5.7 CLIMATE VARIABILITY AND WATER RESOURCES: A STUDY IN THE PARAIBA VALLEY, BRAZIL

Ana P. Barros*[1], Silvio J. Simoes[2], and David A. Raff[1]
(1) Harvard University, Cambridge, MA
(2) Universidade Estadual Paulista, São Paulo State, Brazil

1. Introduction

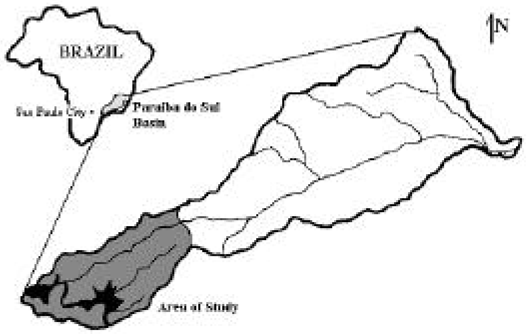
Hydropower has long been considered a sustainable and renewable energy source (Braga, 2001). In Brazil, for example, almost 90 percent of all electricity is produced in hydropower plants. Although standard planning and design of dams and reservoirs take into account hydroclimatic variability in the historical record, the underlying climate regime is assumed stationary. Recently, this premise has been increasingly under scrutiny with regard to uncertainty in the long-term assessment of water resources (Shiklomanov, 1999). We examine this issue by focusing on the recent hydroelectric energy crisis in Brazil.

In 2001, a severe drought was blamed for the severe reduction in water levels in the reservoirs of many Brazilian hydroelectric power plants. The federal government was forced to announce a national rationing plan to avoid blackouts from June till the onset of the rainy season (late October, early November). By September 2001 the reservoirs were working at minimum capacity (about 20% of the total volume), evidence of the failure of existing energy and water resources management plans to meet unexpected shortages. One interesting feature of the 2001 drought was the mismatch between the modest magnitude of the meteorological drought (a small precipitation deficit as compared to the long-term mean) and the severity of the hydrological drought (large runoff deficit). The motivation for studying the Paraíba river basin is to investigate the temporal variability of the rainfall-runoff response in the region vis-a-vis the physical mechanisms linking atmospheric forcing (climate) to terrestrial response (hydrologic regime), and thus explain the changes in water resources availability.

2. Case-Study

The Paraíba basin (or Paraíba valley, Figure 1), links the two major metropolitan centers of São Paulo and Rio de Janeiro, was chosen for this study for two reasons: a) the presence of three regional multi-purpose reservoirs; b) the availability and reliability of a dense regional hydroclimatological observing network. It comprises nearly 15,300 km^2, and is characterized by heterogeneous topography, geomorphology, hydrology and soils. Historically, human activity imposed dramatic transformations of the regional landscape with a reduction in forested areas from nearly 81% to 8.0% over the last 300 years (Dean, 1995; Fujieda et al., 1997). Currently, the landscape is a complex mosaic of grazing, forest, and urban areas. Part of the basin is densely populated with high concentration of industrial activities along the river. Population in the Paraíba valley increased 300 per cent in the last thirty years, from approximately 518,000 in 1960 to approximately 1,690,000 in 2000 (IBGE, 2001). Cities continue to expand near, or on alluvial plains contributing to the reduction and elimination of wetland ecosystems. Because of its strategic geographical position, multi-purpose reservoirs (electricity generation, flood control and flow regulation) were built first in the 1950s, and later in the 1970s.

Figure 1: Map of Brazil and geographical location of the Paraíba river basin.



---

*Corresponding author address: Ana P. Barros, Harvard University, Pierce Hall 118, 29 Oxford St., Cambridge, MA 02138
email: barros@deas.harvard.edu

a. Data

For this study, we focused on characterizing the temporal variability of regional hydroclimatology in the historical records. Temperature data are scarce; the longest record was obtained from the Air Force Meteorological Centre for 1981-2001. The hydrological data within this region include a network of 107 raingauges installed at a variety of altitudes (450 m – 1700 m) some of which have been in place since the 1930's, and a network of 22 streamgauges operational since the 1950's. Within the context of this study 29 rainfall gauge sites are analyzed and 2 stream gauges. The selection criteria for rainfall gauge sites were concurrent records of 1959 – 1996 and less than three percent interpolated data. The stream gauges were chosen with respect to their proximity to rainfall gauges and also such that their records are not influenced by dams.

