Placing Potomac River Droughts in Context Using Synthetic and Paleoclimatic Data

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Abstract

Water supply planning for the Washington, D.C. metro area has historically been geared toward the worst drought conditions within the hydrologic record. Recent work expanded the planning context through use of a synthetic hydrology dataset developed using autoregressive models. Analysis using synthetic data and a forecast of 2025 demands showed only a slight chance of water supply shortages under drought conditions more extreme than the 1930-31 event—a 0.2% chance in any year, with only 6 days of shortages over the entire 540 year simulation. ICPRB is expanding the drought risk analysis in two ways. One is by performing statistical analyses on the outputs of water supply system simulations using the synthetic hydrology. These analyses will shed light on the severity and risk of the 1930-31 drought as well as the more severe droughts introduced by the synthetic dataset. ICPRB is also using reconstructions of climatic variables (e.g., Palmer Drought Index, precipitation) to expand the scope of drought risk analysis. Results using the synthetic data show drought risks to be slightly greater than would be estimated with the historical record. Quantitative results using the paleoclimatological data are highly uncertain but suggest the potential for extreme droughts if the basin were to shift into a dry hydrologic regime. Implications for planning and policy are discussed and directions for on-going work are described.

Introduction

Water supply for most of the Washington, D.C. metropolitan area (WMA) comes primarily from the Potomac River, with the nearby Patuxent and Occoquan Rivers serving as additional sources. Three WMA water suppliers draw from the Potomac: 1) the Washington Aqueduct of the U.S. Army Corps of Engineers, 2) the Washington Suburban Sanitary Commission, and 3) Fairfax Water. These water suppliers jointly own storage in Potomac River reservoirs and coordinate their operations in order to maximize reliability of the WMA water supply system. The Interstate Commission on the Potomac River Basin (ICPRB) serves as the primary technical and administrative lead for this coordination between the utilities, especially during times of drought. For details on how the WMA water supply system is managed see Hagen et al (2005) and ICPRB (2005).

Water supply planning for the WMA was traditionally geared toward the drought of record, generally held to be the 1930-31 event. The drought of 1966 resulted in the lowest recorded flow, but the duration of the 1966 drought was shorter than the 1930-31 drought. Every five years, ICPRB evaluates the reliability of the water supply system using 20-year demand forecasts and a simulation model based on a hydrologic dataset going back to 1929 (Hagen et al 2005). Simulated performance under the drought of record serves as the primary benchmark for this evaluation, although the most recent study (ICPRB 2005) simulates performance using synthetic hydrology in addition to the historical simulation. Both the historical and synthetic simulations showed the WMA water supply system to be adequate for meeting forecasted 2025 demands.

In early 2002, conditions warned of the potential for a summertime low flow situation more severe than those experienced in the 1930s and 1960s. The basin experienced below normal precipitation, record low groundwater levels and record low daily streamflows in the winter and spring of that year. While the 2002 event did require drought operations, it turned out to be less severe than the 1930-31 drought. However, this experience, coupled with the uncertainties of a changing climate, highlighted the need to evaluate the WMA water supply system against droughts more severe than those in the existing historical record. To that end, ICPRB developed a 540-year long synthetic hydrology dataset using autoregressive integrated moving average models (Kiang & Hagen 2004). This approach preserves the basic statistical properties of recorded data (such as mean and autocorrelations), but essentially expands the sample size resulting in events more extreme than those captured in the recorded dataset (Salas et al 1980; Hirsch 1979). The reliability of the WMA water supply system was tested using this synthetic dataset and several demand forecasts. The extreme events of the synthetic dataset taxed the WMA water supply system more severely than recorded droughts, but the analysis showed the system to be quite robust. In one demand scenario, there were only 6 days of water supply shortages (requiring demand reduction actions) throughout the entire 540-year simulation, and no system failures (see ICPRB 2005 for a full report on these results).





