International Conference on Hydroinformatics

8-1-2014

Delaware Reservoirs' Drought Risk Assessment: A Paleo View

Naresh Devineni

Gokce Ceylan

Recommended Citation

Devineni, Naresh and Ceylan, Gokce, "Delaware Reservoirs' Drought Risk Assessment: A Paleo View" (2014). *CUNY Academic Works.*
http://academicworks.cuny.edu/cc_conf_hic/340

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

DELAWARE RESERVOIR'S DROUGHT RISK ASSESSMENT: A PALEO VIEW

NARESH DEVINENI, GOKCE CEYLAN
Department of Civil Engineering, City University of New York (City College), USA

The Delaware River provides half of New York City's drinking water, is a habitat for wild trout, American shad and the federally endangered dwarf wedge mussel. A drought during the 1960s stands as a warning of the potential vulnerability of New York City to severe water shortages. The water releases from three New York City dams on the Delaware River's headwaters impact not only the reliability of the city's water supply, but also the potential impact of floods, and the quality of the aquatic habitat in the upper river. The Delaware water release policies are constrained by the dictates of two US Supreme Court Decrees (1931 and 1954) and the need for unanimity among four states: New York, New Jersey, Pennsylvania, and Delaware, and New York City. Coordination of their activities and the operation under the existing decrees is provided by the Delaware River Basin Commission (DRBC). Questions such as the probability of the system approaching drought conditions based on the current Flexible Flow Management Plan and the severity of the 1960s drought are addressed using long record paleo-reconstructions of flows. For this study, we developed reconstructed total annual flows for 3 reservoir inflows using regional tree rings going back upto 1754 (a total of 246 years). The reconstructed flows are used with a simple reservoir model to quantify droughts. We observe that the 1960s drought is by far the worst drought based on 246 years of simulations (since 1754). However, there are intermediate drought warning periods and proper adaptation would be sufficient during these periods. Modified release rules that aid thermal relief to wild trout in the upper Delaware can be explored without much stress to the system during most periods.

INTRODUCTION

The upper Delaware River Basin System which supplies the city of New York is one of the largest urban water supply systems. With a cumulative storage capacity of 1.5 Billion m^3 from major reservoirs, the Delaware River Basin supplies about 3 Million m^3/day for the consumptive water use to the city of New York. The Delaware River Basin Commission (DRBC) along with the New York City Department of Environmental Protection is primarily responsible for managing the releases from the major reservoirs to meet the daily water demand of the city of New York and to maintain downstream ecosystem [1]. Quantitative evaluation of these reservoir systems (for example, reservoir rule curves and estimation of return periods of extreme events) is based on relatively short historical records of data. Given that the drought of record in the basin was in the 1960s, it is not clear that these records can accurately represent its return period or provide guidance for effective drought preparation and system operation.

Reconstruction of streamflow records using proxy information such as tree ring data can provide crucial information for robust long term planning of such reservoir systems. Reservoir operating rules could be improved with better understanding of long term risks and methods to detect changes in climate/streamflow regime. Numerous studies have focused on the use of tree-ring widths for developing proxy climatic and hydrologic series using traditional regression techniques [[2], [5], [3], [4]]. These traditional methods of reconstructing streamflows using tree ring data develop a regression model fit to the observed streamflow with the tree ring chronology as predictors. The streamflow data in the paleo period are obtained using the estimated regression coefficients (model parameters) on the historical tree ring scores. The paleo-reconstruction process often considers multiple proxies and multiple hydroclimatic records to be reconstructed. The resulting multivariate regression problem can be high dimensional leading to difficulties in accurately estimating parameter uncertainty and model structure and hence properly characterizing the joint distribution of the target variables. To address this issue, recently, [6] developed a Hierarchical Bayesian Regression model for simulating the posterior probability distribution of the regression coefficients and streamflow values at multiple locations using tree ring chronologies in the upper Delaware River Basin.

