrologic environments due to climate change.

This report is first part on the study of "Stochastic Analysis and Modelling of Hydrologic and Climatologic Time Series" of Northern Canadian Environment due to climate change.

Sommaire à l'intention de la direction

On montre que de simples tests statistiques d'égalité des moyennes et des variances, ainsi que des modèles d'entrée-sortie Box-Jenkins à une variable, sont utiles pour détecter les changements hydrologiques. En utilisant la décomposition structurale de séries quotidiennes de données sur le ruissellement en éléments périodiques et stochastiques et la fonction de réponse graduelle des processus quotidiens de ruissellement par rapport aux processus quotidiens de précipitations, on obtient des paramètres qui peuvent servir à l'évaluation des changements causés par le changement climatique dans les milieux hydrologiques.

Abstract

Temperature, precipitation and streamflow data from the Northeast Pond River watershed were analyzed to identify any trends and estimate their magnitudes. Graphical trend detection was carried out using ten-year moving average and robust locally weighted regression modelling. Mann-Kendall trend test was also done, and the magnitude of detected trends was estimated using Kendall slope estimates. Trends were detected for each of the three variables, and their magnitudes and directions appear to be season-dependent. Temperature showed a downward trend in winter and an upward trend in spring, summer and fall seasons, with the change varying between 0.1 and 7 degrees per year. For each of the four seasons the change in precipitation varied between 0.6 and 13 mm per year, with the greatest upward trend being in October and the greatest downward trend in February. Over the period, monthly mean streamflow changed by less than 0.5 cm per year. Frequency analysis showed that the lognormal and Weibull probability models are equally good choices for precipitation and streamflow in the watershed. In the case of temperature, the normal model gives the best fit for late fall to early spring while the lognormal model is best for the rest of the months.

Résumé

On a analysé les données sur la température, les précipitations et l’écoulement des cours d'eau du bassin versant de la rivière Northeast Pond afin de déterminer les tendances existantes et d'en évaluer l'importance. On a détecté les tendances graphiques à l'aide d'une moyenne mobile de dix ans et d'une modélisation robuste par régression à pondération locale. On a également effectué des tests de tendances de Mann-Kendall et on a estimé l'ordre de grandeur des tendances décelées à l'aide d'estimations des pentes de Kendall. On a décelé des tendances pour chacune des trois variables, et il semble que leur ordre de grandeur et leur direction dépendent de la saison. Les températures présentaient des tendances à la baisse en hiver et à la hausse au printemps, en été et en automne, avec des changements compris entre 0,1 et 7 degrés par année. Pour chacune des saisons, le changement dans les précipitations était compris entre 0,6 et 13 mm par année; on observait la plus forte tendance à la hausse en octobre, et la plus forte tendance à la baisse en février. Au cours de cette période, les variations mensuelles moyennes de l'écoulement des cours d'eau étaient inférieures à 0,5 cm par année. Une analyse de fréquences indiquait que le modèle de probabilité lognormal et celui de Weibull sont également utiles pour l'évaluation des précipitations et de l'écoulement des cours d'eau dans le bassin versant. Dans le cas de la température, le modèle normal donne le meilleur ajustement pour la période comprise entre la fin de l'automne et le début du printemps, alors que le modèle lognormal est préférable pour les autres mois.
ANALYSIS OF OBSERVED HYDROLOGICAL AND METEOROLOGICAL DATA TO IDENTIFY AND MODEL TRENDS DUE TO CLIMATE CHANGE

J. Y. Diiwu¹, A. G. Bobba², R. P. Rudra¹

INTRODUCTION

Concern over changes in climate caused by rising atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years. Despite a better understanding of climatic processes, many of the effects of anthropogenic climate changes are still poorly understood. This notwithstanding there are bound to be geophysical and socioeconomic impacts of the changes in climate (Manabe and Weatherald, 1987; Lettenmaier and Gan, 1990). These include major changes in water availability caused by alterations in temperature, precipitation and streamflow patterns. Such hydrologic changes will affect nearly every aspect of human well being, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management at watershed and regional levels. Also, altering precipitation patterns may greatly affect the onset, duration and severity of extreme events such as floods and droughts (Nemec and Shaake, 1982). It is therefore extremely

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important to understand how changes in climate would affect water supply at the watershed and regional levels.

