Validation of Climate-Based Lake Okeechobee Net Inflow Outlooks

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Abstract

The application of climate-based outlooks for operational planning in south Florida is an ongoing reality. Currently, the operational schedule for Lake Okeechobee considers the expected seasonal and multi-seasonal net inflow based on Croley's method and an in-house empirical method, both of which rely on the Climate Prediction Center's seasonal climate outlooks, and on sub-sampling of historically-observed inflows under analog historical climatologic conditions. A refined method which incorporates antecedent conditions into the inflow forecast is also discussed. The purpose of this paper is to compare the performance of various methods for calculating net inflow outlooks for Lake Okeechobee for the period 1995 through 2005 against actual inflows.

Introduction

The progress that is being made towards a more complete and in-depth understanding of the dynamic forces that drive global climate variability has created the potential for predicting seasonal and multi-seasonal regional climate shifts well in advance. Although such longer-lead climate outlooks have a large degree of uncertainty, they provide additional information for water managers who constantly have to assess the effects of current operational decisions on future hydrologic conditions as they affect natural and human systems. Traditional rule curves (or regulation schedules) for reservoir operations are "static" in the sense that operational decisions are made only when the reservoir water level crosses a predetermined curve. The South Florida Water Management District (SFWMD) proposed and the United States Army Corp of Engineers (USACE) adopted a "dynamic" flood control regulation schedule for Lake

Okeechobee. This schedule not only considers water levels and the season of the year but also incorporates the seasonal and multi-seasonal climate based hydrologic outlooks. This regulation schedule is known as the Water Supply and Environmental (WSE) regulation schedule because it allows significant benefits for the precious natural ecosystems of south Florida without adversely impacting regional water supply. The operational schedule includes two parts: (A) A traditional set of regulation schedule lines which define the various operational zones; and (B) An associated set of decision trees that recommend the type and magnitude of discharge made within each operational zone for each outlet.

The competing goals and objectives for managing Lake Okeechobee water levels and flood discharges may be summarized as follows:

a) Water Supply: Agricultural and urban water users naturally desire that the Lake be treated as a storage reservoir, therefore maximizing storage to best meet water use requirements without threatening the integrity of the levee system enclosing the Lake. Water storage below 3.0 m above sea level is not accessible for water use.

b) Flood Protection: Extended periods with the Lake stages above 5.0 m and/or hurricane surge could cause levee failure through piping and erosion. Failure of the levee system may result in catastrophic loss of life and property damage. Lake historic inflows during the wet season have been up to an equivalent depth of 3.0 m of water over the Lake surface area. Considered alone, water supply and flood control objectives would call for a 4.7–5.2 m operational schedule. Water levels are allowed to reach a maximum after the peak of the hurricane season (October 1st) and just prior to the dry season which begins in November. Prior to the hurricane season (June 1st) water levels are required to be at their lowest levels.

c) Lake Ecological System: Lake Okeechobee ecologists usually recommend that the Lake water levels be managed with approximately the same seasonality as those for flood protection but 0.60 m to 0.90 m lower than what the Lake water users would desire. The Lake littoral zone generally lies between 3.8 m and 4.6 m and covers an area of about 518 km^2.

d) Everglades Ecological System: Everglades ecologists seek water levels that are similar to those which would have occurred in the pre-drainage natural system. During periods of below normal rainfall, when water levels in the Everglades are significantly below normal, flows from the Lake are desirable for the natural ecosystems. However, during periods with more normal rainfall, when water levels are near normal ranges, the risks and benefits of making such releases to the Everglades become more complex.

e) Estuary Ecological Systems: Estuary ecology depends on the interaction and balance between fresh and salt water ecosystems. Large freshwater flows are undesirable because they interrupt the natural conditions that otherwise exist in the estuaries. Large discharges from the Lake to the estuaries are especially undesirable during wetter periods when local runoff may already be stressful to estuaries. During drier periods, minimum freshwater flows from the Lake are desirable.

The WSE schedule has been designed to balance the above objectives of managing Lake Okeechobee by incorporating climate outlook based net inflow forecasts explicitly (Trimble et al., 2006). The ability to successfully predict net inflow to Lake Okeechobee allow for the opportunity to meet the competing objectives in a more proficient manner. The remaining sections of this paper evaluate the success of various climate based methodologies for predicting seasonal and multi-seasonal inflow.

