IMPACT OF CLIMATIC ANOMALIES ON DESIGN OF LAND APPLICATION SYSTEMS FOR DISPOSAL OF WASTEWATER

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INTRODUCTION

Many activities and structures which are a vital part of everyday life are strongly sensitive to weather and climate. Infrastructure such as urban development, transportation systems, reservoirs, business operations, and agricultural practices are designed using data that describe climate conditions under which this societal framework will exist. A critical part of these design processes is the assumption that climate is constant. As a result, most weather-sensitive structures and practices have been designed and built using existing climate data and the premise that climate is stationary and never-changing.

Today there is a greater awareness of the potential for short-term fluctuations in climate conditions on scales of decades or centuries. This realization has come about because of the availability of long-term climatological records and advanced technology for data management and computer analysis. These advances have allowed an enhanced understanding of the temporal aspects of climate. For example, Chagnon et al. (1993) showed that the increase in flooding in the Chicago area over the last 30 years is due more to a shift to a wetter regime with more heavy rains than to the ever increasing urbanization. Water structures designed in the Midwest using heavy rainfall data from the last 40 years would be very different from those designed using data from the first 40 years of this century.

Climate is marked by fluctuations, typically periods of five to 20 years, in which certain types of weather persist (Chagnon 1992). Examples over the past 15 years in the U.S. have been higher temperatures, more storms and droughts, and greater variability in the year-to-year weather. Yarnal and Leathers (1988) related interdecadal variations in temperatures and precipitation in Pennsylvania to changes in atmospheric circulation over the state. They found that the mean position and shape of the wave forms in the mid-tropospheric flow aloft produced clear interdecadal variations. Specifically, they showed that lower amplitude flow was related to higher temperatures and more variable precipitation, whereas higher amplitude waves produced lower temperatures and conspicuous dryness in the 1960s and a very wet 1970 decade in the state.

Climate records in Mississippi demonstrate this same pattern of constant fluctuation. Figure 1 shows that the years from the 1920s through the mid 1950s were warmer than before or after that period and that a noticeable change began in about 1957 that continues into today. The figure also shows that annual totals of precipitation have been more highly variable since about 1980, with several groups of years below normal followed by groups of years that were above normal. The influence of such fluctuations may be especially striking in design considerations.

Pote and Wax (1994) developed a computer simulation method to model the operations of land application wastewater disposal systems in the southern region of the U.S. using 30 years of daily weather data. This analysis was later expanded to include five sites across the southern region. Over the time series, one decade was remarkably different from the other two in design results at all five sites. The difference is attributed to the influence of a climate fluctuation like those described above. The purpose of this study is to demonstrate the effect of such an abberation on climatological design criteria and to identify the responsible weather pattern.

BACKGROUND

Pote and Wax (1994) studied the experience of a small coastal city to illustrate the need for considering climatic attributes in design of land application systems. The facility used land application as the final disposal of treated effluent. Problems with the new system, which were related primarily to periodic flows too high for the irrigation system, the plants, and the soil to accept, developed rapidly. Review of the design of the city's system revealed that there was little scientific literature on which to base hydrologic limitations of land application designs.

Based on this one location, it was concluded that an improved approach to designing land application systems could include running several years of actual daily weather data through a simulation of the system. This procedure could allow the determination of the incidence and severity of failure and the testing of design alternatives. Availability of digitized long-term daily weather records for many locations should make this a viable method for predicting the performance of these systems in varying climatic settings. Five sites were chosen for the analyses: Clemson, SC; Fairhope, AL; State University, MS; Stuttgart, AR; and Thompson, TX.

METHODS

Simulation of the operation of a land application disposal system on a daily basis over the thirty year period 1961-1990 used holding pond and application field size as the major dependent variables in the model. A base wastewater flow of one million gallons/day (**mgd**) was assumed at each site.

