Operational Hydrology in South Florida Using Climate Forecast

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ABSTRACT

The South Florida Water Management District (SFWMD) uses unconditional and conditional position analysis as one of several decision tools in planning the operation of the system. The Object Oriented Routing Model (ORM), a lumped parameter hydrologic simulation model for the SFWMD system, is reinitialized to current conditions for every year in the simulation period. Model results are presented as stage time series of percentile traces for Lake Okeechobee and other impoundments in the system. Conditional position analysis is obtained when a given (dry or wet) climatic forecast is incorporated into the analysis.

INTRODUCTION

The South Florida Water Management District (SFWMD) manages the water resources of South Florida for the benefit of the region, balancing the needs of present generations with those of future generations. Equally important elements of this stewardship are the conservation and development of water supply, the protection and improvement of water quality, the mitigation of impacts from flood and drought, and the restoration and preservation of natural resources.

Drainage in South Florida, for the purpose of land reclamation, began in the middle 1800's and has evolved into an extensive and complex network of lakes, reservoirs, canals and levees, interconnected by different types of water control structures. The current system, known as the Central and South Florida (C&SF) Project, was designed and built by the U.S. Army Corps of Engineers (USACE) and the local sponsor is SFWMD. The C&SF project is multi-purpose and provides flood control and protection, water supply for municipal, industrial and agricultural uses, prevention of salt-water intrusion, environmental water supply for the Everglades and

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protection of natural resources. The C&SF project has made it possible for millions of people to live in central and south Florida.

The heart of the SFWMD system (Figure 1) is Lake Okeechobee, the second largest fresh water lake located contiguously within the U.S. The Kissimme River and Fisheating Creek provide most of Lake Okeechobee inflows. The SFWMD system includes approximately 1400 mi (2250 km) each of both levees and canals, more than 200 water control structures and 18 major pump stations. Lake Okeechobee has two outlets, the Caloosahatchee River to the west and the St. Lucie Canal to the east, which discharge through the tidal estuaries to the ocean. Four major canals (West Palm Beach, Hillsboro, North New River and Miami) convey water supply to the Lower East Coast (LEC) and flood control releases from Lake Okeechobee to the south. These canals traverse the Water Conservation Areas (WCAs) and capture excess runoff from the Everglades Agricultural Area (EAA). The 5 WCAs, WCA-1, WCA-2A, WCA-2B, WCA-3A and WCA-3B, work as shallow, above the ground impoundments. The rich soils in the EAA, located in between Lake Okeechobee and the WCAs, are used for production of sugar cane, sod and winter vegetables. Lake Okeechobee supplies water to both the EAA and the communities around the Lake (Lake Okeechobee Service Areas, LOSA). An important feature of south Florida hydrology is the continuous interaction between ground water and surface water.

The water control system of south Florida is complex, not only in its configuration, but also in its operation. It is a multi-objective system. Conflicting water needs necessitate the use of appropriate water management decision tools. The ability to look into probable future responses of the system, given the current state and future climatic forecasts, is a valuable tool to water managers. Position analysis (Hirsch, 1978) examines the future behavior of the system by estimating the risks associated with a given operational plan over a period of a few months.

The SFWMD is currently using position analysis as a decision tool in planning the future operation of the system at the monthly and seasonal level. To perform position analysis, a hydrologic simulation model is reinitialized to historical or known storage conditions on a given date, for every year in the simulation period. Processing of model results allows the evaluation of probabilities associated with different type of events. Position analysis can be applied to any variable represented in the simulation model.