The results of this evaluation suggest that the WMA water supply system is adequate for meeting water supply demands even under drought conditions more severe than what is captured in recorded data. This is an important result because it suggests that in the short-term (perhaps 5 to 10 years) there is little need to begin planning for additional water supply storage to serve the WMA. But questions remain. Just how severe was the 1930-31 drought and what can be said about the likelihood of such an event occurring in the future? How severe are the events contained in the synthetic hydrology dataset and what is their likelihood of occurring? How often can we expect the WMA system to require drought operations? Analyzing streamflow and reservoir storage results from both the historical and synthetic simulations can help address these questions.

The synthetic hydrology described above is based on the statistical patterns of the recorded dataset. Therefore, its use incorporates an implicit assumption that climatic conditions over the last 75 years will continue through the planning horizon. What if climate change over the next several decades has a significant impact on Potomac River hydrology? What kinds of drought events should we expect under different climate conditions? Paleoclimatologic data may provide insights into these issues. Paleoclimatology is the study of climate in times before formal instrumental records were kept (NOAA 2006). Paleoclimatologic data include reconstructions of hydrologic measures based on tree-ring chronologies, sediment samples or other

measures. These reconstructions can be used in a number of ways to shed light on current and future drought risks for a water supply system.

This paper describes initial work to address some of the questions posed above using both the synthetic hydrology developed by ICPRB and publicly available paleoclimatologic data. Results using the synthetic hydrology are used to estimate the probability and severity of historical droughts and the implications this may have for the WMA. Relationships between paleoclimatologic reconstructions and drought metrics for the WMA are investigated. These relationships are used to make some broad statements about long-term drought risk for the WMA and to chart future directions for additional work in this area.

Methods and Data

Simulation Model ICPRB has developed and maintains a detailed simulation model of the Potomac Basin and WMA water supply system—the Potomac Reservoir and River Simulation Model (PRRISM). The model simulates WMA water demands, reservoir operations, and resulting river flows on a daily timestep. PRRISM can be run with the historical dataset spanning 1929 to 2002, or with the 540-year synthetic dataset. PRRISM's output includes daily flows at Little Falls, reservoir releases, and reservoir storage. The model was used to generate much of the data discussed in this paper, especially for the 540-year synthetic dataset. A description of PRRISM can be found in ICPRB (2005).

River Flow Data Daily average Potomac River flow at Little Falls (Figure 1) was a primary focus of much of the analyses described here. Flows at Little Falls are directly and measurably affected by several human activities. First, all the WMA water supply withdrawals are taken upstream of Little Falls and returned to the river as wastewater treatment effluents downstream of Little Falls. In addition to publishing gage flow records at Little Falls, USGS adjusts the gaged Little Falls flows to add these withdrawals back into the streamflow record, creating an "Adjusted" streamflow record for Little Falls. Therefore, the Adjusted Little Falls data represent flows that would have occurred in the absence of withdrawals. Second, several reservoirs in the Potomac basin alter the natural flow patterns, usually skimming high flows in spring and augmenting low flows in the summer. A more natural flow series is desirable for this analysis because it will more accurately reflect the severity of a given drought, especially during summer low flows. Therefore, the Adjusted Little Falls flow data were further adjusted to remove the impact of upstream reservoir regulation. This was done based on the area adjustment method, using data on reservoir inflows, outflows, drainage areas and assumed time of travel from the reservoirs to Little Falls. The resulting Little Falls natural flow dataset is in million gallons per day (MGD) and covers March 1, 1930 to September 30, 2002.

As mentioned above, ICPRB has developed a synthetic hydrologic dataset. This dataset includes inflows at all the reservoirs and inflows to the Potomac river reach

where the WMA water supply intakes are located. The synthetic data are used in PRRISM, which calculates natural flows at Little Falls in a manner similar to that described above. Therefore, the stochastic and historical Little Falls datasets are comparable.