Historical trends in hydrologic variables are important for water resource planning purposes. Such trend information can be used to hypothesize future climatic scenarios for management decision-making (Bobba et al., 1997, 1999). Thus there is a need to identify hydrologic trends in Canadian watersheds that may be attributable to climate variability and change, and model such trends for future planning purposes. The study was therefore carried out to identify and model trends in observed time series of temperature, precipitation and streamflow.

The Northeast Pond River watershed was selected for the study. The study watershed, which has an area of 3.90 km² is located approximately 20 km west of St. John’s in Newfoundland. The climate of the study area is dominated by the Labrador current, which consists primarily of arctic waters. The area has a marine climate, characterized by short but pleasant summers and mild winters (Environment Canada, 1995; Bobba et al., 1997). Monthly mean temperature, precipitation and stream flow were analyzed for the period 1952 to 1983. The monthly means were computed from daily observed data. Daily temperature and precipitation data were obtained from St. John’s meteorological station, and daily streamflow data were obtained from the gauge at the watershed outlet at Portugal Cove (Bobba et al., 1997).
METHOD OF ANALYSIS

Summary Statistics

The trend analysis was preceded by computation of the descriptive statistics of the time series. The statistics obtained were the mean, median, standard deviation, and the range. The mean and median are intended as measures of central tendency of the time series, while the standard deviation and range give measures of how the series is spread about the central values (McCuen, 1993). The summary statistics obtained for the time series of temperature, precipitation and streamflow are presented in Tables 1, 2 and 3 respectively.

Frequency Analysis

Frequency analysis was carried out to determine appropriate probability models that may be used to make probability statements about the occurrence of the hydrologic variables. The probability models were identified by carrying out probability plots for some well known probability functions: normal, lognormal, Weibull and extreme value functions. For each variable the probability plot in which the sample points are closest to a straight line and within the 95% confidence limits was selected as the best fit plot. The probability function corresponding to the best fit probability plot was then selected as the most representative probability model for the variable (McCuen, 1993). The selected probability models are presented in Table 4. The corresponding best fit probability plots are presented in Figures 1 to 48. The first and third quantiles were then determined from the probability plots; these are presented in Tables 1 to 3 alongside the summary
statistics. The second quantile is also the median, while the zeroth and fourth quantiles are the minimum and maximum values specified in the range. The quantiles are useful because, just like probability models, they can be used to make probability statements about future trends in the variable.

Seasonal Trend Analysis
Trend analysis was carried out for each of the twelve months January to December for the period 1952 to 1983. This was intended to minimize the effect of seasonal variations on the trends in the variables. The twelve months were then grouped into four seasons as follows: winter, December to February; spring, March to May; summer, June to August; and fall, September to November. The trend analysis was then carried out using two graphical trend detection methods, ten-year moving average and robust locally weighted regression (Cleveland, 1979), and the Mann-Kendall non-parametric trend test (Mann, 1955; Kendall, 1975).

Ten-Year Moving Average
For each of the twelve months the ten-year moving average was computed to identify trends in the time series. The ten-year moving average technique has the advantage of removing any periodicities in the data.

Robust Locally Weighted Regression (RLWR)
The RLWR technique combines locally weighted regression with polynomial smoothing. The major advantage of the RLWR technique is that it does not allow outliers to distort
the smoothing. The technique involves determination of: the order of the polynomial to be locally fitted to each point of the scatter plot, the weighting functions to be used at each point, and the number of iterations to be performed in the fitting procedure. The closest neighbours of each point are assigned the largest weights, while the points which are furthest away from it are assigned the least weights. This minimizes the effects of outliers on the fitted curve. At each point the polynomial to be fitted is of the general form (Cleveland, 1979):

\[ y_k = B_0 + B_1 x_k + B_2 x_k^2 + \ldots + B_d x_k^d \]

where \( B_i \) are parameters to be determined by weighted least squares using weights \( w_k(x_i) \) for \((x_k, y_k)\). Following the recommendation of Cleveland (1979) the values \( d = 1 \) and \( f = 0.5 \) were taken for the smoothing parameters. The RLWR and ten-year moving average curves are presented alongside the time series plots in Figures 49 to 84.