Methodologies for Determining Climate-based Net Inflow Predictions

Net inflow for Lake Okeechobee is defined as net rainfall (rainfall minus evapotranspiration) on the Lake plus total inflow entering the Lake through both natural streams and various water control structures. For the purpose of net inflow calculation, the dry season in south Florida includes the months of November through April while the wet season spans the period May through October. The seasonal forecast encompasses the upcoming six month period, starting with the current month. The multi seasonal forecast is formed with the remainder of the current season, starting with the current month, plus the oncoming season, and therefore, the duration of the multi seasonal window has a maximum of 12 and a minimum of 7 months.

Computation of Lake net inflow outlook values rely on the historical time series for the period 1914 through 1998 as defined in the Water Control Plan for Lake Okeechobee (USACE, 2000). Various different methods have been used to produce the required seasonal and multi seasonal forecast (Wilcox et al, 2004). One of the methods originally applied is based on the use of structured data sets and follows the methodology described by Croley (1996). Croley's method allows transformation of the historical sample distributions so that they match forecast distributions for rainfall, as produced by the National Oceanic and Atmospheric Administration (NOAA) Climatic Prediction Center (CPC). The CPC produces climate outlooks for the United States for a one-month window for the next month and 13 three-month overlapping windows going into the future, in one month increments [http://www.cpc.ncep.noaa.gov/products/predictions/]. Information derived from these climate windows is used to calculate monthly weights using Croley's methodology. These weights are applied to the historical data and summed, thus generating desired net inflow windows (USACE, 2000). A fundamental assumption in the implementation of the Croley's methods is that the probability shifts in precipitation outlooks are directly applicable for net inflow time series.

A second method used to produce forecasts is the South Florida Water Management District empirical method (USACE, 2000). It relies on regression equations and empirically derived coefficients to produce the seasonal and multi seasonal forecast volumes as a function of tercile Lake net inflow volumes for one- and three- month duration windows, shifted according to CPC rainfall outlooks for the same windows. Again, these volumes are aggregated up to the appropriate duration in order to generate the required outlook windows.

Sub sampling techniques are the currently preferred means of obtaining Lake seasonal and multi-seasonal net inflow outlooks. These methods isolate specific months from the historical sample according to criteria based on different global climate indicators which have been found to play a role in determining south Florida climate (Mestas-Nunez and Enfield, 2003). These indicators, also known as teleconnections, include the Atlantic Multidecadal Oscillation (AMO), the El Niño-

Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The strength and phase of these phenomena are estimated in terms of large scale oceanic and meteorologic anomalies and expressed as climate indices. The hydrologic outlooks are computed as the expected values of monthly flow volumes, considering only those months for which the selected indicators apply. A numerical average value of all months meeting the prevailing condition is calculated for each month and then individual months are aggregated to obtain seasonal and multi-seasonal windows for LOK net inflow. Checks are performed to ensure that the sample size for any given month is not reduced to too small a population as a result of the sub-sampling criteria.

In addition to the previously mentioned methods, neural network and table compression techniques have been applied to help predict net inflow outlooks (Trimble et al, 1998; Hewett et al, 2000). These methods utilize a variety of climate indices (both current and with lag time of 3-6 months) from several general categories: Sea Surface Temperature -- ENSO, AMO; PDO; Solar activity -- Sunspot numbers, trends & cycles; Geomagnetic activity; terrestrial and solar; Drought Indices – Palmer Drought Severity Index (PDSI); While these approaches have shown promising results, the uncertainties involved with these technologies have made them risky for real-time implementation and as such, simpler methods such as sub-sampling are currently preferred.

Once aggregated volumes of predicted net inflow for the seasonal and multi-seasonal window are calculated, they are converted to equivalent depth over the entire Lake by using an estimate of Lake surface area of 467000 acres (1890 km^2). The resulting depths are then classified into one of four prediction categories: Dry, Normal, Wet or Very Wet. Classification of the values is used to help make operational decisions in determination of the need for flood control discharges from the Lake. These net inflow classifications, known as 'class limits', were developed through an extensive planning process involving the USACE, the SFWMD and other stakeholder agencies and groups in order to achieve an acceptable balance between the competing objectives listed in the previous section. As such, the classification limits are not intended to explain all the actual hydrologic variability, but rather to recognize a shift in the probability distribution of likely hydrologic conditions in the upcoming seasons expressed as net inflow for the purposes of information for a decision making matrix. For example, a classification of Very Wet in combination with other factors may result in a higher probability of making flood control discharges. Taking advantage of this recognized shift in likely outcomes allows for the opportunity to make these discharges with a more natural hydroperiod so that will have less impact on the downstream ecologies.