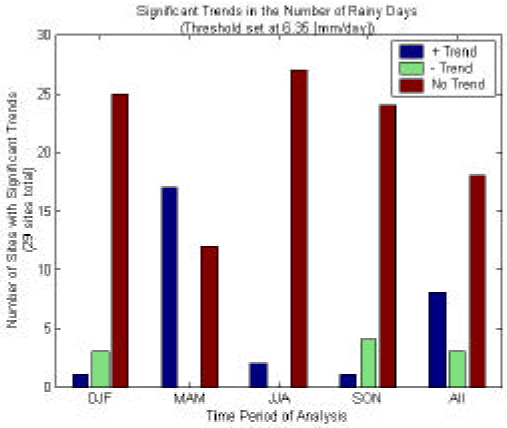
b. Analysis

Previous studies have documented the bimodal character of the annual cycle of precipitation in southeast Brazil, with dry and wet seasons consistent with the transition from tropical to mid-latitude climate regimes (Braga & Molion, 1998; Nery et al., 1999).

In the Paraíba valley, the average annual precipitation is on the order of 1,400 mm, but exhibits large inter-annual variability ranging between 800 mm to 2000 mm. Severe droughts occurred in 1943/1944, 1953-1957, 1963, 1968, 1984, 1994, 1997 and 2001; whereas 1947, 1976, 1983 and 2000 were exceptionally wet years.

The daily rainfall data was analyzed with respect to the number of days on which rain occurred greater than 6.35 mm, a hydrological significant value. The numbers of days were then fit with the general linear model and the slope of this model was tested for significance ($p \leq 0.05$). The analysis was performed on the entire time series as well as by seasonal time scales. December-January-February (DJF) represents the summer months, the rainiest months of the year, March-April-May (MAM) are the autumn months and experience some rainfall, June-July-August (JJA) are the winter months and represent the driest season, and September-October-November (SON) are the spring months. The results can be seen graphically in Figure 2. The MAM time period is the only time period where the majority of sites show a significant trend; a tendency towards more days of rain. The summer months, DJF, have more sites decreasing in the number of rainy days than increasing as does do the spring months, SON. The most significant statement from Figure 1 is that there is a trend towards more days of rain during the autumn and it would appear that the trend is rain on fewer days during the spring and summer.

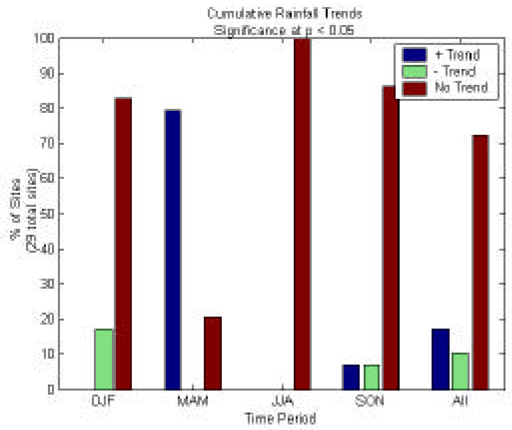
Figure 2: Number of sites with significant trends in the number of rainy days between 1959 – 1996.



Cumulative rainfall data was also analyzed for the seasonal time periods as specified previously (Figure 3). While most sites do not show any significant trends, the ones that do reiterate that there is an inter-annual shift in rainfall frequency and amounts. For the summer months the only sites that show significant trends are tending towards less rain and in the autumn the sites that show a significant trend are all tending towards an increase in cumulative rainfall. The relationship between rainfall amounts and number rainy days indicates that the increase in MAM rainfall during autumn manifests itself by an increase in the occurrence of light rainfall during long periods rather than short-duration heavy rainfall events. Runoff production in response to light rainfall is unlikely, because the infiltration capacity of soils typically exceeds the rainfall rate, and therefore, unless the soil is initially saturated, rainfall is stored as soil moisture.

