Water Resource Management Under Changing Climate: Role of Seasonal Forecasts

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WATER RESOURCES IMPACT

WATER RESOURCE MANAGEMENT UNDER CHANGING CLIMATE: ROLE OF SEASONAL FORECASTS

Upmanu Lall and F. Assis De Souza Filho

Continuing concern regarding global climate change underscores something that has been intuitively understood by many for quite some time. Climate has an epochal nature. In a given river basin, climate and hence water availability may vary greatly in a given decade or century. Given the dramatic and systematic variability of climate over such time scales, it may be difficult to attribute regional trends completely or largely to CO_2 forced global climate change. On the other hand, an improved understanding of phenomena such as the El Niño Southern Oscillation is making it possible to better understand both the inter-annual variations in climate and their regional effects in a large part of the world. In many cases, seasonal and longer forecasts of streamflow that use such climate information may provide a new tool for water resources management that allows adaptation to changing climate. This article illustrates this point through an example.

The example we consider is drawn from the state of Ceara in Northeast Brazil. Ceara is a semi-arid tropical region with a rainy season that lasts from January to June. The region is well known for the widespread impacts of drought. During 1877 to 1879, between 150,000 and 500,000 people are estimated to have died from water scarcity. Since the drought of the 1970s, extensive reservoir and irrigation network development has provided a certain measure of stability and resilience against drought. The reservoir system has enough storage to meet two to three years of municipal demand as well as seasonal irrigation demand for one to two years. The range of variation in the total annual rain or flow is dramatic from year to year. For instance, the historical (1912 to 2000) annual inflow at the largest reservoir, Oros, varies from 0 to 210 m^3/s with an average of 30 m^3/s, and a median annual flow (i.e., 50 percent of the time the flow is less than or greater than this value) of 16 m^3/s. As can be seen in Figure 1, the 11-year average (median) flow varies between 14 (7) and 46 (35) m^3/s over the 83 years of data shown. The rivers are dry in June through December. This is the irrigation season.

Is there a way to "share" the risk induced by uncertain future conditions, or by the use of a forecast . . .

The dramatic decadal and inter-annual variability in flows suggests that runs of wet and dry years dominate. Thus, reservoirs may be low for multiple years, intensifying competition between current and future irrigation and municipal uses. A reservoir operator may be motivated to use a cautious operating policy, which restricts irrigation use as reservoir levels drop. Unfortunately, given an evaporation rate that is approximately 2 meters/year, associated water losses can be substantial. At the same time, there is a chance that even in the midst of a dry spell, one may have an extremely wet year, leading to reservoir filling and spilling. If one could predict whether the next January to June will be wet or dry, then one could adapt the operating strategy from year to year, and be able to cope with changes in average (median) inflow that vary over a factor of 3 (5) in different decades. Thus, even if fairly substantial climate changes were imposed on the region, one could have a strategy for adapting the operation of existing resources to them. Here, one assumes that future climates may have similar multi-year wet/dry spells, but that the chance of seeing such a spell may change (Palmer, 1993).

The rainy season in Ceara is determined largely by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is a band of low pressure, which forms over the regions of the warmest waters and landmasses in the tropics, typically between 15°S and 15°N. It is seen in satellite images as a band of bright clouds located just north or south of the equator. The ITCZ tends to migrate to the warmest surface areas throughout the year. In January, the high sun occurs in the Southern Hemisphere causing a southward displacement of the ITCZ. As the high sun period travels from the Southern Hemisphere to the Northern Hemisphere, the ITCZ follows by migrating northward attaining its maximum northward displacement during the month of June. The migration, strength and position of the ITCZ determined to an extent by the development or El Niño or La Niña conditions in the Pacific and also by the temperatures in the equatorial Atlantic Ocean. In the equatorial Atlantic Ocean temperatures are known to persist for a decade or longer in a well-defined spatial pattern. Typically, the pattern has temperatures to the north of the equator negatively correlated with those on the Southern side. When temperatures near the coast of Ceara are warm, a high degree of convection and rainfall occurs. Conversely, drought follows when storms are moved away as the warm pool changes location. The Atlantic temperature fields as well as the equatorial trade winds are also influenced by the El Niño activity in the equatorial Pacific. The El Niño/La Niña events typically do not persist for more than a year or two. Thus, knowledge of Atlantic conditions may help us characterize the base state of rainfall in Ceara, while additional information as to the Pacific may help speculate on the rainfall tendency for the coming year. Correlations of the January to June Oros inflow with concurrent sea surface temperatures (SSTs) are shown in Figure 2. Surprisingly, a correlation map between this year's April to June ocean temperatures with next year's Oros reservoir inflow is not very different