Tables 1 and 2 present the currently used class limits for seasonal and multi seasonal classification (Cadavid, et al 2006). It is important to note that the classifications are intended for use in operational decision making and not to denote climate trends in south Florida.

Table 1. Classification of Seasonal Lake Okeechobee Net Inflow

Lake Net Inflow (million acre-feet) [hm^3]	Equivalent Depth* (feet) [m]	Outlook Classification
> 0.93 [1147]	> 2.0 [0.610]	Very Wet
0.71 [876] to 0.93 [1147]	1.51 [0.460] to 2.0 [0.610]	Wet
0.35 [432] to 0.70 [875]	0.75 [0.229] to 1.5 [0.459]	Normal
< 0.35 [432]	< 0.75 [0.229]	Dry

* Based on an average Lake surface area of 467000 acres (1890 km^2)

Table 2. Classification of Multi Seasonal Lake Okeechobee Net Inflow

Lake Net Inflow (million acre-feet) [hm^3]	Equivalent Depth* (feet) [m]	Outlook Classification
> 2.0 [2467]	> 4.3 [1.311]	Very Wet
1.18 [1456] to 2.0 [2467]	2.51 [0.765] to 4.3 [1.311]	Wet
0.5 [617] to 1.17 [1454]	1.1 [0.335] to 2.5 [0.764]	Normal
< 0.5 [617]	< 1.1 [0.335]	Dry

* Based on an average Lake surface area of 467000 acres (1890 km^2)

Accounting for Antecedent Conditions and Daily Observations

In order to help improve the confidence and usability of the Lake Okeechobee net inflow outlooks, it is important to consider the antecedent conditions in the tributary basins to Lake Okeechobee (Table 3). For example, if the tributary basins are initially saturated by recent rainfall, then projected tributary runoff for a given future rainfall scenario would be expected to be greater causing an increased likelihood of larger inflows to Lake Okeechobee as compared to a drier initial tributary condition. In the latter case a greater portion of the rainfall will be absorbed into local storage thus reducing the runoff. Regression analysis based on a number of parameters including observed rainfall and inflow has been applied to develop a methodology for adjusting historical inflow before it is used in Lake net inflow outlook predictions.

Table 3. Example of the Usefulness of the Incorporation of Antecedent Condition

September, 2002	Seasonal		Multi-Seasonal	
	Value (ft)	Category	Value (ft)	Category
Croley	1.97	Wet	2.14	Normal
Croley with Antecedent	2.09	Very Wet	2.26	Normal
Estimated Historical *	2.58	Very Wet	2.67	Wet
Improvement	0.12 closer to historical		0.12 closer to historical	

* Estimated Historical net inflow for windows through April 2003 based on provisional data

It is important to note that while the antecedent condition adjustment will likely produce a more accurate forecast, there is no guarantee that the classification category of the prediction will be affected. This is evident in Table 3 where the seasonal hydrologic outlook is increased by enough to change categories, but the multi-seasonal outlook is not. In addition to accounting for antecedent conditions, it is prudent to replace predicted inflow values (from the various estimation methods) for the current month with available observed data in order to obtain the most accurate estimate of Lake Okeechobee Net Inflow possible. Estimates of observed net inflow are obtained based on the following equation in which *i* is a given implementation day in the current month and LOK_Outflows is defined as the sum of the major Lake Okeechobee control volume structure outflows.

$$\text{Net\_Inflow}_{Observed} = \text{LOK\_Storage}_{Day\ i} - \text{LOK\_Storage}_{Day\ 1} + \text{LOK\_Outflows}$$

Since the seasonal and multi-seasonal windows are time varying and always extend from the beginning of the current month to the end of the final month in the defined window, the calculated volume of observed inflow is included as an adjustment to both net inflow outlooks. For a given method, a pro-rated portion of the predicted volume for the current month is removed and replaced with the corresponding estimated observed inflow that has already occurred. This can be summarized as:

$$\text{Net\_Inflow}_{Season} = \text{Net\_Inflow}_{Season} - (\text{Net\_Inflow}_{Current\ Month})*({}^{i}/_{\#\ days\ in\ Month}) + \text{Net\_Inflow}_{Observed}$$