Reservoir Storage Data Most of the reservoirs in the WMA water supply system were constructed in the early 1980s. Therefore, the record of actual storage in these reservoirs does not cover the two worst droughts on record. In addition, the existing storage records are based on different reservoir operational strategies at different points in time. PRRISM is used to remedy both of these problems—it produces storage data covering the entire period of record and uses the operational strategies that are currently in use today. Using PRRISM, daily storage values were simulated for all of the water supply reservoirs in the entire WMA system, and these were summed to create a daily data series of total system storage in millions of gallons (MG) covering 1930 through 2002. As mentioned above, PRRISM can be run with the 540-year synthetic dataset as well, resulting in 540-year datasets of reservoir storage.

Measures of Drought Severity The severity of a drought can be measured in a number of ways. This paper relies primarily on two metrics to analyze drought risk on the Potomac River: the minimum annual flow at Little Falls, and the minimum annual total system reservoir storage. Both of these metrics are calculated using the datasets described above.

Tree Ring Reconstructions A wide variety of tree ring reconstructions are available from the Paleoclimatology program of the National Climatic Data Center (http://www.ncdc.noaa.gov/paleo/paleo.html). These reconstructed datasets include several measures that could be useful for analyzing long-term drought risk in the Potomac River basin: precipitation, streamflows, lake levels, Palmer Drought Severity indices, and sea surface temperatures. The possibility of developing quantitative relationships between each of these reconstructed measures and Potomac flow and storage metrics was explored. Unfortunately, none of the reconstructed streamflow and lake level datasets are for water bodies in the greater Potomac region, so they are not likely to have a strong relationship with the Potomac River hydrology and were not explored. Only one of the precipitation reconstructions covers the Potomac region, but the data are described as unreliable by the author (Fritts, 1991). Analysis of this reconstructed precipitation dataset by ICPRB showed very weak correlations with Potomac flow metrics, so analysis of the reconstructed precipitation dataset was discontinued.

There are number of reconstructions of the Palmer Drought Severity Index (PDSI). One of these reconstructions provides summer PDSI values for the entire U.S. at 286 grid points (Cooke et al, 2004; see <u>http://www.ncdc.noaa.gov/paleo/newpdsi.html</u> for a map). Six grid points from this dataset are close to or within the Potomac River basin (see Figure 2). Each of these 6 grid points was tested for its relationship to Potomac River drought metrics using instrumental PDSI values (i.e., based on actual

recorded data for 1900-2002) for each point. The PDSI data were correlated with the Potomac metrics described above. The strongest relationship is between summer PDSI values for node 255 (enlarged dot in Fig. 2) and annual minimum Potomac River flow at Little Falls. Figure 3 shows a plot of this relationship. A linear relationship was fit to these data and was used to reconstruct Potomac River flow statistics (described in subsequent sections).









Analysis Using Synthetic Data

The synthetic data were used to generate statistical distributions of drought metrics that can be compared with values of these same metrics for historical droughts. For example, Figure 4 shows the cumulative distribution function of annual minimum total system reservoir storage based on PRRISM output using the synthetic input data and forecasted 2025 demands. In addition, Figure 4 shows where historical drought events fall in this distribution. Figures 5 shows a similar graph but for the annual minimum natural flow at Little Falls. The distribution in Figure 5 is also based on the synthetic dataset and individual points are shown for actual drought events.

Together, the results shown in Figures 4 and 5 provide useful insights. From one perspective, the drought of 1966 is the worst drought on record because it results in the lowest Potomac River flows, as shown in Figure 5. The drought of 1966 was a severe drought but not a very long drought—1966 flows result in 55 days of deficits relative to average monthly 2025 demands. The drought of 1930 was not quite as severe in terms of low flows, but it was much longer, resulting in 121 days of deficits relative to 2025 demands. Because of this, the drought of 1930 depletes reservoir storage much more than the drought of 1966 and has been cited as the "drought of record" for this system (Hagen et al., 2005).