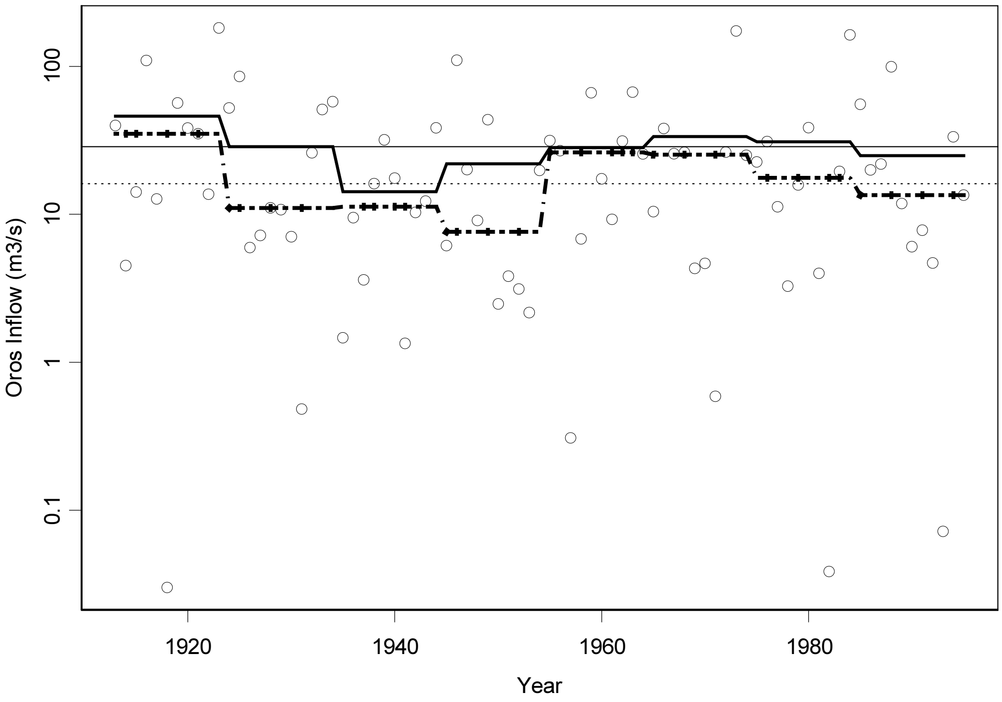


Figure 1. Annual Inflow (m^3/s) Into Oros Reservoir, Ceara, N.E. Brazil Shown as Dots. Note that the y-axis is logarithmic. Eleven-year running average flows (solid lines) and 11-year running average medians (dashed lines) are shown. The ratio of maximum to minimum average (median) annual flow in different 11-year blocks is approximately 3(5). The hypothesis of equal averages over these periods is rejected at the 5 percent significance level. The 1912 to 1995 average (solid) and median flow (dash) are also shown.