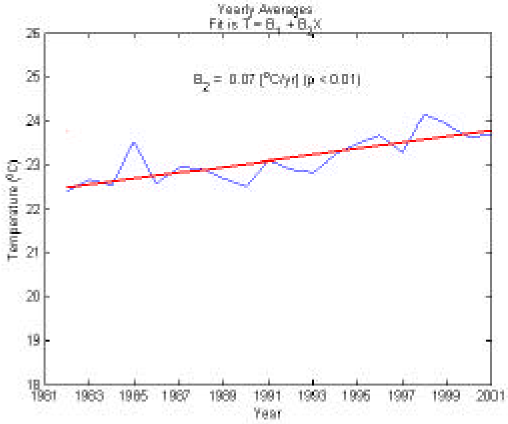
The inter-annual variability in rainfall has great impact on runoff production. Accordingly, the streamflow records in the Paraiba valley also exhibit large inter-annual variability. However, because of the dynamics of soil water storage and evapotranspiration, a significant asymmetry should be expected in the phase and magnitude of runoff response to variability in rainfall forcing. This is illustrated here by examining the rainfall and streamflow records for two index catchments within the Paraíba valley (Piagui and Pinhao). These catchments were selected because they have not yet been developed, and because they are representative of the dominant hydrological characteristics within the basin. It should be noted that other research in the area of this study found some very complex results but most importantly that rainfall and streamflow trends should be considered together (*e.g.,* Marengo et al. 1998). After examining normalized cumulative monthly deviations of streamflow and rainfall over the last 40 years it was found that more pronounced and persistent anomalies occur in the streamflow rather than in the rainfall data. This behavior is consistent with the role of evapotranspiration and soil moisture storage in the regional water budget. During the rainy season, when the soil is saturated, runoff production is determined by the net difference between precipitation and evapotranspiration (P-E). During the dry season, rainfall is stored in the upper soil layers, recycled back to the atmosphere through evapotranspiration, or released to the groundwater system by percolation, without generating surface runoff.

Figure 3: Number of sites with significant trends in cumulative rainfall for 1959 – 1996.



Despite the limited length of monthly temperature records (20 years), a significant positive trend was found of 0.07 ^{o}C / year (Figure 4). The causes for warmer air temperature are unclear. The results obtained are consistent with reports of warmer surface temperatures globally and locally on most continents during the 1980s and 1990s (Jenkins et al., 2002). Nevertheless, what is relevant for this discussion is that the increase in observed temperatures is consistent with an increase in evaporative fraction (E/P), a decrease in runoff production, and thus reduction of surface water inputs to hydroelectric reservoirs.

Figure 4: Yearly averaged temperature data with general linear model fit. The time series is from 1981 - 2000



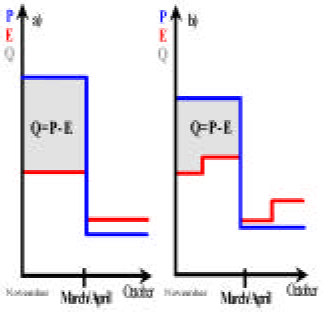
A conceptual summary of the hydrological implications of the data analysis is illustrated in Figures 5a (average year) and 5b (dry year). Generally, the following assertions can be made: 1) a decrease in heavy rainfall during the rainy season is compensated by an increase in light rainfall during the dry season; 2) an increase in temperature in the rainy season leads to an increase in evapotranspiration; and 3) as a result of 1) and 2), runoff production as estimated by [P-E] decreases and thus input to the reservoirs decreases. Moreover, an increase in light rainfall and rainy days in the dry season recharges the soil moisture reservoir, but an increase in temperature in the dry season leads to an increase in evapotranspiration in the winter (JJA), and a decrease of soil moisture levels at the beginning of the rainy season, thus further decreasing the potential for runoff generation in the spring (SON). That is, a small phase shift in the seasonality of rainfall, coupled with a small increase in temperature, can lead to a large decrease in runoff production. The impact of these subtle climatic changes on the hydrological regime is magnified during drought, such as in 2000-2001, because the DJF rainfall deficit is larger.

