**Lab 10: Water resource management decisions for Ceará, Brazil**

The state of Ceará, situated in a semi-arid region, is one of nine states in Brazil's Northeast, a relatively highly populated region and one of the country's least developed. It has over 7.4 million inhabitants, with 39% residing in the capital city of Fortaleza. Of the rural population that makes up 48% of the entire state's population, 79% are employed in agricultural activities and 76% are considered poor by local standards. While state GDP has had substantial growth in the last fifteen years, the productivity of agriculture has been relatively low. The percentage of agriculture in the state GDP has dropped from 30% in the 1950s to approximately 7%. The Fortaleza metropolitan area, where most of the industry and service jobs are located, is responsible for 85% of the GDP, although the urban poverty fraction is still estimated to be 58%. In 1999, the rural illiteracy rate was 44% while the urban rate was 20.4%. Small holdings of less than 10 hectares represent 70% of all holdings but only 5.4% of total area.

Four small, connected reservoirs – Pacajus, Pacoti, Riachão, and Gavião - serve the metropolitan area of Fortaleza, with an estimated population of 2.9 million. Fortaleza receives an average of 6.9 $m^3$/s of water from the Gavião reservoir. These reservoirs are basically fed by a collection of small rivers that compose what is called the metropolitan basins. There is a small industrial district on the margins of the Pacajus reservoir, and these industries pump water directly from the reservoir. Another industrial district is located in Maracanaú, closer to the metropolitan area, drawing approximately 0.10 to 0.20 $m^3$/s from the Gavião reservoir. The Maracanaú industrial pole also draws water from the Acarape do Meio reservoir. The Pecén industrial district is currently served by the small Sítios Novos and Cahuipe reservoirs, and official plans established the Pecén pole as the terminal station of the Eixão, a large canal with a capacity of 22 $m^3$/s, connecting the Castanhão reservoir to the metropolitan area. The Jaguaribe Valley is connected to the Metropolitan Basins through the Canal do Trabalhador. This canal was constructed in 1993, during a serious water crisis, and has a capacity of 6 $m^3$/s.

The canal brings water from the Itaiçaba pumping station to the Pacajus reservoir, over more than 110 kilometers. The minimal difference in geographic slope makes the water run very slowly in this canal, which is therefore considered inefficient. Currently, the Canal do Trabalhador attends only to the local demand of some communities and small scale irrigation along its path. Irrigated agriculture is not common around the metropolitan area of Fortaleza. The most important agricultural product of the metropolitan basins is rain fed cashew, from which cashew nuts are produced and exported.

In this lab exercise, you are asked to help the water management officials of Ceará to decide the amount of water released for a given year by taking into account of the stream-flow forecast based on climate indices such as ENSO and PDO (Pacific Decadal Oscillation). We selected three years represents wet (1989), dry (1993), and normal (1995) conditions. Ensemble forecasts were made and the median forecast for the monthly stream-flow for each of the three years are given in the spreadsheet. Also given are the actual stream-flow observations for these three years, the climatology (long term average), the evaporation coefficients, the reservoir capacity and the initial storage of the reservoir.

Since flood is not a big concern for the region, decisions will only need to be made about water allocation. Assume that the demand for water in each month is the same throughout the year, at 78 million $m^3$ ($Mm^3$). Among those, 30 $Mm^3$ has to be used by municipal purposes, 25 $Mm^3$ by industry, and the remaining 23 $Mm^3$ used by agriculture. Your objective is to optimize the water usage by assigning values to water used by each category. In order to guarantee municipal usage, the first 30 $Mm^3$ of water is valued at \$5000/$Mm^3$, first 25 $Mm^3$ of industrial usage is valued at \$3000/$Mm^3$, and the first 23 $Mm^3$ of agricultural usage is valued at \$2000/$Mm^3$. The excess water for a year with more water than the target is valued at \$1000/$Mm^3$ for any category.

We will use the excel sheet Sanka showed in lecture for the case with evaporation included but make a few modifications. First change the stream-flow data and evaporation coefficient, as well as the reservoir capacity and target allocation for each month. Additionally, we only need three decision variables, Dm, Di, Da, representing demands for municipal, industry, and agriculture. Each month's water allocation equals the sum of the three components. First use solver to find the maximum amount of water that can be released for a given year; then construct the objective function to allocate the water to each category. (This will require you to run the solver twice, first maximizing the yearly release, and then maximizing the yearly profit). Do this for each of the three years with forecasted stream-flow and for the climatological stream-flow to answer the following questions:

1. How much water was allocated each month to each of the three categories for 1989, 1993, and 1995?
2. What is the net annual income of the water allocation for each year?
3. How much water is spilled in each case?
4. If forecast stream-flow is not available, climatological stream-flow data will be used for water allocation. What is the amount of water allocated for the three years if climatological stream-flow data were used instead of the forecast?

To evaluate the water allocation based on forecast stream-flow, you can substitute back the observed stream-flow for each year and examine the outcome of the water allocation. Look at the months we failed to deliver enough water and the amount of water spilled due to forecast error. These should be compared to the climatological allocation plan to see if the forecast can give a more realistic water allocation.

5. Are there any improvements of using the forecast stream-flow as opposed to using the climatology? In what way the forecast helped the water resource management in each case?