Based on a simulation using the historical streamflow record, the drought of record is estimated as a 1-in-74 year event (i.e., a .0135 probability). The synthetic dataset is a statistically feasible expression of the historical flows and provides another way of estimating the probability of drought events. Comparing the minimum storage resulting from the 1930 drought to the distribution of annual minimum storage generated using the synthetic data shows the probability of the 1930 drought to be about .0155, or about a 1 in 65 year event. So a drought event of this nature may be slightly more likely than estimates from the historical record would suggest, though the difference is quite small.

Beyond the probability of the most extreme events, this analysis also provides information about the occurrence of smaller droughts. To date, water supply augmentation from WMA reservoirs has been required only twice (in 1999 and 2002) since the utilities began their cooperative relationship in 1981. Simulations using the historical record of hydrology (1929 to 2002) suggest that 2025 demands result in a 20% probability of drought operations in any given year. With the larger synthetic dataset, the probability of drought operations with 2025 demands is nearly 30%.

This estimated probability of drought operations could be significant. Drought operations for the WMA system do impose some costs. One such cost is an increase in pumping costs because one utility must switch to a different intake during droughts in order to maintain in-stream flows in that reach of the river. Drought operations may also impose a cost because of increased staff time at the utilities and ICPRB, which takes staff time away from research projects and other commitments. Figure 4: CDF of annual minimum storage using synthetic model runs



<u>Figure 5</u>: CDF of annual minimum natural flow at Little Falls using synthetic model runs



There will, however, be other costs that may warrant further consideration. The reservoirs in the Potomac basin and the stream reaches just below the reservoirs serve as significant recreational resources for the local regions. Though they were not built with this purpose in mind, the reservoirs can impact recreation significantly. More

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frequent drought operations means that these reservoirs will be drawn down during the summer and fall more often. It is possible that this will have a significant economic impact on the affected regions.

It is also possible that more frequent drought operations will elicit a public response from affected user groups. In 1999, one of the reservoirs was used for water supply for the first time since it had been built. The resulting drawdown did result in some negative public response from recreational groups and homeowners around the reservoir. Communications have improved since the 1999 drought helping to mitigate public responses to the use of the reservoir. However, if drawdowns at this or other reservoirs become more frequent, public stakeholders may become more vocal about the issue. This possibility simply highlights the need to continue developing positive working relationships between water managers in the WMA and other user groups within the Potomac basin, and maintaining clear communication channels to educate the public and elected officials about drought operations.

In addition to the potential impact on recreation, increased drought operations for the WMA water supply system has implications for regional drought management plans. For example, the drought management plan from the Metropolitan Washington Council of Governments (MWCOG, 2001) recommends voluntary water restrictions for the region when water supply storage in the Potomac basin drops below 60% of capacity for five consecutive days. Analysis of PRRISM runs using the synthetic data suggests that there is a small chance of this occurring with forecasted 2025 demand (perhaps a 1-2% chance in any year; see ICPRB 2005 for more details). This drought management plan is relatively new and still evolving. The results of these synthetic model runs can continue to inform policy-makers as regional drought management strategies are modified and improved.

Reconstructing Annual Low Flows at Little Falls

As shown in Figure 3, summer PDSI values for node 255 have a 0.72 correlation ($R^2 = .523$) with annual minimum natural flow at Little Falls. A linear function was fit to the data. The resulting equation describing annual minimum flow at Little Falls as a function of summer PDSI is shown below.

$$F_t = 1147.75 + 230.70P_t$$

Where F_t = annual minimum flow at Little Falls in year t; and P_t = average summer PDSI at node 255 in year t.

The equation fits the data well, as shown by the following statistics.