3. Discussion and Conclusion

The analysis of rainfall daily records for the Paraíba valley does not show consistent trends toward drier and wetter conditions on annual time-scales since the 1950's. These results contradict those of Sant'Ana Neto (1995), who found significant upward trends for all regions of São Paulo State analyzing annual and monthly rainfall records.

However, analysis of seasonal patterns show that, for the period 1959 - 1996, rainfall has tended to decrease during the rainy summer season (DJF) and the spring (SON) and tended to increase during the autumn (MAM), and less pronouncedly during winter (JJA). Trends in temperature data showed an increase and the increases in MAM and JJA rainfall are smaller than the increase in potential evapotranspiration, thus leading to drier soils at the onset of the spring rains. In general, this suggests a weakening of the seasonal cycle, which, if persistent, could lead to a sustained streamflow deficit in the long run.

Figure 5a and 5b: Conceptual accounting model describing the changes in hydrological processes during drought as compared to average conditions defined based on annual time-scales.



Typically, climatic variability such as that reported here does not make the front pages of news media. There is no direct loss of human life to report, nor impressive major physical damages to document. These are subtle changes that creep up slowly, but have the potential to invalidate the quantitative foundation of long-term water resources plans and thus threaten quality of life and environmental sustainability. This calls for careful, place-based monitoring and analysis of the climate system, and the expansion of water resource assessment studies to include intra-annual time-scales and seasonality shifts in the terrestrial water cycle as a whole.

4. References

Braga, B.P.F., 2001: Integrated urban water resources management: A challenge into the 21st Century. *Water Resources Development*, **17** (4): 581-599.

Braga, B.P.F.; Molion, L.C.B., 1999: Assessment of the impacts of climate variability and change on the hydrology of South America. In: J.C. van Dam (ed.). *Impacts of Climate Change and Climate Variability on Hydrological Regimes*. Cambridge, Cambridge University Press. p. 21-35.

Dean, W., 1995: With broadax and firebrand. *The destruction of the Brazilian Atlantic Forest*. Berkeley, University of California.

Departamento Nacional de Produção Mineral, 1948: *Atlas Pluviométrico do Brasil*. Brazil, Ministério da Agricultura. 25p.

Estado de São Paulo 2000: Projeto Qualidade das Águas e Controle da Poluição Hidríca na Bacia do Paraíba do Sul. BIRD / São Paulo State Government Partnership. CD-ROM.

Fujieda, M.; Kudoh, T.; de Cicco, V.; Carvalho, J.L., 1997: Hydrological processes at the subtropical forest catchments of the Serra do Mar, São Paulo, Brazil. *Journal of Hydrology*, 196: 26-46.

IBGE (Instituto Brasileiro de Geografia e Estatistica), 2001: Censo demográfico Brasileiro. (www.ibge.gov.br)

Jenkins, G.S.; Adamon, G.; Fongang, S., 2002: Changes in West Africa. *Climatic Change*, **52**: 263-286.

Marengo, J.A.; Tomasella, J.; Uvo, Cintia R., 1998: Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil, and northwestern Peru. *Journal of Geophysical Research,* **103**(D2): 1775-1783.

Nery, J.T.; Vargas, W.M.; Martins, M.L.O.F., 1999: Estrutura da precipitação do Estado de São Paulo. *Revista Brasileira de Recursos Hidrícos*, **4** (4):51-61.

Sant’ Ana Neto, J., 1995: As chuvas no Estado de São Paulo: Contribuição ao estudo da variabilidade e tendência da pluviosidade na perspectiva da análise geográfica. *Ph. D. Thesis, Faculdade de Filosofia, Letras e Ciências Humanas*, São Paulo University .

Shiklomanov, I.A., 1999: Climate change, hydrology and water resources: the work of the IPCC, 1988-1994. In: J.C. van Dam (ed.). *Impacts of Climate Change and Climate Variability on Hydrological Regimes*. Cambridge, Cambridge University Press. p.8-20.