**Mann-Kendall test**

A non-parametric test was chosen for the trend test to avoid the dependence of the test on the probability distribution of the population. The Mann-Kendall test is used because of its simplicity and the fact that the sample size is less than 40 (Hollander and Wolfe, 1973). The test is used to determine if a time series is moving upward, downward, or remaining relatively level over time. This is accomplished by computing a statistic based on all possible data pairs, that represents the net direction of movement of the time series. All possible differences \( x_i - x_j \) are calculated, where \( x_j \) precedes \( x_i \) in time. This difference will either be positive \((x_i > x_j)\), negative \((x_i < x_j)\), or zero \((x_i = x_j)\) for each of the pairs. The number of positive differences minus the number of negative differences is
calculated; this becomes the test statistic, the Mann-Kendall statistic $S$. A positive value of $S$ indicates an upward trend, a negative value indicates a downward trend and a value of zero indicates that there is no change over time. Significance of the test is assessed by comparing the values with those of the standard normal variate. The test statistic is defined as (McCuen, 1993):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{Sgn}(y_j - y_i)$$

where

$$\text{Sgn}(\theta) = \begin{cases} 
1, & \text{if } \theta > 0 \\
0, & \text{if } \theta = 0, \\
-1, & \text{if } \theta < 0.
\end{cases}$$

$E(S) = 0$

$Var(S) = n(n-1)(2n+5)/18$

If $S$ has an approximate normal distribution, then the test statistic $z$ is (McCuen, 1993):

$$z = \begin{cases} 
(S-1)/(\text{Var}(S))^{0.5} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
(S+1)/(\text{Var}(S))^{0.5} & \text{if } S < 0
\end{cases}$$

where $z$ is the value of the standard normal variate with zero mean and unit standard deviation.

In the case where a trend is detected, a non-parametric estimate of the magnitude of the trend is indicated by the Kendall slope estimate (Hollander and Wolfe, 1973). In this study the estimate is taken as the mean of the slope estimates for the lines connecting all
possible pairs of data in the time series. The Kendall slope estimates $K_s$ obtained in the study are presented alongside the corresponding Mann-Kendall statistics in Table 5.

RESULTS AND DISCUSSION

Summary Statistics

From Tables 1 to 3 the standard deviation of temperature is higher for the winter months, with the highest value being for February. The standard deviation then gradually decreased for spring months and into the summer and fall. The lowest standard deviation value is for October. This seems to indicate that the variation in temperature during the month was highest in winter and lowest in fall. The mean and median temperature values seem to indicate that between 1952 and 1983 July and August were the warmest months in the watershed.

In the case of precipitation, standard deviation is highest for fall months, decreases for winter and spring and attains its lowest for the summer months. From these values it may be deduced that the variation in precipitation during the month was highest in fall and lowest in summer. The mean and median precipitation values seem to indicate that most precipitation in the watershed occurred in winter and least in summer between 1952 and 1983.

The mean and median streamflow values seem to indicate that the most streamflow occurred in the watershed in early spring and the least in summer. The standard deviation
values for streamflow seem to indicate that in the watershed the lowest variation in this variable occurred in summer while the highest variation occurred in early spring to late fall between 1952 and 1983.

The quantile values for precipitation seem to indicate that during the winter months the lowest 25% of precipitation that occurred were below 4.5 cm while the highest 25% were between 6.8 and 7.6 cm. The corresponding values for spring were 3.8 cm and between 4.6 and 6.6 cm respectively; for summer they were 1.9 cm and between 3.2 and 5.4 cm, while the values for fall were 4.3 cm and between 5.7 and 7.3 cm.