Discussion and Summary

For operational decisions, as discussed earlier, Lake tributary conditions and Lake inflow outlooks are categorized into four categories: Dry, Normal, Wet or Very Wet. These classes are used in the WSE operational decisions, so it is important to validate the skill of various outlook prediction methods in obtaining proper classification predictions. In order to compare different methodologies of calculating net inflow outlooks for Lake Okeechobee, analysis was performed for the period 1995-2005. The CPC climate outlooks were initiated in 1995 and therefore allows for validation of each methodology. Figure 1 shows the traces of the different methodologies together with the observed inflow (aggregated to the appropriate seasonal windows) for this period. At first glance, it may appear that the largest portion of the variability can be explained by the seasonal cycle. However, this is not the case as very large inflows occurred during several of the normally dry season months including the November through March 1997-1998, December-March 2002-2003, and 2004-2005 November-March. These were all El Nino events. Likewise very low inflows occurred during several of the normally wet season months including May-October 1996, May-October 2000 and the May-July 2004. Additionally, all methods missed on the prediction of the below normal rainfall during the wet season of 2000.

It is clear that the methods applied to estimate inflows are unable to approach the actual variability of the Lake inflows, although sub-sampling techniques do explain a greater amount of the observed variability in the inflows relative to the other methodologies. However, as stated earlier, these methods are not aimed at explaining all of the hydrologic variability, but rather are used to support an operational decision matrix to help water managers make more informed choices. In fact, in practice the inclusion of net inflow outlooks combined with information from short term meteorological forecasts and current hydrologic conditions have proved very fruitful in the operational planning for Lake Okeechobee. For example, in the case of the 2000-2001 drought, the WSE operational decision tree would have recommended greater caution in the application of the climate based hydrologic outlooks because of developing drought conditions in the Lake tributary. For more details see the Lake Okeechobee and EAA Operational Manual (USACE, 2000) or visit the SFWMD WSE Operational web site at: http://www.sfwmd.gov/org/pld/hsm/reg_app/lok_reg/index.html.

Within the context of an operation support tool, one of the most important metrics for determining the usefulness of an inflow forecasting methodology is its ability to predict the correct classification for decision making. Figure 2 illustrates the number of seasonal 'hits' for each category for the seasonal and multi seasonal hydrologic outlook while Figure 3 illustrates the percentage of hits for each category. The sub-sampling technique using Atlantic Multidecadal Oscillation and the El Nino Southern Oscillation (AMO/ENSO) together provides a greater degree of skill than those based on the CPC outlooks. The integration of antecedent conditions appears to improve this approach as well. Looking deeper into the skill of the hydrologic outlooks a breakdown of the performance is evaluated for each category. Figures 4 through 7 illustrate the hit percentages for each category for seasonal and multi-seasonal outlooks. For the dry category (Figure 4) the seasonal outlook depict very little disparity among the four methods. The multi seasonal outlooks for 'dry' category did very poorly. For the normal category (Figure 5) Croley appears to out perform others methods for the seasonal outlook while the empirical method had the best performance for the multi seasonal outlook. For the wet category (Figure 6) the results of the seasonal outlook are mixed and the sample size is small. The multi seasonal outlooks for the wet category illustrated good performance for sub sampling with antecedent conditions, the Croley and the Empirical methods. The very wet category (Figure 7) the seasonal and multi seasonal outlooks are dominated by the sub sampling methods. Due to the smaller sample size of the normal and wet categories, the WSE operational decision tree lumps categories into two groups, wet to very wet and normal to dry. The AMO-ENSO sub sampling methodologies give more weight to the flood protection objective during the warm phase of the AMO as illustrated in this report while it gives more weight to water supply objectives during the cold phase of the AMO. The analysis of the cold phase is not considered in this report since the period 1995 through 2005 was entirely within the warm phase.

Investigations into improving predictions of dry conditions during the warm phase of the AMO are ongoing. This is important because many of the most severe droughts in the historical record have been during the warm phase of the AMO. The 2000-2001 drought appeared to be associates with both the PDO and ENSO being in the cold phase which increases the chances of drought in south Florida. However, these conditions also favor active tropical seasons which could deliver large rainfall and storm surge if one or more of these storms pass over Florida. This is a dilemma that may only be resolved by improved understanding of climate diagnostics so that hydrological outlooks could be made with more skill.