The tree ring chronologies represent the annual growth cycle of the trees resulting from less dense (inner portion) early-wood formation during the photosynthetically active growing season (late spring and summer) and the more dense (outer portion) late-wood formation during the fall and winter. These chronologies vary in size each year depending upon the regional climate phenomena. Consequently, the tree rings (measured as the width of early-wood plus late-wood) are wider during years with greater moisture availability and narrow during drought years. Hence, analogous to streamflow, the growth index is an integrator of moisture and energy availability in the region. This commonality between annual growth index and streamflow enables us to develop predictive models that can be used to understand the long term variability of the climate in the region. We developed reconstructions of the annual streamflows over the three major reservoirs (Canonsville, Neversink and Pepacton) in the upper Delaware River Basin using the eight annual tree ring chronologies as predictors to reconstruct the annual flows in the reservoirs. Details of this model and the verification results can be found in [6]. In this study, we utilize these long run streamflow simulations to better quantify the drought risk for the three main water supply reservoirs for the New York City.

NYC WATER SYSTEM DETAILS

Figure 1 shows the operational rule curves for the combined storage of the three reservoirs. L1 curve represents the flood control zone and the three zones, L3, L4 and L5 represent various drought watch zones. These indicators are used to maintain adequate storage in the reservoirs for reliable water supply for NYC. The downstream releases and the water supply for NYC are determined based on the daily combined storage. Seasonal release rates for the reservoirs can be found in the Delaware River Basin Commission’s Flexible Flow Management Plan (FFMP) [1]. Water releases from the dams are made according to the Supreme Court decree which allows NYC to divert from the dams, upto 800 million gallons per day for water supply, as long as a minimum flow requirement of 1750 cfs is maintained at Montague, NJ downstream of the dams. These operating rules governing water management rely on performance testing using the 1960's drought of record as the standard. While performance of a release policy during the hydrologic conditions of the 1960's drought is an important metric, based on impacts on fisheries during summer low flow periods in recent dry years, some have raised questions about the wisdom of reservoir operating policies that are designed primarily to avert the 1960's drought risk [7]. Ideally, an alternative set of operating policies would seek to optimize performance under normal or trending-dry conditions while adequately protecting Basin water supplies in case of occurrence of an extreme drought. Hence, for planning purposes it is important to understand the risk of occurrence and severity of the "planning drought". In this study, we use the paleo-reconstructed streamflow data with a simple reservoir model to quantify the drought risk for the system.