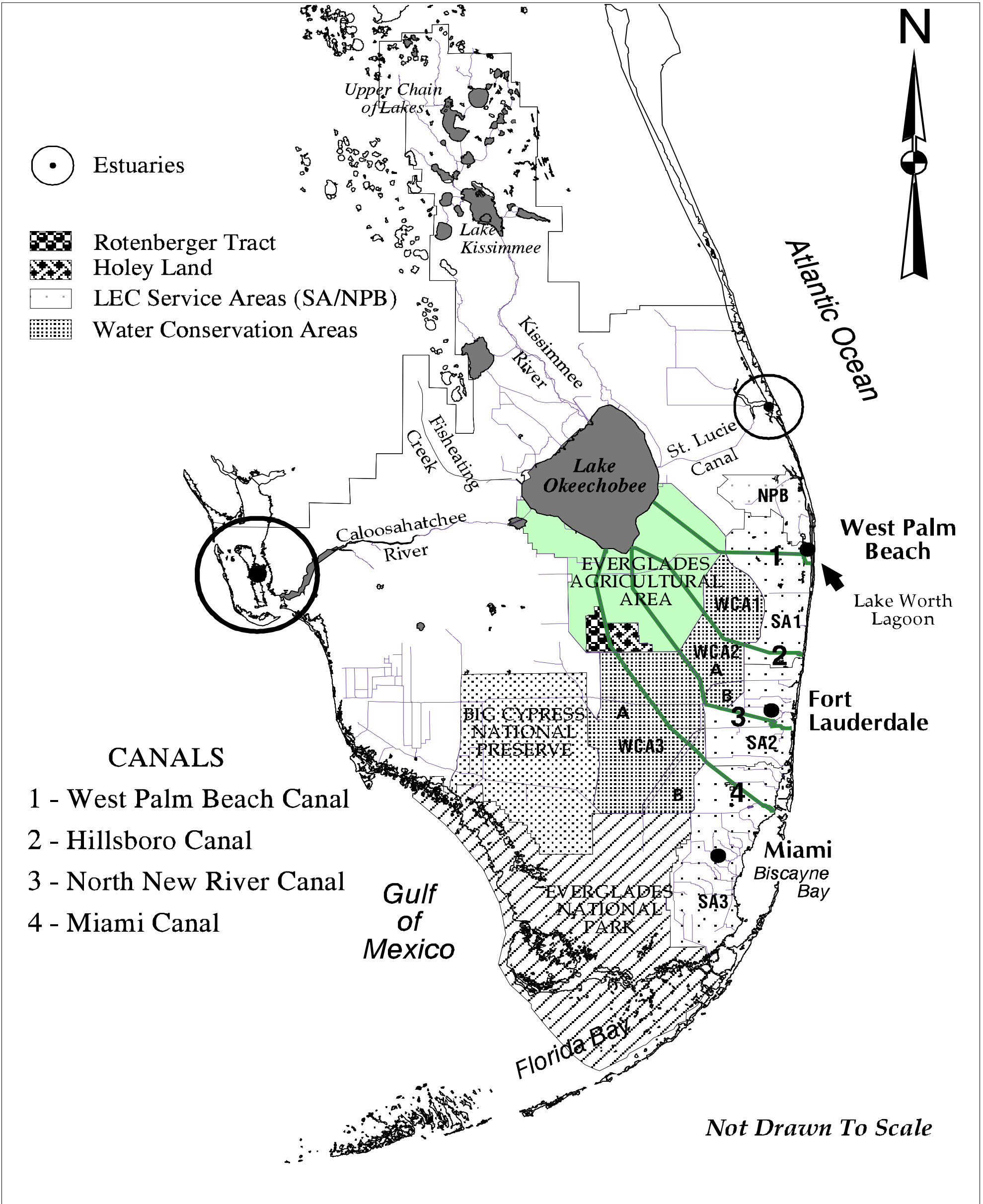

Figure 1. The current South Florida water control system.

Conditional position analysis is obtained when model results are shifted (up or down) according to a given (wet or dry) climatic forecast.

The SFWMD has extensively developed and applied the South Florida Regional Routing Model (SFRRM) (Trimble and Marban, 1989). The SFRRM, based on mass balance, conceptualizes the water control system as a series of interconnected reservoirs and basins. The SFRRM has been re-coded and improved as the Object Oriented Routing Model (ORM).

Several reasons favored the selection of the ORM as the first hydrologic simulation model to use in operational planning by the SFWMD: 1) Extremely easy to learn and use, 2) Turn around and execution times are fast, and 3) As a lumped parameter model, re-initialization of the system is an easy task. Other models, such as the South Florida Water Management Model (SFWMD, 1999), are currently being conditioned to run in position analysis mode.

The implementation of operational planning at the SFWMD has been a joint effort with USACE, Jacksonville District, Water Management and Meteorology Section.

This paper provides a brief description of the SFRRM and the ORM. It describes the methodologies used to do position analysis and conditional position analysis. It also gives an accounting of the major advantages and shortcomings found in applying these methodologies to the south Florida water control system.

THE SFRRM AND THE ORM

Both the SFRRM and the ORM conceptualize south Florida hydrology as a linked system of "pots" or "basins". The methodology implemented in the models is a daily mass balance approach, applied to the main reservoirs and basins in the system. The SFRRM was developed as an easy to use tool to analyze the response of the system to different structural or operational modifications (Trimble, 1986; Trimble and Molina, 1991).

The SFRRM and the ORM are capable of simulating the hydrology and the management of the current system. They include Lake Okeechobee, the LOSA, the EAA, the WCAs and the LEC Service Areas. The time step for the simulations is daily. Currently, the SFWMD has the capability of running the ORM using 31 years (1965-1995) of daily historical hydro-meteorological data.

Storage in each reservoir fluctuates from day to day in response to flows in or out: overland flow, rainfall, evapotranspiration (ET), seepage, and surface water discharges through water control structures. For the simulation of reservoirs, the models use the concept of Modified Delta Storage (MDS). The simulated storage in any day (t) of the simulation is given by:

$$S(t) = S(t-1) + MDS(t) + QIN(t) - QOUT(t) - ET(t) - SPG(t) \qquad (1)$$

$$MDS(t) = \Delta S_{HIS}(t) - [QIN_{HIS}(t) - QOUT_{HIS}(t)] + ET_{HIS}(t) + SPG_{HIS}(t) \quad (2)$$

where S is the simulated storage, QIN and QOUT are simulated inflows and outflows, ET is the simulated evapotranspiration, and

SPG are simulated seepage losses. The historical components, identified by the subscript HIS, are defined similarly. The daily historical storage change, ΔS_{HIS}, is obtained from recorded stages and the stage-storage relationship for the reservoir. Structure flows are obtained from historical records, while ET and seepage may be estimated as a function of historical pan evaporation and stages. Eq. (1) considers only the components of the water budget that will be altered under the simulation. Rainfall is considered to change storage during the simulation exactly as it did historically and for this reason is not included in the simulated storage (eqs. (1) and (2)).