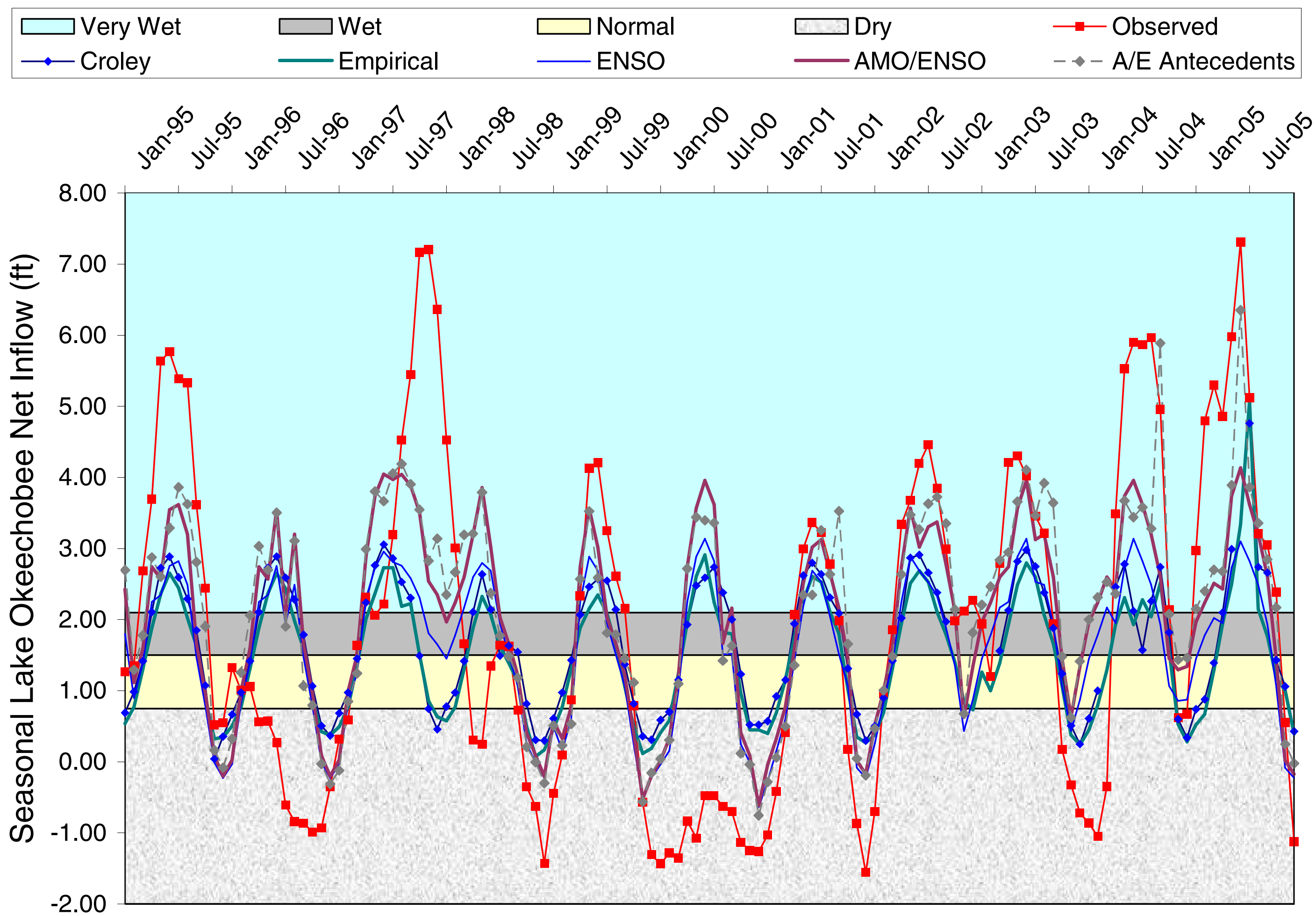

Figure 1. Seasonal Lake Okeechobee Net Inflow Prediction Comparison

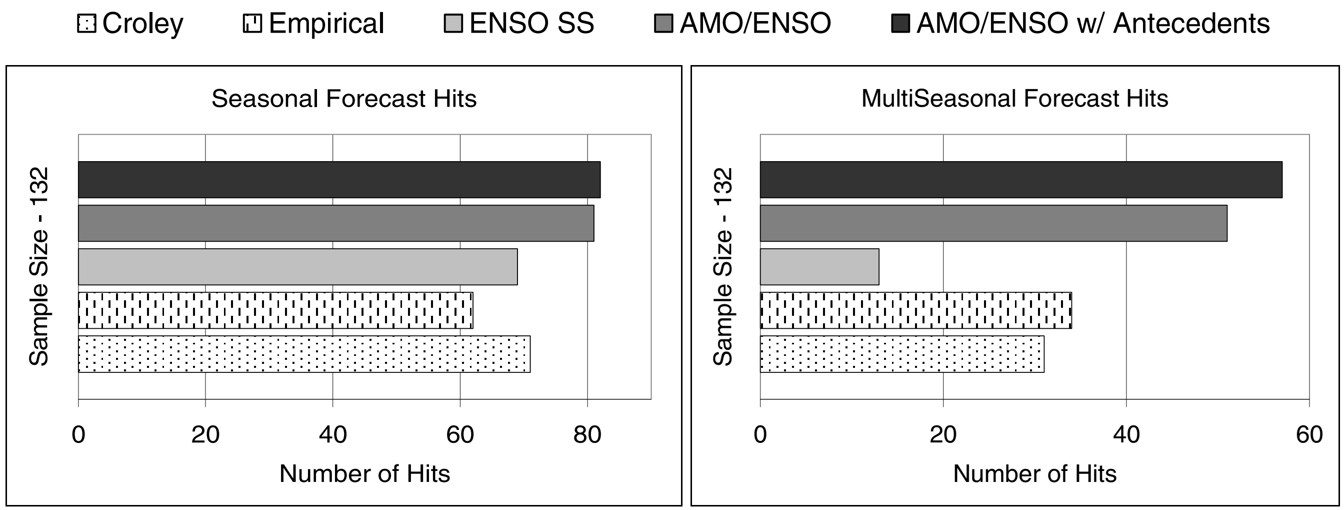

Figure 2. Number of Correct Category Predictions (hits) for Lake Okeechobee Inflow Forecast Methodologies

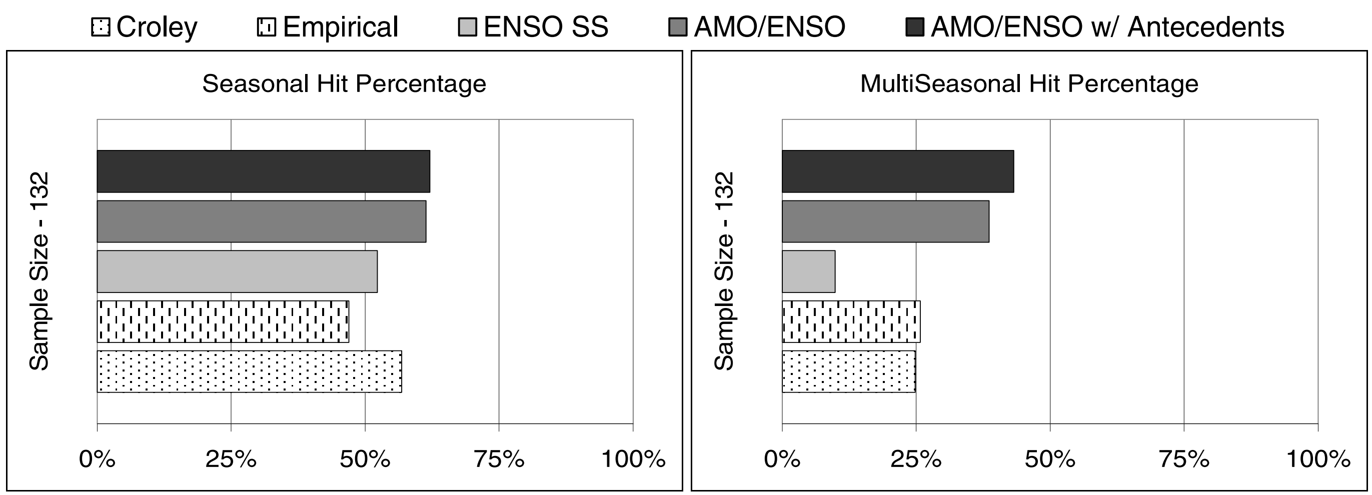

Figure 3. Percentage of Correct Category Predictions (% hits) for Lake Okeechobee Inflow Forecast Methodologies