 $R^2 = .523$ Adjusted $R^2 = .516$ Standard Error = 368.8 This equation was used with the reconstructed PDSI dataset to backcast, or reconstruct, annual minimum flows at Little Falls back to the year A.D. 367. Figure 6 shows a plot of this reconstruction for 1930-2002, along with the actual annual minimum flows for that period. The model mimics actual events well, closely tracking actual data for most of this period. There does not appear to be a bias in low flow predictions: in some years the model does predict lower flows than actually occurred(1936, 1991, 1999), but in some years it predicts higher flows than actually occurred (1964, 1965, 1966, 1930)



Figure 6: PDSI-based reconstruction model vs actual flows for 1930-2002

Figure 7 shows the entire reconstruction of annual minimum flows based on the PDSI reconstruction. The heavy, dashed line on Figure 7 is the all time minimum natural flow at Little Falls, which would have occurred in 1966 in the absence of water supply withdrawals (recall that the flow data used here are adjusted to account for water supply withdrawals). The reconstructed dataset falls below this all time minimum flow in 21 of the 1,637 years.

The absolute lowest flow predicted by this reconstruction model is about 92 MGD. This could be a catastrophic event (depending on how long this magnitude of low flow persisted) as it is below the in-stream flow requirement *before* water supply withdrawals and such an event would quickly deplete reservoir storage. There is a good deal of uncertainty around this number because of error in the original PDSI reconstruction and error in the flow reconstruction. Ignoring the uncertainty associated with the PDSI reconstruction itself, the uncertainty from the regression of annual minimum flow onto the reconstructed PDSI values produces a wide range of potential predictions. For example, the 95% prediction interval for the 92 MGD

minimum flow example noted above results in a range of approximately 0 to 982 MGD. In general, the regression presented above provides a good fit. However, the large uncertainties make it difficult to draw hard conclusions from the reconstructions.





The PDSI-based data do suggest that there have been periods in which Potomac River hydrology was much drier than it has been over the last several decades. A plot of the moving average (Figure 8) of the annual minimum flow reconstruction points to some of these periods. The 10-year moving average (the light dotted line in Figure 8) indicates that there have been several periods during which conditions were much drier than anything seen in the historical record (e.g., the mid 1500s; 1840-1900). It is possible that these periods of the reconstruction represent droughts much more severe than those in the historical or synthetic dataset.

The 50-year moving average (the dark line in Figure 8) points to longer term changes in the hydrologic regime (as measured here by the moving average of the annual minimum flow). Figure 8 includes the overall average for the entire reconstructed dataset (the dark dotted line). The 50-year moving average suggests that the 20th century was a wet one and work by Lins and Slack (1998) indicates that the Mid-Atlantic (as well as other regions) has been getting wetter since about 1940. Does this suggest a lower risk of extreme droughts over the next several decades? That is a difficult question to answer. Most of the lowest values for the reconstructed minimum flows occur during dry regimes, but some of them closely follow wet periods. For example, 1635 is the 3rd lowest annual minimum of the reconstructed dataset and it occurs in a period during which the 50-year moving average indicates a

dryer-than-average period. But that extreme low flow of 1635 comes just three decades after the 50-year moving was in a wet period. The findings coincide with work done by Cook and Jacoby (1983) on Potomac River flows at Point of Rocks, about 40 miles upstream of Little Falls. This result raises a question for water planners. Should future water supply alternatives be evaluated in terms of how well they could address the possibility of shifting into a lower flow regime? While this research does not answer the question, it certainly raises the issue.



Figure 8: Moving average of the flow reconstruction

Discussion and Conclusions

ICPRB's synthetic dataset and the PRRISM runs based on the synthetic data both offer a wealth of information about drought risk for the WMA water supply system. These data can be used in a number of ways to estimate drought probabilities for this region. This paper presented a few approaches for making these estimates but the analysis could be expanded based on other methods in the literature.