The equations are applied in two steps. First, historically recorded data is processed to compute MDS. The reservoir is returned to a pre-management condition for each daily time step. In this sense, MDS represents net inflow to the reservoir. An important feature of MDS is its ability to account for unknown or unrecorded inflows and outflows to the reservoir, through the ΔS_{HIST} term. Viewed this way, MDS is an input time series to the SFRRM or the ORM simulations. The second step is executed during the simulation. It adds MDS to the initial storage and calculates the new discharges, including ET and seepage, based on the projected storage quantities, but with new management schemes in effect. ET volume is a function of surface area inundated by water, and seepage is a function of stage in the reservoir.

Water deliveries from one region to another are made according to flood control, water supply or environmental needs. The conveyance limitations built into the models were chosen to simulate daily discharge values in such a way that historical average flows are reproduced on a monthly or seasonal basis, and not to incorporate hydraulic conditions that may exist for shorter periods of time. Most of the conveyance limitations were derived from historical data.

The ORM is the SFRRM recast as an object oriented model. Therefore, the ORM inherits most of the features of the SFRRM. In the ORM, water moves between basins through flowways, in response to the water management objectives. Each of the elements -- basins, flowways and water management objectives -- is represented by objects in the ORM.

Basins and flowways are fundamental objects that represent the conceptualized physical system of basins and their linkages. Basins are generally aligned along hydrologic basin boundaries with well-defined inflows and outflows. Internal hydrologic complexities are hidden, simplified, lumped or pre-processed so that only inter-basin transfers are simulated at the regional level. Flowways represent the physical connection between basins, e.g. structure, canal, or structure-canal combinations.

Basins typically have water supply or flood control needs that can not be adequately met through their own internal resources. Management objects are used to assess the condition of a basin and quantify the deficit or excess needs that must be resolved at the regional level. Transfer objects provide the mechanism for exchanging water between basins. These objects manage a collection of supplier or flood outlet conduits that move water between a "served" basin and one or more affected basins. A conduit simulates the actual operation of a flowway. Operational controls for a flowway are contained in policy objects. Policies are the expression of management constraints that may set or limit the quantity of water moved through the flowway. For example, water supply releases through a flowway are stopped if stages in the upstream basin drop below an environmentally sensitive level. If no policies are specified, a conduit will direct the flowway to move enough water to satisfy the water supply or flood control need, subject to the conveyance capacity of the flowway.

POSITION ANALYSIS

Position analysis is a special form of risk analysis. Its purpose is the evaluation of water resources systems and the risks associated with operational decisions (Hirsch, 1978; Smith et al., 1992). This evaluation is accomplished by estimating the probability distribution function of variables related to the water resources system, conditional on the current or a given state of the system. The terms position analysis and unconditional position analysis are used interchangeably in this article.

Assume that water managers require information on the future behavior of the system, conditional on the state of the system on June 1, 1999. Then, position analysis is required. The ORM is run for the period of simulation and the storage at the beginning of June 1, for every year and every reservoir in the system, is reset to the value corresponding to June 1, 1999. A total of 30 realizations of system response to different climatic inputs are obtained, each equally likely to take place in the future. Each realization or scenario starts on June 1 of a given year and ends on May 31 of the next year. Complete realizations are available starting in June 1, 1965 and ending May 31, 1995.

Any variable, for which output is produced as part of an ORM simulation, could be subject to position analysis. For instance, in the case of stages and for a given day, one single daily value is extracted for every year in the simulation period, yielding a sample of size 30 for that day. An empirical probability distribution function is derived for this sample. There are a total of 365 empirical distributions for daily stages, conditional on the state of the system on June 1, 1999. Next, quantiles are obtained and the time series of percentiles are assembled. These plots define the empirical conditional distribution (percentiles) for one day and describe the evolution of the distribution throughout the forecast year. An example of the unconditional position analysis is presented in Figure 2.