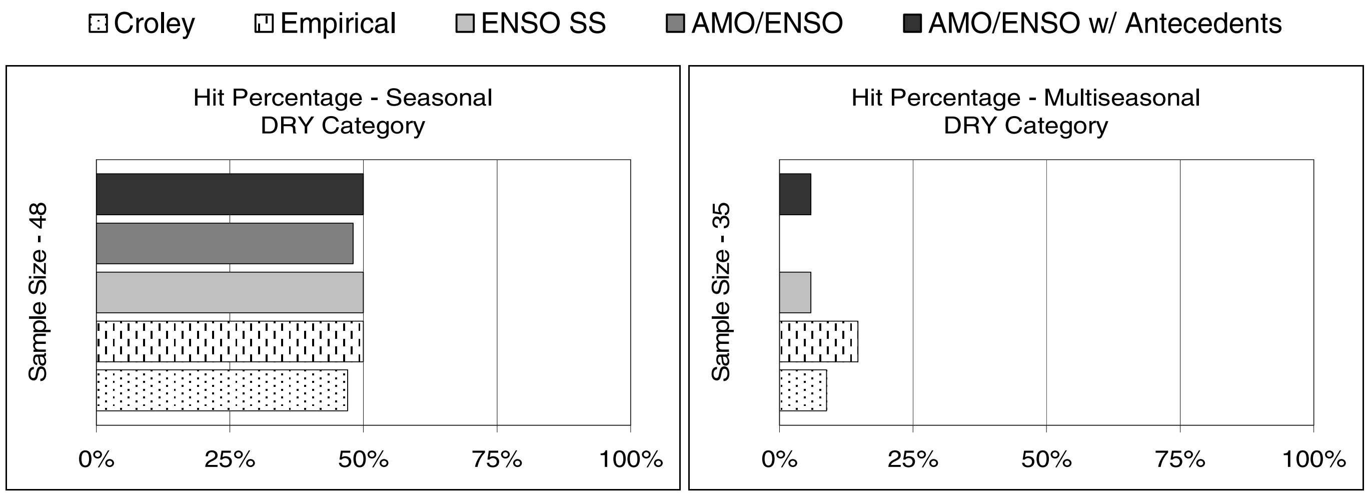

Figure 4. Percentage of Correct Dry Predictions for Lake Okeechobee Inflow Forecast Methodologies

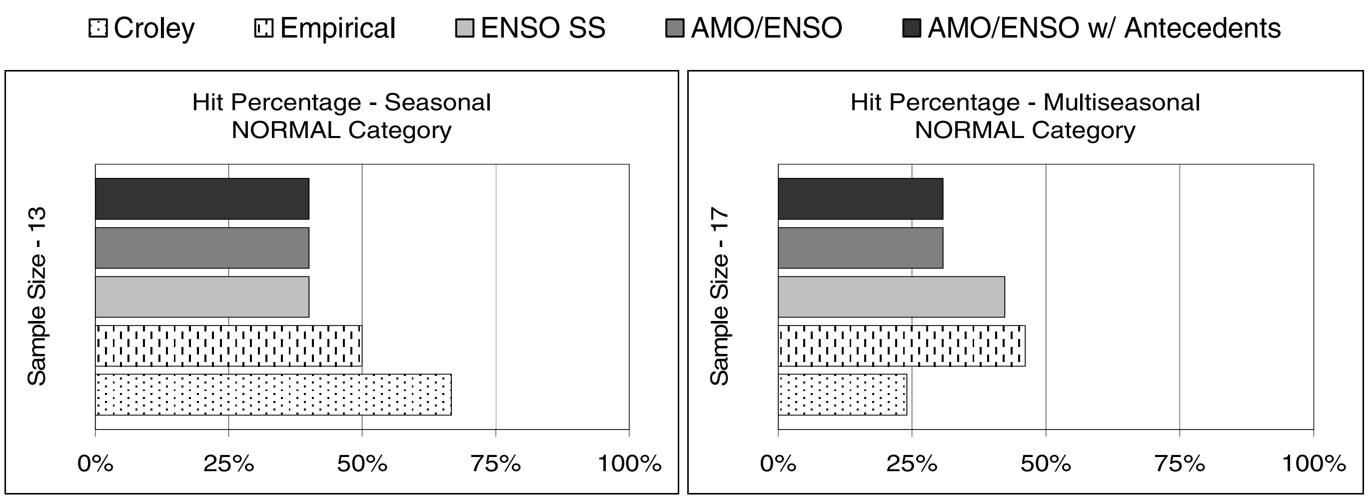

Figure 5. Percentage of Correct Normal Predictions for Lake Okeechobee Inflow Forecast Methodologies