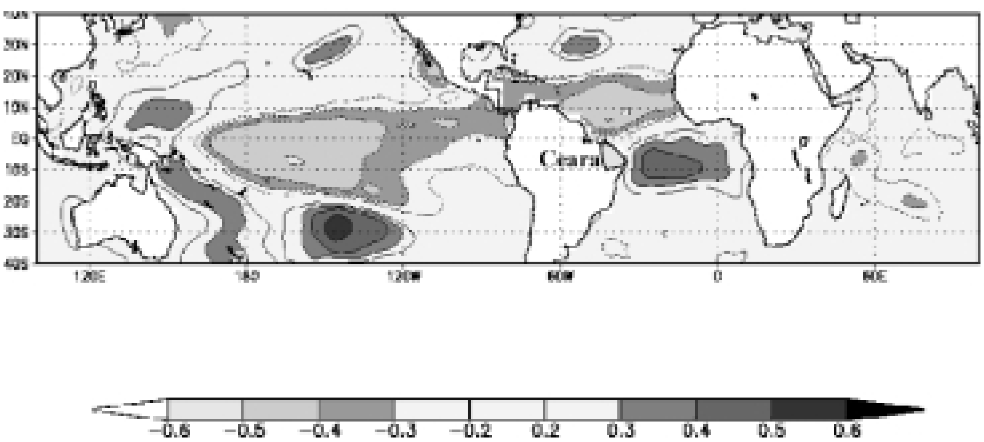


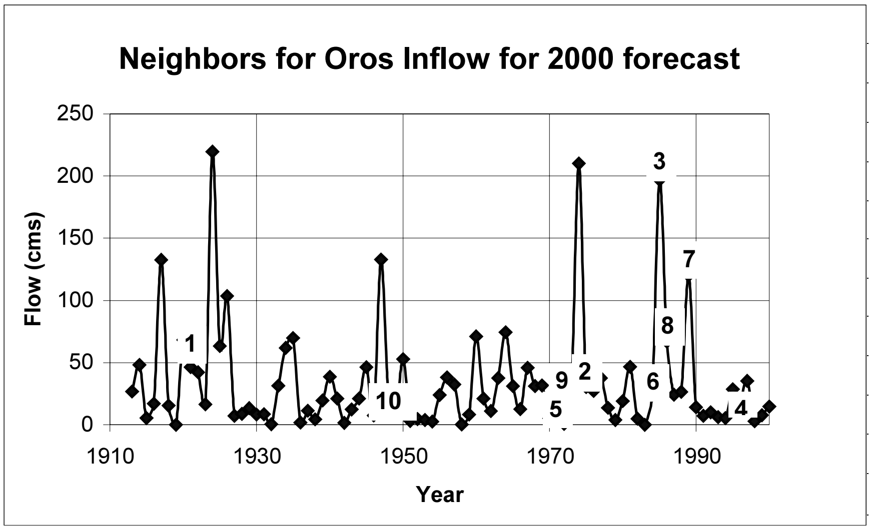
Figure 2. Correlation of 1948 to 1995 January to June Oros Inflow With Concurrent Sea Surface Temperature (SST). Correlations greater than 0.22 in magnitude are significantly different from zero at the 5 percent level (analysis performed using http://climexp.knmi.nl/ and NCDC v2 SST data).

(De Souza and Lall, 2003), given the over-year persistence of ocean conditions (particularly in the deeper water).

Two complementary approaches are now possible to develop streamflow forecasts using such information. The first uses General Circulation Models (GCMs) of the Ocean and Atmosphere and observed, current conditions to predict the state of the atmosphere (and hence rainfall) on a coarse grid (approximately 500 km by 500 km) over the entire earth. The generally slowly changing ocean conditions provide the source of predictability for such a model. However, since the GCM resolution (grid box size) is coarse, the rainfall product (average over a 500 km by 500 km box) is not directly suitable for use with hydrologic models. Consequently, Regional Atmospheric Models (RAM) may be run at a finer resolution (10 to 50 km) on a relatively large region around the location of interest using the GCM values at the boundaries of that area as the driving information. The rainfall from these models may then be used as input to rainfall-runoff models to generate streamflow. Each GCM and RAM may have systematic biases in its prediction at a given location. These biases are usually corrected by regression. Each model may also respond in a different way to small errors (uncertainties) in the observed ocean conditions that are used to initialize the model. As a chain of models is used, these uncertainties (from the model and from the bias correction procedure) are propagated, and hence the forecasts are presented as probabilities of future rainfall (flow) conditions. Methods for combining probabilistic forecasts from multiple models are also being used (Rajagopalan *et al.*, 2002).