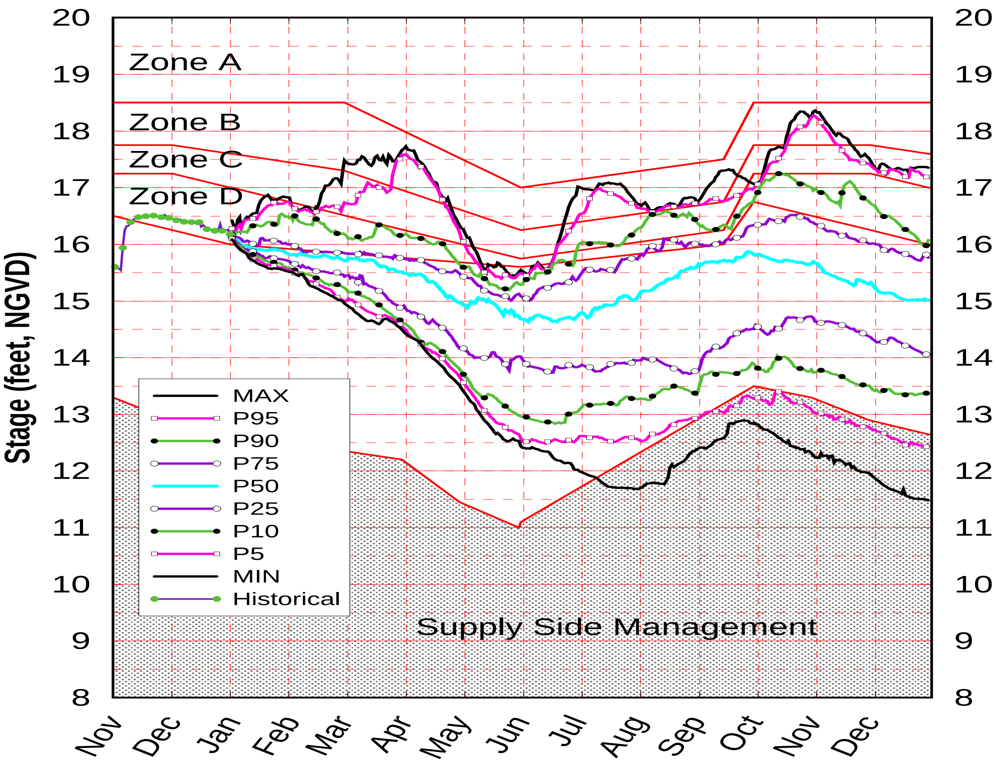

Figure 2. Lake Okeechobee Unconditional Position Analysis
Stage Initialized to 16.17 feet on 01/01/1999

CONDITIONAL POSITION ANALYSIS

The methodology adopted to perform conditional position analysis follows the procedures described by Croley (1996). The objective is to estimate the future response of the system in probabilistic terms, given the current state and a future climatic forecast. For instance, it may be important for water managers to know the possible future behavior of daily Lake stages given the state of the system on June 1, 1999, and given a high probability that the SFWMD will be under dry conditions for the next six months.

Croley's (1996) methodology is based on using Climate Outlooks, which are produced by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). CPC outlooks are provided for a one-month window for the next month, and 13 3-month overlapping windows going into the future, in one-month increments. The climate outlooks are presented in maps, which are posted monthly (the 3rd Thursday of the month) (http://www.cpc.ncep.noaa.gov). For each time window, the maps give the probability of rainfall being above normal, normal and below normal. The rainfall values for classification in these three ranges are defined as the lower, middle and upper terciles of a normal distribution fitted to observed rainfall for the last three decades (1961-1990).

Previously published applications of conditional position analysis (Croley, 1996) use climate outlooks for precipitation and temperature, since inflow volumes in those cases are proportional to precipitation and temperature (snow ablation). The conditional position analysis application for south Florida uses the CPC climate outlook for rainfall only, since as temperature increases in south Florida, ET increases and runoff decreases. The presentation for the remainder of this article will focus on rainfall.

The use of climate outlooks in operational hydrology is based on the formulation of structured data sets. Structured data sets are obtained after the available rainfall sample is manipulated to reproduce the climate outlooks. For instance, if the forecast distribution calls for an above normal condition, values in the scenario falling in the above normal range are repeated more frequently than normal or below normal values. Repetition of values forms the structured data set. When a single climate outlook window is considered, the number of replications are given by (Croley 1996):

$$r_A = N_S\,P_A / n_A \;;\; r_B = N_S\,P_B / n_B \;;\; r_N = N_S\,P_N / n_N \qquad (3\ )$$

where the A, B and N subscripts denote above, below and normal. P_A, P_B and P_N are the climate outlook probabilities, n_A, n_B and n_N are the number of values in the original sample falling in each range, N_S is the structured data set sample size, and r_A, r_B and r_N are the replication factors in each range. For instance, each value in the original sample falling in the above normal range is repeated r_A times. The larger N_S, the closer r_A, r_B and r_N will be to integer values. Note that the following statements are valid:

$$P_N = 1 - P_A - P_B;\; n_N = n - n_A - n_B;\; N_S = r_A n_A + r_B n_B + r_N n_N \qquad (4)$$

where n is the sample size or number of original scenarios. Instead of working with replications and having to select N_S, Croley introduced weights w_A, w_B and w_N, defined as:

$w_A = P_A\ n / n_A$; $w_B = P_B\ n / n_B$; $w_N = P_N\ n / n_N$ (5)

The weights can also be expressed as:

$w_A = r_A\ n / N_S$; $w_B = r_B\ n / N_S$; $w_N = r_N\ n / N_S$ (6)

Weights are replication factors re-scaled to the original sample size.

The description of the weights presented so far has dealt only with one climate outlook window. However, the CPC provides outlooks for a total of 14 windows. Now it is necessary to estimate a set of weights w_i, i = 1,..,n. All the weights are different in value and each weight is associated to a particular scenario. They must satisfy simultaneously a maximum of 14 different climate outlook conditions given by

$$\left.\begin{array}{l}\hat{P}_A^g = a_g \\ \hat{P}_B^g = b_g\end{array}\right. \quad , g = 1,\ldots,14 \qquad (7)$$

where $\hat{P}_A^g$ and $\hat{P}_B^g$ represent the forecast probabilities for each forecast window g. Note that the probability of being in the normal range is no longer included, since it is the complement over 1.0 of the sum of the other two probabilities.