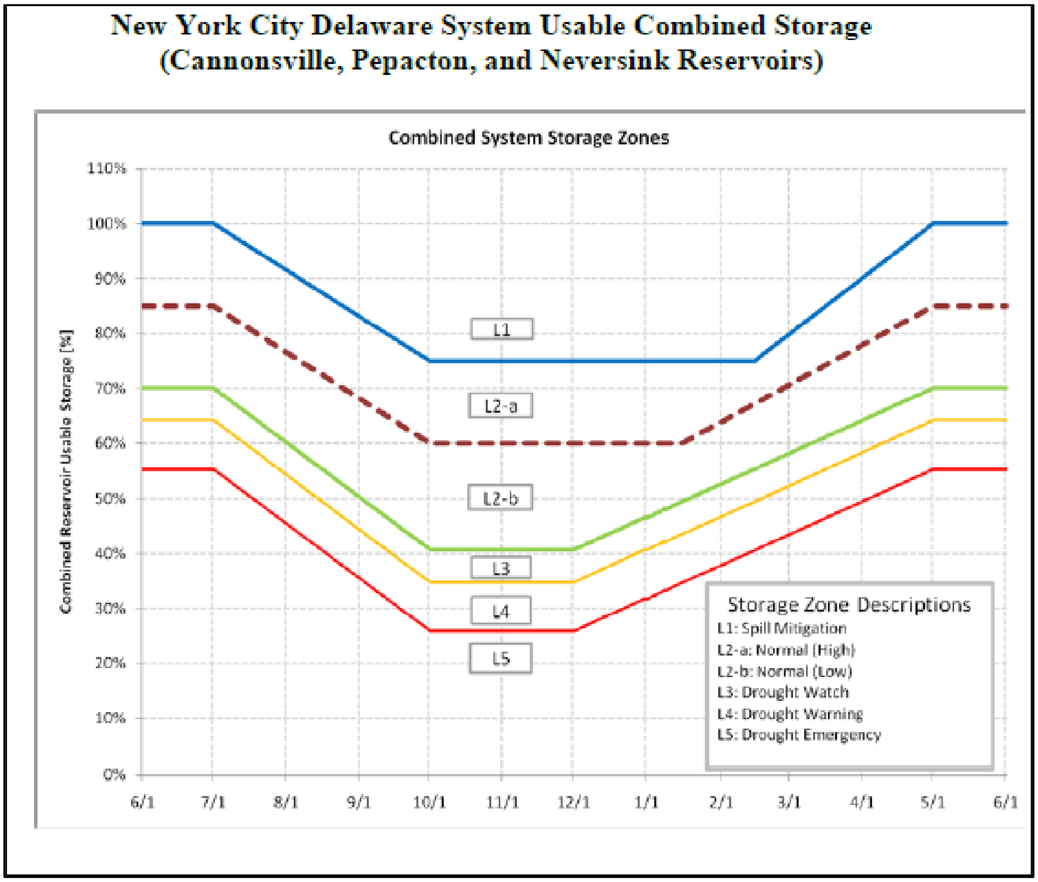

Figure 1. Storage zones and rule curves for the NYC Reservoir System.

RESERVOIR MODEL FORMULATION AND ANALYSIS

A simple reservoir mass balance model is formulated using the basic continuity equation for each simulation *i* and day *t* as follow:

$$S_t^i = S_{t-1}^i + Q_t^i - E_t^i - \left(Div_t^i + Con_t^i + Dir_t^i\right) \tag{1}$$

where S_{t-1}^{i} and S_t^i are initial and current combined reservoir storage, Q_t^i is the reconstructed flow, E_t^i is the daily evaporation, and Div_t^i, Con_t^i, Dir_t^i are the directed releases for NYC water supply, conservation releases for ecological health and directed releases to maintain 1750 cfs at Montague respectively. The storage equations are constrained between minimum storage of 0 and a maximum storage of $S_{\max}$.

$$0 \leq S_t^i \leq S_{max} \quad (2)$$

In the event, the daily storage falling below the minimum storage, we encounter deficit

$$Deficit_t^i = -S_t^i \; \forall \; S_t^i < 0 \quad (3)$$

In the event, the daily storage exceeds the maximum storage capacity, we observe spill

$$Spill_t^i = S_t^i - S_{max} \; \forall \; S_t^i > S_{max} \quad (4)$$

Daily evaporation, E_t^i, is computed as a function of initial storage

$$E_t^i = \psi_i \sqrt{S_{t-1}^i} \quad (5)$$

where ψ_i is the daily lake evaporation rate after adjusting with the pan coefficient of 0.7. Looking across all the simulations, we compute the probability of daily storage less than different target storage levels -- L3, L4 and L5 (drought watch, warning and emergency) and the probability of daily storage greater than the refill target storage L2. $Prob(S_t < L3)$ is estimated from the number of simulations in which $(S_t \ < L3)$ out of the total number of simulations, 1000. Similarly $Prob(S_t > L2)$ is estimated from the number of simulations in which $(S_t \ > L2)$ out of the total number of simulations.

Prior to performing the retrospective reservoir analysis using the reconstructed streamflow, model verification was performed from 1982 to 2000 (for which the actual daily reservoir storage is available) by comparing the model's ability to simulate the observed daily storages. Observed flows and reported releases from 1982 to 2000 were used as forcings for the model to verify the mass balance and its ability to reproduce storage levels. Figure 2 shows the observed and model predicted daily storages. Fig. 2 clearly shows that the simple reservoir model is quite reasonable in predicting the observed storages upon simulating with observed flows and reported releases. This gives the confidence in employing the simulation model presented here for further analysis that utilizes the reconstructed flows for assessing drought risk.

Given the reconstructed streamflow simulations and the initial storage conditions, we estimated the $Prob(S_t < L3)$, $Prob(S_t < L4)$ and $Prob(S_t < L5)$ that would result upon releasing water from the three dams according to the FFMP tables. Figure 3 shows the estimates of these probabilities and the tercile probability indicators at 0.33 and 0.67. Figure 3 clearly shows that the estimates of the $Prob(S_t < L3)$, $Prob(S_t < L4)$ and $Prob(S_t < L5)$ from reconstructed streamflows are above 66% during the 1960s indicating a greater than normal probability of the reservoir being under drought watch, warning or emergency. This is perfectly in line with the expectations that the probability of not maintaining minimum storage will be high during drought conditions.