The second approach to streamflow forecasting is statistical. The ocean areas whose temperatures are best indicators of future rainfall at a given location are empirically identified through an examination of historical data. Typically, these are relatively large areas. Experiments may then be performed with GCMs to see if changing the surface boundary conditions in those areas lead to the empirically identified rainfall response. Once suitable ocean (SST) predictors are identified, an empirical statistical model for streamflow may be built. This will typically be used for probabilistic forecasts also. Desouza and Lall (2003) provide an example of a novel statistical method for Ceara. Their approach generates scenarios or ensembles of potential inflows for the next January to June season, in the previous July, using April to June SSTs from selected locations in the Atlantic and Pacific Oceans. The scenario is constructed by assigning a probability to each year in the historical data, based on the similarity of the current SST conditions to corresponding periods in the past. These probabilities are used to randomly draw each historical year, and hence the associated monthly inflows at all sites (see Figure 3).

The skill or reliability of climate or streamflow forecasts is usually of concern to water resource managers. While statistical measures of skill can be computed, they may not mean much to a reservoir operator who may be faced with potential losses either from using the forecast or from ignoring it. If a forecast is not used, the manager can argue that adverse conditions and outcomes during operation were an act of God, or a natural hazard. The use of a probabilistic forecast requires a change from the default mode of operation, and hence constitutes risk taking on part of the manager, even if the forecast probabilities are much more accurate than those implied by using historical scenarios. In Ceara, water managers traditionally allocate reservoir contents under a forecast of zero inflow for the coming year. Consequently, they may suffer higher evaporation and spill losses, and impose a higher incidence of irrigation restrictions than may be warranted if accurate probabilistic forecasts were available. In risk management (e.g., for flood control), probabilistic information is often used together with estimates of benefits and losses from each possible action (e.g., a particular reservoir release or water allocation), and the "best" decision is indicated by the action that maximizes Expected Net Benefits, or the average difference between benefits and losses, given the uncertainty as to the outcomes. Such an idea may make sense to a manager who



Index	Year	Weight (percent)
1	1921	14
2	1975	9
3	1985	6
4	1996	6
5	1971	5
6	1984	5
7	1989	5
8	1986	3
9	1973	3
10	1949	3
Sum		59

Figure 3. Top 10 Historical Neighbors for the 2000 Ceara Forecast and Their Probabilities. The neighbors are based on the similarity of the current SST conditions to the corresponding periods in the past. A reservoir operator could simulate future reservoir storages and supply demand scenarios using each of these years as candidates, and then make a decision as to allocation based on their willingness to take risks. The correlation of the median forecast inflow and observed future flow in a blind test (i.e., the data forecast is not used in building the model) is 0.7 for Oros (figure from De Souza and Lall, 2003).

has a large number of projects and seeks to come out ahead on average across these projects and over his/her management tenure. Individuals try to buffer their risk of loss (e.g., due to floods or fire) by purchasing insurance and hence sharing the risk. Is there a way to "share" the risk induced by uncertain future conditions, or by the use of a forecast, such that reliable use of such products can be enhanced for the social good, above and beyond what may be done by a few adventurous managers? Alas, the traditional priority based water rights systems do not usually allow for such innovations. In Ceara, we are exploring the development of a new tiered water contract system. Each contract would guarantee a user a certain amount of water for a set period (10 years or 1 year), with a specified reliability. The higher the reliability and the longer the duration, the higher the unit price for a contract. The idea is that reliable contracts could be issued in July for the upcoming year if the forecast and reservoir contents warrant them. The premium for these contracts would function effectively as an insurance payment, and in the event of nonsupply the contract holder would be compensated. Such a system could increase reservoir use efficiency and may better buffer future inflow uncertainty, whether it be associated with a climate informed forecast or with ignorance about the future.

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