The equations in (6) can be generalized to the case when all the replication factors are different as:

$w_i = r_i\ n / N_S$, i = 1,…n (8)

$$\sum_{i=1}^{n} w_i = n \qquad (9)$$

The unconditional position analysis case is obtained when all the weights are equal to one.

Let x_i, i=1,..,n represent a sample in which each value is associated to a different scenario. The following expressions are used to estimate statistics for the structured data sets (Croley, 1996):

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} w_i\ x_i \qquad (10)$$

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} w_i\ (x_i - \overline{x})^2 \qquad (11)$$

$$\hat{P}[X \le y_j^n] = \hat{P}[X \le x_{i(j)}] = \sum_{m=1}^{j} \frac{w_{i(m)}}{n+1} \quad , j = 1,\ldots,n \qquad (12)$$

where y_j^n are the ordered statistics and i(m) points to the location of the mth ordered statistic in the original sample. For instance, if $y_j^n = x_k$, then i(j) = k. The above equations estimate the mean, standard deviation and empirical cumulative distribution function for the structured data set.

In terms of the weights, the equations in (7) can be written as:

$$\begin{aligned} \frac{1}{n}\sum_{j=1}^{n} w_j\, \mathrm{I}_{\{A_g\}}(x_j^g) &= a_g \\ \frac{1}{n}\sum_{j=1}^{n} w_j\, \mathrm{I}_{\{B_g\}}(x_j^g) &= b_g \end{aligned} \qquad (13)$$

where $\mathrm{I}_{\{.\}}(.)$ is the indicator function. It takes the value of 1 if $x^g_j \in A_g$ and 0 if $x^g_j \notin A_g$, and A_g and B_g represent the set of values above normal and below normal, for window g, respectively. At the same time, x_j^g is the rainfall depth for scenario j, window g. The equations in (13) state that the weights should preserve the apriori forecast probabilities. Note that eqs. (5) and (13) are equivalent since both are counting the number of values above and below normal.

For the application of conditional position analysis, 30 scenarios are available. A total of 30 weights also need to be computed. There are 30 unknowns and at most 29 equations: one from eq. (9) and 28 from (13). There are infinite solutions to this system of equations. The situation becomes more difficult when some of the climate outlooks indicate climatological conditions, which means that the probabilities of being above, below or normal are equal to one third. When this is the case, outlook conditions are not included in the set in (13).

To cope with this problem, Croley (1996) suggests solving the following optimization problem to estimate the weights:

$$\min \sum_{i=1}^{n} (w_i - 1)^2 \qquad (14)$$

subject to the constraints defined by eqs. (9) and (13).

The optimization problem may produce a solution that is not feasible, namely, some of the weights are negative. Instead of introducing additional non-negativity constraints to the optimization problem, Croley (1996) proposes an iterative process to obtain a feasible solution. The CPC climate outlooks included in eqs. (13) are assigned a priority. Initially, a solution is attempted using all the constraints. If all the weights are positive, then a solution has been found. If some weights are negative, a new solution is attempted by constraining the weights found negative in the previous step to be equal to zero. If the newly computed weights are all positive, a solution has been found. If negative weights are still present in the solution, the CPC outlook with the lowest priority is dropped, weights made zero in the previous trial are unconstrained, and a new solution is obtained. The process continues in a similar fashion by constraining negative weights to be equal to zero and by dropping additional CPC outlook conditions by priority, until a feasible solution is obtained.

The basic assumption in conditional position analysis is that the weights obtained based on rainfall can be applied to any other variable from the simulation, to obtain the conditional distribution for that variable. Once a solution is found for the weights, eq. (12) is used to derive the conditional distribution for each day and produce the time series of percentiles. An example of the conditional position analysis results for Lake Okeechobee is given in Figure 3.

Zero or negative weights are an indication of the inability of the method to produce a conditional distribution if the scenarios corresponding to those weights are kept in the sample.