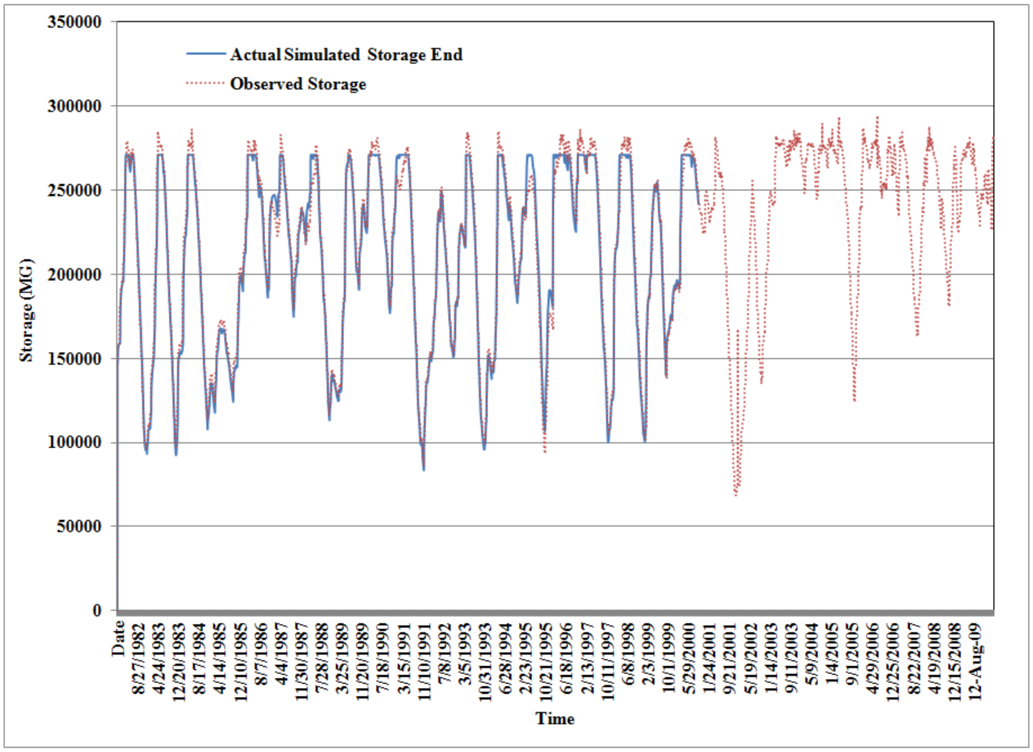

Figure 2. Comparison of daily model storages with observed storages from 1982 – 2000.

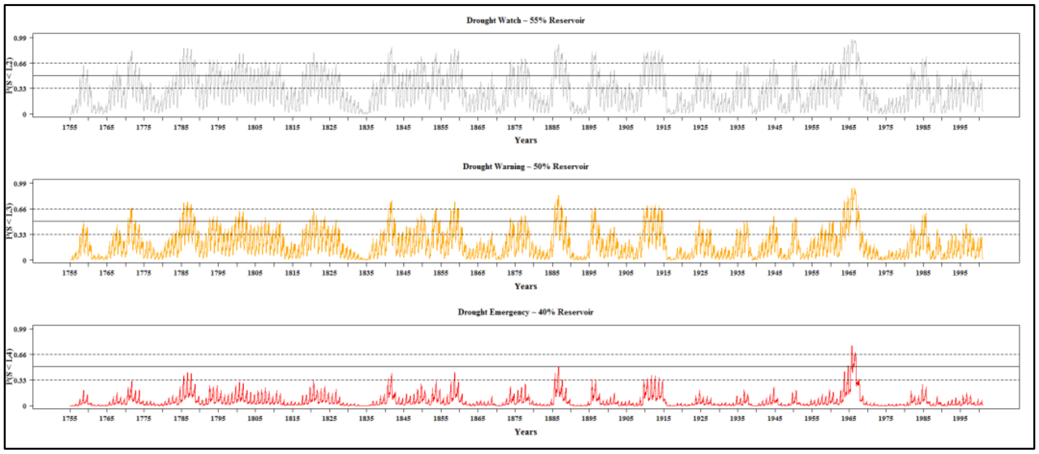

Figure 3. Probability estimates obtained from the reservoir model forced with reconstructed streamflow simulations and FFMP releases.

A perusal of probabilities across all the years going back to 1754 indicates that while the probability of the reservoir system being under drought watch or warning is above the climatological level, there is only a moderate probability of the reservoir system being under drought emergency ($Prob(S_t < L5)$. This indicated that the risk of severe sustained drought is low and can be effectively managed using operational adaptation options. While the drought of the 1960's was the worst drought over the 247 years for the upper Delaware Basin based on duration below drought thresholds, the likelihood of a similar drought reoccurring cannot be completely undermined.