For each day, the model first calculated daily wastewater flow (**mgd**) using the equation

$$W_{day} = 1.0303*B + 1.3983*P_{day} + 0.7690*P_{day-1} + 0.4931*P_{day-2} - 0.0812$$

where B = base wastewater flow
P_{day} = precipitation same day
P_{day-1} = precipitation previous day
P_{day-2} = precipitation two days previous

to account for the effects of precipitation (**P**) on the base flow. Next, the model calculated climatic water consumption capacity (**E**) and determined days on which field application of effluent could occur. If daily **P-E** was positive, the model set the amount of wastewater that could be applied to the field as zero for that day. Otherwise, if daily **P-E** was negative, the model converted that amount to **mg** and applied that amount of wastewater to the field that day.

Next, if the combination of the amount of wastewater in cumulative storage from the previous day, plus the daily flow calculated for that day, minus the amount of wastewater applied to the field that day was greater than zero, that amount was held as cumulative storage. Otherwise, cumulative storage was set at zero for that day. Finally, the amount of cumulative storage for each day was used to determine the size of storage ponds at a depth of 12 feet required to contain the cumulative storage.

Several assumptions were included in this model. First, no effluent was applied to the field beyond that amount which could be used by **E** in excess of **P** on a daily basis. This approach limits the movement of nutrients since they become potentially available to the plants by passive uptake. Second, the effluent was always applied at the maximum level of **E**. Third, when **P** occurred it influenced the available **E** for no more than one day; if daily **P-E** was positive, that amount greater than zero was assumed lost to either runoff or to deep percolation by the beginning of the next day. Fourth, all factors in the model could be equally applied at all five sites. Fifth, consumption of wastewater by infiltration was not addressed in the model, making the model more conservative and more accurate for low infiltration soils.

The model was run numerous times at each site, using varying application field sizes to find the minimum workable size. Minimum workable size was defined as a system in which the holding pond was around 10% of the size of the application field, and holding ponds at all five sites were similar in size. After thus determining a minimum field size, the model was run additional times with field size increasing by 40 A each time.

Each simulation was named for the application field size in the model; thus there were 640 A models, 600 A models, and so forth. This empirical procedure was used to search for an optimal system size, based on the interaction between holding pond size and application field size at each location that would assure successful operation yet minimize land used for the system.

The maximum storage requirements for each month in the 30-year period were established from the results of the selected optimal simulation at each site and were tabulated to serve as the design criteria. Each of these monthly data sets was ranked in descending order to establish probabilities by quantiles. Thus it was possible to determine maximum storage requirements in any given month at selected probability levels (99, 90, 50, and 10%) for each location in the region. Additionally, these data sets were used to find the probability of success of a range of holding pond sizes (60, 50, and 40 A with a depth of 12 feet) at each location.

Results of the spatial analyses revealed the existence of a temporal anomaly at each location, wherein design requirements differed substantially during the mid 1970 years. This revelation necessitated a search for the reason for the anomaly. Since the model was sensitive to the number of precipitation days occurring, that information was tabulated from the climate databases for each year at each site. Cumulative precipitation days were then computed for comparison with the design results.

Next, an analysis was conducted to determine if a fluctuation in atmospheric circulation patterns occurred over the region, impacting both the number and timing of precipitation days and creating a persistent condition that produced rain events. The Clemson site was selected for this part of the analysis because the anomaly was most pronounced at that site. Daily weather maps were used to classify each day of 1965, 1975, and 1981 into one of two synoptic situations over the southeast--one enhancing and the other inhibiting persistent rainy conditions at the Clemson site. The number of times the synoptic type that enhanced persistent rain days was present was tabulated by months for the three years.

RESULTS

Figure 2 shows the maximum storage requirements for each month of the 30-year period as established from the results of the selected optimal simulation at each site. It can be seen in the figure that each site manifests a pattern in the middle of the time period in which maximum storage requirements are consistently the highest of the entire period. Note that all the recommended systems can meet maximum storage requirements with holding ponds around 60 A, but that the majority of maximum storage requirements can be met with a 40 A pond. The temporal anomaly is responsible for the larger holding pond requirement--without that anomaly in the record, system design storage requirements would have been reduced by at least one-third. The analyses indicated that those years with an excessive number of rain days or with extended wet periods needed the larger holding pond capacity.