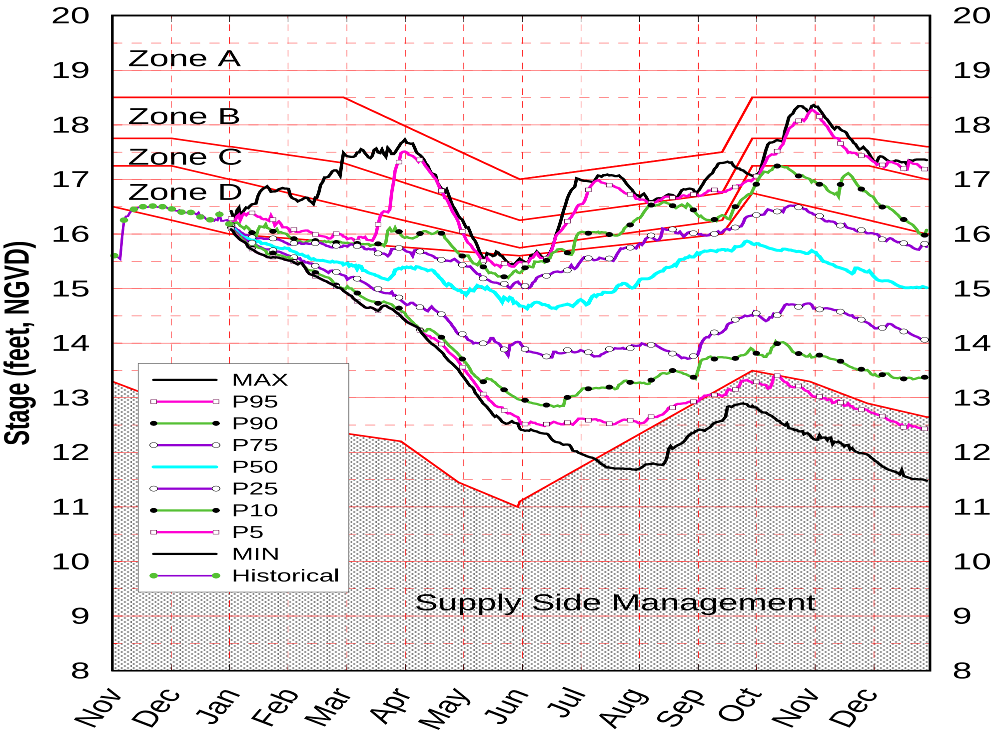

Figure 3. Lake Okeechobee Conditional Position Analysis
Stage Initialized to 16.17 feet on 01/01/1999

RESULTS

Unconditional position analysis is a straightforward procedure. Conditional position analysis is a more elaborated process and does not always yields useful results. There is no warranty that conditional position analysis results will be available every month. Some of the problems found in applying conditional position analysis are described as follows:

1. The CPC outlook for south Florida usually provides only a few forecast windows, most of which, especially during the wet season, are termed climatological, indicating normal behavior is expected.
2. Typically, only a few of the CPC outlook probability windows are used to find the solution. In the search for a feasible solution for the weights, climate outlook windows far into the future are dropped first. It might be necessary to drop several outlook conditions before a solution is found.
3. The method might fail to produce a reasonable conditional position analysis solution.
4. Whenever the CPC outlooks for windows including the current month indicate climatological conditions, the SFWMD has opted to not produce the conditional position analysis.
5. Comparison of unconditional and conditional cases may produce unexpected results. For instance, if the CPC outlook calls for a dry condition for the forecast year, some of the conditional percentiles may plot above the corresponding unconditional ones, for some periods of the forecast year, when the opposite behavior is expected. Several reason explain this behavior: 1) Weights derived for initial months in the forecast year are applied to months well into the forecast year, 2) Weights derived for dry or wet conditions are applied to windows were most of the values fall within the opposite range, and 3) Sample variability in the derived empirical distributions.

Most of the problems described above stem from the fact that weights are associated to scenarios and not to windows or months. If a feasible solution is found, weights associated to each scenario are applied uniformly throughout the forecast year. A possible modification to the method is to allow the weights to vary within the year. Whenever a feasible set is found, weights are applied only to months included in the windows associated with the solution. Weights for the other months are made equal to one. In some cases, changes in weights from one month to the next generate abrupt changes or unexpected behavior in the percentiles. To avoid this, it was decided to implement a linear interpolation scheme for the weights. The weight values for each month are centered in the middle of the month. Values for intermediate days are linearly interpolated between the values at the middle of the months.

The conditional position analysis results produced by the SFWMD are really a combination of conditional and unconditional analysis.

The following is a typical set of results produced monthly, for both unconditional and conditional position analyses, provided a valid conditional position analysis solution exists. Examples are given for some cases and they correspond to the position analysis performed on January 1, 1999. Three windows were included initially for the conditional case for January 1, 1999: January, January-March and February-April. The CPC outlook prescribed dry conditions, with the probabilities of being below normal in the range 50-60% and the probabilities of being above normal varying between 3 and 13 %. The final solution for the weights included the January window and the below normal condition for the January-March window. It was required to drop three conditions before a feasible solution was found:

- Time series of percentile traces for Lake Okeechobee (Figures 2 and 3) and for the main WCAs (WCA-1, WCA-2A and WCA-3A). The different zones shown in Figures 2 and 3 are Lake Okeechobee management zones.
- Time series of stages for Lake Okeechobee and for the main WCAs (WCA-1, WCA-2A and WCA-3A), showing the response of the system for dry and wet years. Dry and wet years are selected by performing frequency analysis on the aggregated MDS for the system, for the forecast year under consideration. Figure 4 presents the dry years plot for Lake Okeechobee.
- El Niño years and La Niña years time series plots for Lake Okeechobee and the main WCAs. These graphs are prepared whenever south Florida is expected to be under the influence of mild to strong El Niño or La Niña conditions for part of the forecast year. The graphs are prepared with values from the ORM simulation, corresponding to years on which these conditions were observed historically. Depending on the number of years under each condition, the graphs may show years or percentile traces. These graphs are based on sub sampling according to given criteria. Figure 5 is an example of La Niña years plot for Lake Okeechobee.
- Zone probability graphs for Lake Okeechobee. For the entire year, these graphs give the probability that the stage in Lake Okeechobee falls in any of its management zones. A tabular version of this graph is also produced (Figure 6).