**Probability Models**

The probability plots presented in Figures 1 to 48 show that the probability model for monthly temperature in the watershed is season-dependent. The normal model appears to give the best fit for data for late fall to early spring, while the lognormal model appears to give the best fit for temperature data for the rest of the months. This is not surprising since some negative temperatures were recorded during late fall to early spring and so the lognormal model did not give a good fit.

For precipitation and streamflow both the lognormal and Weibull models appear to fit the data equally well for all the months. It may be worth noting that that the choice between lognormal and Weibull models as the representative probability model for precipitation and streamflow in the watershed should be determined by computational convenience.
Graphical Trend Detection

The RLWR and ten-year moving average plots are shown in Figures 49 to 84 alongside the times series plots. The RLWR and ten-year moving average trends are similar in direction for each variable in all the months.

In spring, summer and fall months temperature showed an upward trend except in August for which no trend was detected. Also, temperature showed a downward trend in the winter months except in December for which no trend was detected. In the case of precipitation there is no upward trend in spring, summer and fall months, except for July and November when downward trends were detected. For streamflow an upward trend was detected for late spring, part of summer and most of fall, while a downward trend was detected for the months of January, April and November and no trend for February, March and December. The precipitation trends in late spring to late fall are similar to the streamflow trends during that period of the year, as one would expect. However, the precipitation trends in winter and early spring did not translate into similar trends in streamflow in those months probably because of the effects of storage during that period.

Mann-Kendall Statistics

The computed Mann-Kendall statistics presented in Table 5 confirm the trends detected using RLWR and ten-year moving average techniques. However, the absolute values of the statistics seem to indicate that only a few of the detected trends are significant. The Kendall slope estimates (in Table 5) appear to indicate that from 1952 to 1983 monthly temperature in the watershed changed between 0.1 and 7 degrees per year, precipitation
changed between 0.6 and 13 mm per year, while streamflow changed by less than 0.5 cm per year. Analysis of longer duration time series would be needed to confirm those trends that do not appear to be significant.

CONCLUSIONS

Time series of temperature, precipitation and streamflow for the period 1952 to 1983 for the Northeast Pond River watershed in Newfoundland were analyzed for trends on a seasonal basis. Both graphical methods and Mann-Kendall trend test detected trends in the time series for most winter, spring, summer and fall months. However, some of the trends did not appear to be significant probably because the time series was not long enough to show such trends as significant at the watershed level. The analysis also showed that both the lognormal and Weibull probability models are good choices for precipitation and streamflow. In the case of temperature the normal model gives the best fit for late fall to early spring, while the lognormal model is best for the rest of the months.

RECOMMENDATIONS FOR FURTHER WORK

In light of the foregoing results it is recommended that:

1. Similar analysis be carried out for other watersheds in the region to confirm or reject the detected trends due to climate change; for such regional analysis all available time series of temperature, precipitation and streamflow would need to be considered.
2. In view of the fact that some trends have been detected, autocorrelation analysis needs to be carried out with the objective of developing a stochastic model for each of temperature, precipitation and streamflow for forecasting and future trend detection.

REFERENCES


Table 1. Summary Statistics for Temperature

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Range</th>
<th>First Quantile</th>
<th>Third Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-3.616</td>
<td>-3.661</td>
<td>2.353</td>
<td>-8.145, 0.321</td>
<td>-5.296</td>
<td>-2.100</td>
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<tr>
<td>February</td>
<td>-4.456</td>
<td>-4.378</td>
<td>2.385</td>
<td>-10.236, -0.882</td>
<td>-5.923</td>
<td>-3.183</td>
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<td>March</td>
<td>-1.976</td>
<td>-2.323</td>
<td>1.750</td>
<td>-4.915, 1.694</td>
<td>-3.268</td>
<td>-0.522</td>
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<td>April</td>
<td>1.651</td>
<td>1.355</td>
<td>1.318</td>
<td>-0.958, 4.658</td>
<td>0.858</td>
<td>2.386</td>
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<tr>
<td>May</td>
<td>5.923</td>
<td>5.427</td>
<td>1.505</td>
<td>3.484, 9.194</td>
<td>4.718</td>
<td>7.309</td>
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<tr>
<td>October</td>
<td>7.153</td>
<td>7.023</td>
<td>0.888</td>
<td>5.758, 9.315</td>
<td>6.524</td>
<td>7.622</td>
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<tr>
<td>November</td>
<td>3.564</td>
<td>3.850</td>
<td>1.429</td>
<td>1.198, 6.230</td>
<td>2.381</td>
<td>4.708</td>
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<td>December</td>
<td>-1.280</td>
<td>-1.202</td>
<td>1.912</td>
<td>-6.190, 2.840</td>
<td>-2.395</td>
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Table 2. Summary Statistics for Precipitation