In addition to estimating the probability of the reservoir system being under drought watch, warning or emergency, we also estimated the probability of the reservoir refill every year by June 1st. This is important, as one of the operational mission of the FFMP release rules is to ensure that the reservoirs are full to capacity at the beginning of the summer season. Recent research shows that the current rules may be effective at ensuring NYC's water supply but are over conservative and impact the fisheries during summer [7]. Further, since the FFMP rules are designed to keep the reservoir at near to full capacity, it leads to periodic spills which are negatively impact downstream residents. Figure 4 shows the estimated probability of reservoir refill on June 1. Here, we define probability of refill as the likelihood of the daily storage being greater than the L2 normal zone level ($Prob(S_t > L2)$).

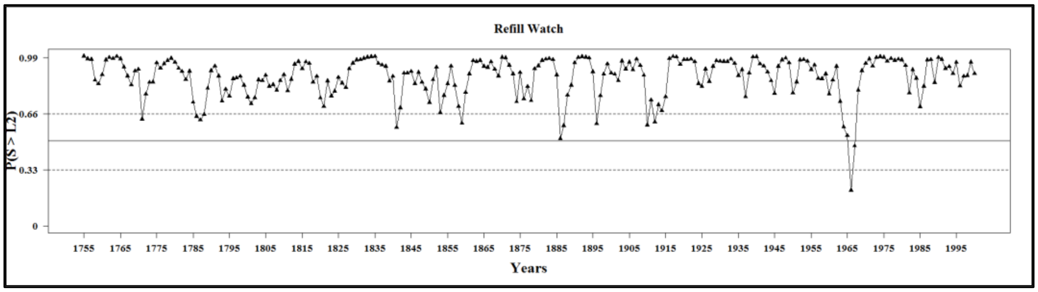

Figure 4. Probability of reservoir refill every year on June 1st.

Figure 4 shows that the probability of reservoir refill during the 1960s drought is low as expected during a run of deficit years. Across the years, we see that there is a greater than 66% probability of the reservoirs refilling by June 1st. The 1912-14, 1880s -1885s, 1785s appear to be other periods of interest. Hence, the simulations provide the ability to analyze reservoir fill and drain probabilities as a function of drought intermittence and recurrence.

SUMMARY

The reconstructions provided insights in to the probability of moderate to severe sustained droughts in the region based on the current release plans. We observe that the 1960s drought is by far the worst drought based on 246 years of simulations (since 1754). There are intermediate drought warning periods; however, acute stress periods are rare. Proper adaptation would be sufficient during these periods. There is a high probability of reservoirs refilling to normal zones by June 1 during most of the years. Probability of spills over these periods reveal that the current FFMP releases can be understood as conservative. Modified release rules that aid thermal relief to wild trout in the upper Delaware can be explored without much stress to the system during most periods.

REFERENCES

[1] *DRBC, Flexible Flow Management Program, http://www.state.nj.us/drbc/FFMP/index.htm. (2007).*

[2] *Stockton, C. W., and G. C. Jacoby., "Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin based on treering analyses". Lake Powell Res. Proj. (1976), Bull. 18, 70 pp., Res. Appl. to Natl. Needs, Natl. Sci. Found., Arlington, Va.*

[3] *Meko, D. M., C. A. Woodhouse , C. H. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer., "Medieval drought in the Upper Colorado River Basin", Geophys. Res. Lett. 34(10, L10705), (2007), 10.1029/2007GL029988*

[4] *Woodhouse, C. A., S. T. Gray, and D. M. Meko, "Updated streamflow reconstructions for the Upper Colorado River Basin", Water Resour. Res., (2006) 42, W05415, doi:10.1029/2005WR004455.*

[5] *Cook, E.R., and G. Jacoby, "Potomac River streamflow since 1730 as reconstructed by tree rings", J. Clim. Appl. Meteorol., (1983) 22, 1659–1672.*

[6] *Devineni, N., U. Lall, N. Pederson, and E. Cook., "A tree ring–based reconstruction of Delaware River basin Streamflow using hierarchical Bayesian regression", J. Climate, (2013), 26, 4357– 4374.*

[7] *Kolesar, P. and J. Serio., "Breaking the Deadlock: Improving Water-Release Policies on the Delaware River through Operations Research", Interfaces, (2011), 41(1): 18-34.*