Among all the graphical results produced, the favorites among water managers at the SFWMD are the wet, dry, El Niño and La Niña years plots, since given their experience they can easily relate to the historical behavior response of the system.

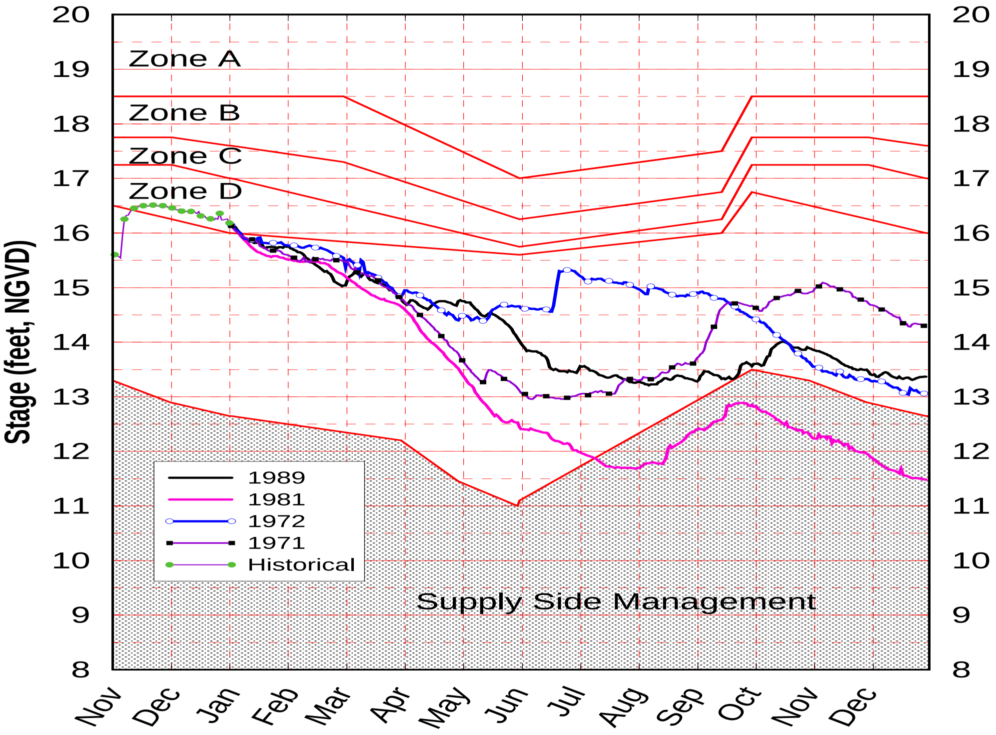

Figure 4. Lake Okeechobee Dry Years Plot
Stage Initialized to 16.17 feet on 01/01/1999

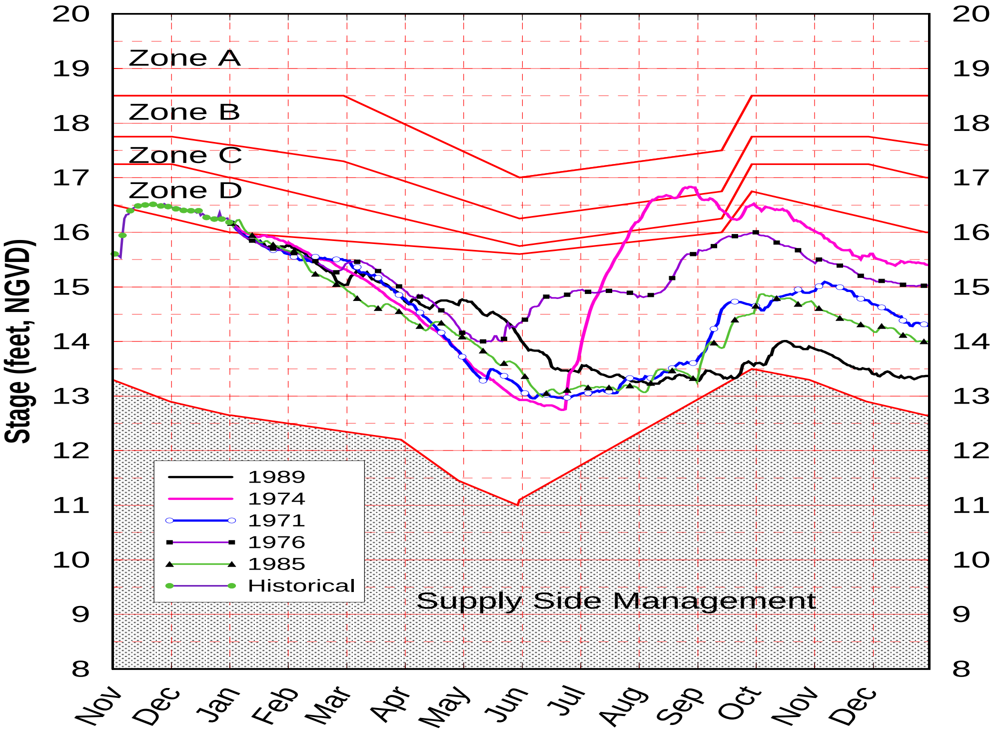

Figure 5. Lake Okeechobee La Niña Years Plot
Stage Initialized to 16.17 feet on 01/01/1999