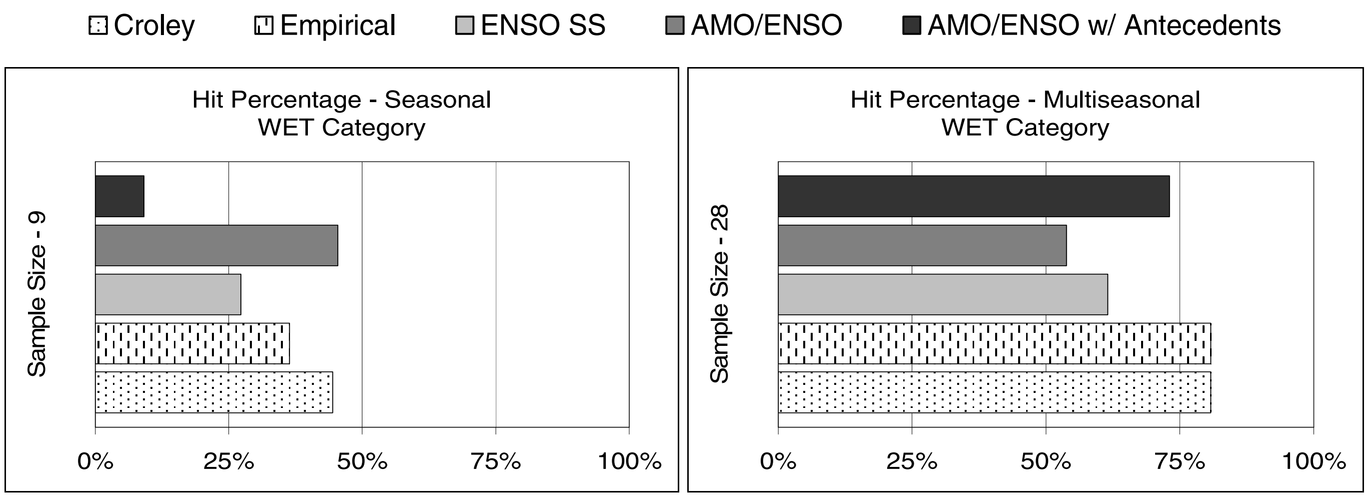

Figure 6. Percentage of Correct Wet Predictions for Lake Okeechobee Inflow Forecast Methodologies

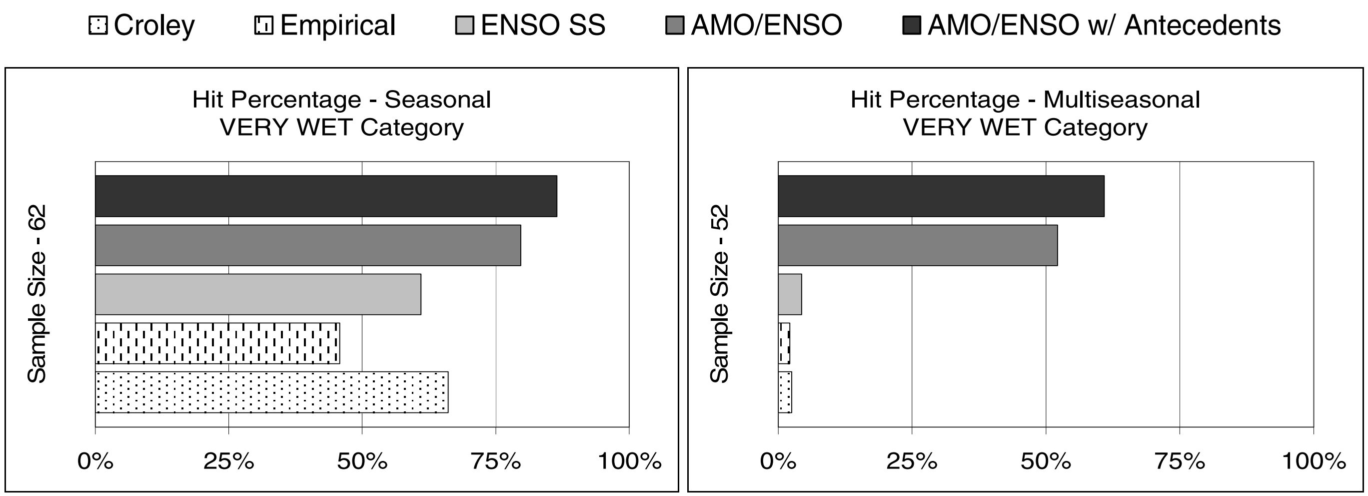

Figure 7. Percentage of Correct Very Wet Predictions for Lake Okeechobee Inflow Forecast Methodologies

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