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<th>Median</th>
<th>Standard Deviation</th>
<th>Range</th>
<th>First Quantile</th>
<th>Third Quantile</th>
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<tbody>
<tr>
<td>February</td>
<td>5.855</td>
<td>5.511</td>
<td>2.085</td>
<td>2.921, 10.979</td>
<td>4.310</td>
<td>6.979</td>
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<td>March</td>
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<td>5.337</td>
<td>1.740</td>
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<td>3.794</td>
<td>6.538</td>
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<tr>
<td>April</td>
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<td>4.268</td>
<td>1.898</td>
<td>1.660, 10.063</td>
<td>2.952</td>
<td>5.582</td>
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<tr>
<td>May</td>
<td>3.474</td>
<td>3.437</td>
<td>1.451</td>
<td>1.326, 6.271</td>
<td>2.136</td>
<td>4.617</td>
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<tr>
<td>June</td>
<td>2.807</td>
<td>2.497</td>
<td>1.466</td>
<td>0.620, 6.727</td>
<td>1.854</td>
<td>3.596</td>
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<td>July</td>
<td>2.459</td>
<td>2.294</td>
<td>1.268</td>
<td>0.526, 5.777</td>
<td>1.660</td>
<td>3.273</td>
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<tr>
<td>August</td>
<td>3.699</td>
<td>2.876</td>
<td>2.272</td>
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<td>September</td>
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<td>October</td>
<td>4.858</td>
<td>4.479</td>
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<td>2.885</td>
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<td>November</td>
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<td>5.123</td>
<td>2.252</td>
<td>2.377, 11.083</td>
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<td>December</td>
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<td>5.019</td>
<td>1.774</td>
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<td>4.252</td>
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Table 3. Summary Statistics for Streamflow

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<tr>
<th>Month</th>
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<th>Median</th>
<th>Standard Deviation</th>
<th>Range</th>
<th>First Quantile</th>
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<tbody>
<tr>
<td>January</td>
<td>0.1512</td>
<td>0.1216</td>
<td>0.1004</td>
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<td>0.1024</td>
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<tr>
<td>March</td>
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<td>0.1719</td>
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<td>0.2214</td>
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<td>0.0261</td>
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Table 4. Best Fit Probability Model

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<thead>
<tr>
<th>Months</th>
<th>Temperature</th>
<th>Precipitation</th>
<th>Streamflow</th>
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<td>Normal</td>
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<td>Lognormal</td>
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<tr>
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<td>Lognormal</td>
<td>Lognormal, Weibull</td>
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Table 5. Mann-Kendall Statistics (S) and Kendall Slope Estimates (Ks)

<table>
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<th>Month</th>
<th>Temperature</th>
<th>Precipitation</th>
<th>Streamflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>S -5</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td></td>
<td>Ks -0.0423</td>
<td>0.0411</td>
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<td>-3</td>
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Figure 1
Normal Probability Plot for Temperature in January

Figure 2
Lognormal Probability Plot for Precipitation in January
Figure 3
Lognormal Probability Plot for Flow in January

Figure 4
Normal Probability Plot for Temperature in February
Figure 5

Lognormal Probability Plot for Precipitation in February

Figure 6

Lognormal Probability Plot for Flow in February
Figure 7
Normal Probability Plot for Temperature in March

Figure 8
Lognormal Probability Plot for Precipitation in March
Figure 9
Lognormal Probability Plot for Flow in March