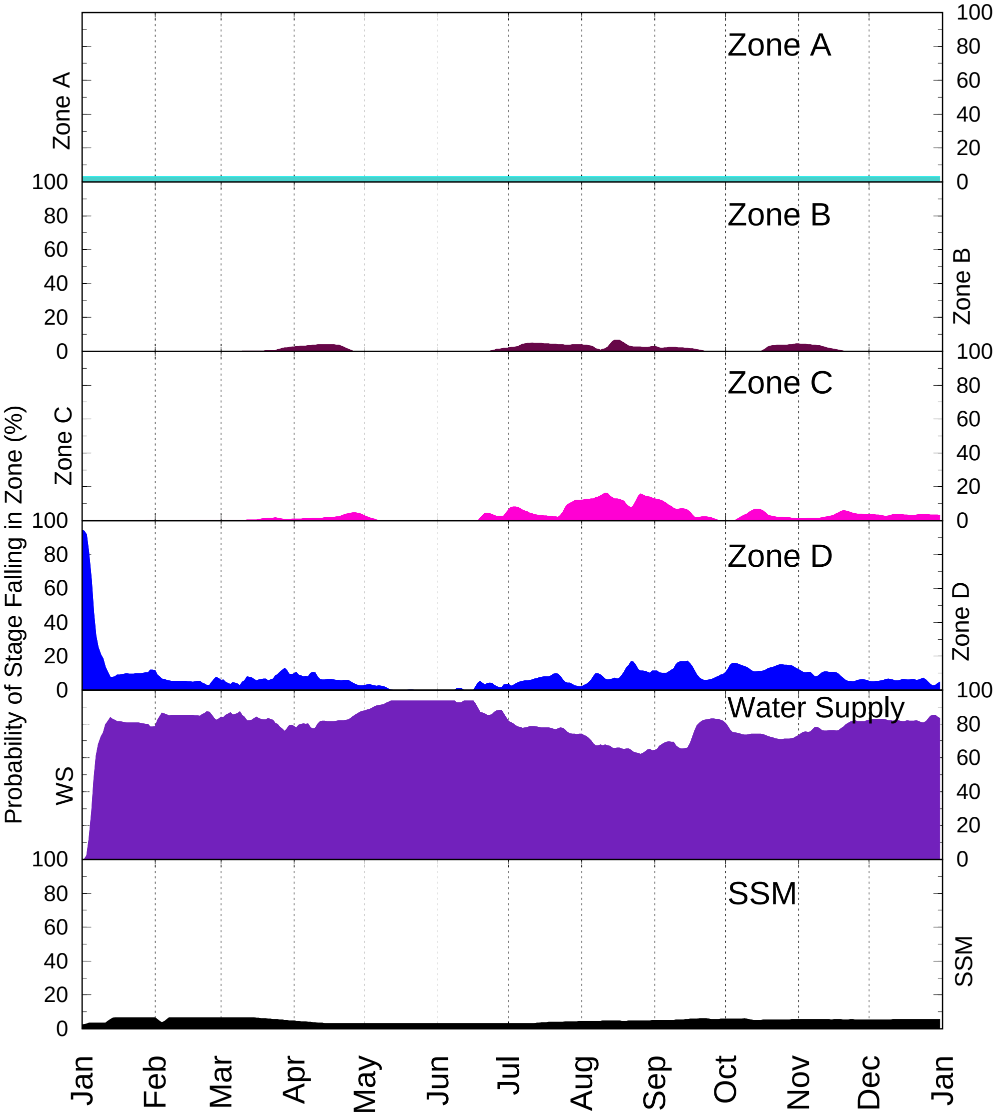

Figure 6. Lake Okeechobee Probability Lines Plot
Stage Initialized to 16.17 feet on 01/01/1999

CLOSING REMARKS

The competent and judicious operation of a complex water management system like the SFWMD is no small task. It relies not only upon the knowledge and experience of the operating engineers, but also upon any or all information at their disposal to assist in the decision making process. Short-term weather forecasts, for example, have been routinely used for years in the daily decision making process. Historically, the seasonal effects of phenomena such as El Niño and La Niña on the regional climate in Florida have been above average and below average precipitation respectively. Unconditional and conditional position analysis are tools to assess the probabilistic state of the SFWMD system for the upcoming months based upon recent climatological history and upon expected climatological trends, such as those generated by El Niño and La Niña conditions. These tools help the operating engineers to adjust and adapt the operations of the system accordingly.

The conditional position analysis results described in this paper are based exclusively upon the CPC Outlooks by the National Climate Data Center. One of the main shortcomings found in the application of the method has been the low rate of success in obtaining a feasible and meaningful solution for the weights. The SFWMD is trying to improve the results by using other forecast products that provide information similar to the CPC forecast. Also, a set of hydro-climatological data, containing a longer period of record (1914-1998), is being assembled for use in operational planning. Finally, the conditional position analysis based on indicators other than rainfall, such as Modified Delta Storage for the Lake, is under consideration.

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