Reliability is ultimately the most important issue facing planners, but knowledge of the frequency of droughts is important as well, because events that require reservoir drawdowns and other actions will impose some costs. A primary reason for developing a synthetic dataset is to test a water supply system against drought conditions more severe than those captured in the historical record. ICPRB's synthetic dataset was used to perform this kind of test and the WMA water supply system was shown to be quite robust under drought conditions much more severe than any in the historical record (ICPRB 2005). The dataset can be used to answer additional questions. The analysis presented here suggests that a drought event

similar to that experienced in 1930 has a slightly higher probability of recurring than would be estimated using only the historical data, and that drought operations may be more frequent than indicated by the hydrologic record. The stochastic streamflow record suggests that in 20 years, we would expect drought operations to be needed approximately 3 out of 10 years on average. This is significant, because since the cooperative system was developed for the WMA in the early 1980s, drought operations have been needed only twice (1999 and 2002).

There is little doubt that the global climate is changing. ICPRB (2005) used sensitivity analysis to explore how warmer, drier conditions might affect both water demand and available supplies and investigated how these changes might affect reliability of the water supply system. Climate change forecast scenarios, which can inform this kind of analysis, project different changes for the eastern U.S. and it is not clear which of these is most likely. The climate has changed in the past as well. Data about past changes at the local level might suggest how the climate may potentially change in the future. Paleoclimatological reconstructions might provide this kind of information.

Cook and Jacoby (1983) reconstructed Potomac River flows at Point of Rocks (about 40 miles upstream of Little Falls; see Fig. 1) back to 1730. Their analysis indicated several severe droughts on the Potomac River, especially an extended period from 1850 to 1873. The authors concluded that 1) Potomac River hydrology oscillates between wet and dry periods on the order of every 10 to 15 years; 2) except for the 1960s, summer flows in the 20th century were generally above median; and 3) the series of low flows during the 1960s have not been surpassed since 1730.

In this paper, a reconstruction of summer PDSI values based on tree rings was explored for its relationship to Potomac River drought metrics. Predictions of annual minimum Potomac River flow based on this PDSI reconstruction suggest that there were droughts much more severe than those captured in the historical record. However, the uncertainty of this relationship makes it difficult to draw firm conclusions. It is possible that better estimates could be made by adding other predictive variables to the regression, such as lake levels (only available for lakes outside the Potomac region), sea surface temperature, or perhaps regional temperatures. Reconstructing Little Falls flows directly from tree ring chronologies may also improve accuracy.

It is possible to draw a few general conclusions from the analysis of the reconstructed annual minimum flows. The data do suggest that there have been extended periods of time during which conditions were much dryer than anything experienced in the last 100 years or so. The period of 1866 to 1900 is particularly interesting because the streamflow reconstruction can be verified with recorded precipitation data. The moving average data suggest that the Mid-Atlantic has been in a wet hydrologic regime for the last several decades. This might lead us to believe that risk of extreme drought is relatively low now and may continue to be low over a 20 or 30 year planning horizon. However, the data also indicate that changes from wet to dry

regimes can occur over a few decades and extremely dry years can come very quickly after a wet period. These results coincide with the work done by Cook and Jacoby (1983).

The findings here suggests the need for continued vigilance in planning for drought in the Washington, D.C. region. Climate change may bring dryer or wetter conditions. Improved knowledge about those potential outcomes can suggest if planners need to consider the possibility of extreme droughts in the region. This is an additional direction for future work.

The detailed synthetic streamflow data developed by ICPRB has proved to be quite useful for water supply planning for the WMA. It has increased our confidence in the long-term reliability of the system and is improving our understanding of drought risk, as demonstrated in this paper. These data are utilized further to support operational planning and other activities. The paleoclimatological data offers a broader context for WMA drought risk. Unfortunately, the quantitative relationships between paleoclimatological reconstructions and river flows do not allow for any precise and certain predictions about drought risk. However, they do suggest the potential for drought conditions more severe than the WMA system is designed for, indicating a need for thoughtful planning.

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