Figure 10
Normal Probability Plot for Temperature in April
Figure 11
Lognormal Probability Plot for Precipitation in April

Figure 12
Lognormal Probability Plot for Flow in April
Figure 13

Lognormal Probability Plot for Temperature in May

Figure 14

Weibull Probability Plot for Precipitation in May
Figure 15

Weibull Probability Plot for Precipitation in May

Figure 16

Lognormal Probability Plot for Flow in May
Figure 17
Weibull Probability Plot for Flow in May

Figure 18
Lognormal Probability Plot for Temperature in June
Figure 19

Lognormal Probability Plot for Precipitation in June

Figure 20

Weibull Probability Plot for Precipitation in June
Figure 21
Lognormal Probability Plot for Flow in June

Figure 22
Weibull Probability Plot for Flow in June
Figure 23

Lognormal Probability Plot for Temperature in July

Figure 24

Lognormal Probability Plot for Precipitation in July
Figure 25
Weibull Probability Plot for Precipitation in July

Figure 26
Lognormal Probability Plot for Flow in July
Figure 27

Weibull Probability Plot for Flow in July

Figure 28

Lognormal Probability Plot for Temperature in August
Figure 29
Lognormal Probability Plot for Precipitation in August

Figure 30
Weibull Probability Plot for Precipitation in August
Figure 31
Lognormal Probability Plot for Flow in August

ML Estimates
Location: -3.07733
Scale: 1.18080

Figure 32
Weibull Probability Plot for Flow in August

ML Estimates
Shape: 1.08053
Scale: 0.0796688
Figure 33

Lognormal Probability Plot for Temperature in September

Figure 34

Lognormal Probability Plot for Precipitation in September
Figure 35
Weibull Probability Plot for Precipitation in September

Millennials
Shape: 2.15888
Scale: 4.58730

Figure 36
Lognormal Probability Plot for Flow in September

Location: -2.81103
Scale: 1.09276
Figure 37
Weibull Probability Plot for Flow in September

Figure 38
Lognormal Probability Plot for Temperature in October
Figure 39
Lognormal Probability Plot for Precipitation in October

Figure 40
Weibull Probability Plot for Precipitation in October
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Lognormal Probability Plot for Flow in October

Figure 42
Weibull Probability Plot for Flow in October
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Normal Probability Plot for Temperature in November

Figure 44

Lognormal Probability Plot for Precipitation in November
Figure 45
Lognormal Probability Plot for Flow in November

Figure 46
Normal Probability Plot for Temperature in December
Figure 47

Lognormal Probability Plot for Precipitation in December

Figure 48

Lognormal Probability Plot for Flow in December
Figure 49

Mean Temperature in January

Figure 50

Mean Precipitation in January
Figure 51

Mean Flow in January

Figure 52

Mean Temperature in February
Figure 53

Mean Precipitation in February

Year

Figure 54

Mean Flow in February

Year
Figure 57

Mean Flow in March

Figure 58

Mean Temperature in April
Figure 59

Mean Precipitation in April

![Graph showing mean precipitation in April from 1952 to 1982.](image)

Figure 60

Mean Flow in April

![Graph showing mean flow in April from 1952 to 1982.](image)
Figure 61

Mean Temperature in May

![Graph showing mean temperature in May over years from 1952 to 1982.]

Figure 62

Mean Precipitation in May

![Graph showing mean precipitation in May over years from 1952 to 1982.]

Figure 65

Mean Precipitation in June

Figure 66

Mean Flow in June
Figure 71

Mean Precipitation in August

Figure 72

Mean Flow in August
Figure 73

Mean Temperature in September

Figure 74

Mean Precipitation in September
Figure 75

**Mean Flow in September**

![Graph showing mean flow in September from 1952 to 1982.](image)

Figure 76

**Mean Temperature in October**

![Graph showing mean temperature in October from 1952 to 1982.](image)
Figure 77

Mean Precipitation in October

Figure 78

Mean Flow in October
Figure 81

Mean Flow in November

Figure 82

Mean Temperature in December
Figure 83

Mean Precipitation in December

Figure 84

Mean Flow in December