Figure 3 shows that, 99% of the time, monthly maximum cumulative storage could be held in a 60 A pond at all locations except Clemson and Thompson. At the 90% probability level, monthly maximum cumulative storage required a pond size of less than 60 A at all locations. Monthly maximum cumulative storage requirements were similar for all locations at the 50% probability level, with a 30 A pond meeting requirements at all sites.

Figure 4 shows that a 60 A storage pond provides success a minimum 97% of the time in all months at all locations. Only the extreme east and west locations do not manifest virtually complete success (99% probability) with a 60 A storage pond. A 50 A pond provides success ranging from 83-99% of the time at the eastern and western extremes of the region, whereas that pond size assures system success from 93-99% of the time at the other locations. A 40 A pond provides success from a low of 80% to a high of 99% of the time across the region, the lows again occurring in the extreme eastern and western locations. It can be seen in Figure 4 that the eastern and western extremes consistently exhibit the greatest variability of success with all three storage pond sizes. Probability of failure in any month, defined as an overflow on any day of the month, is the inverse of the success rate.

The Clemson climate record showed an increased number of precipitation days beginning in 1971 and continuing through the middle of that decade. Figure 5 shows a pattern of declining cumulative precipitation days through the decade of the 1960s followed by a continuous increase through the first half of the 1970s. This is the obvious cause of the inflated design storage requirements as depicted in Figure 2.

Two different atmospheric flow patterns affecting weather in North America, and specifically over the southeast, are shown in Figure 6. The solid line depicts an upper air ridge centered in the middle of the continent with convergent (subsiding) flow affecting areas to the east, favoring atmospheric stability and no precipitation there. The dashed line depicts the displacement of the ridge with a trough aloft influencing weather to the east, a pattern favoring divergent (rising) flow of warm, moist air from the Gulf of Mexico over the southeast, resulting in instability and the development of precipitation in that part of the continent. A shift from one pattern to the other in North America can be the result of many global-scale phenomena--ENSO (El Nino-Southern Oscillation), sea ice extent or changes, volcanic eruptions, sea surface temperatures, or even cold air damming in locations as remote as eastern Asia.

Table 1 presents results of the synoptic weather analysis, showing that the latter upper air flow pattern prevailed during the middle decade of the 30-year study period. This weather pattern is not at all unusual in the southeast and it normally occurs many times each year. However, this analysis points out that there are periods of time when this particular upper air flow pattern exercises persistent control over surface weather events in the form of more precipitation days spaced more closely together. This was precisely the situation that influenced the design criteria for wastewater disposal by land application at all locations in the southern region.

CONCLUSIONS

Spatial aspects of this study show that the best design for land application of wastewater in the southern region requires system sizes ranging from 640 A in the coastal and eastern parts of the region to 400 A in western and inland locations. Furthermore, results show that a recommended-size system with a 60 A storage pond 12 feet deep should fail no more than 3% of the time, a 50 A pond no more than 17% of the time, and a 40 A pond no more often than 20% of the time in all months and at all locations in the region. Conversely, these specifications prevent any failures in 97%, 83%, and 80% of the years, respectively.

The temporal aspect of this study shows that atmospheric circulation patterns and resulting synoptic weather types caused greater numbers of precipitation days more closely spaced together, producing substantially larger design requirements during the mid 1970s. It is unclear why this, or any other weather pattern, becomes fixed for a period of time as happened in the 1970s in the southeast, but it is clear that the result vividly affects environmental and economic activities and functions. This study shows the effect of such a case on the design of hydrologic features wherein an eastward shift in the hemispheric-scale Rossby wave chain resulted in a long-term fluctuation of surface precipitation events in the southeast.

If this climatic abberation had not been present in the record used in the simulations leading to the development of design criteria, systems could have been designed with capacities that were greatly oversized two-thirds of the time or that seriously malfunctioned at least a third of the time. These dire consequences on design criteria could have gone unnoticed with a period of record shorter than 30 years, demonstrating the need for as long a climate record as possible when using weather data in design.

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Table 1. Number of Days With Trough Aloft Present

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1965	6	10	8	2	4	1	0	0	3	5	0	2	41
1975	5	8	9	8	14	11	4	0	7	10	9	8	83
1981	4	3	7	6	7	3	0	1	0	4	0	8	43

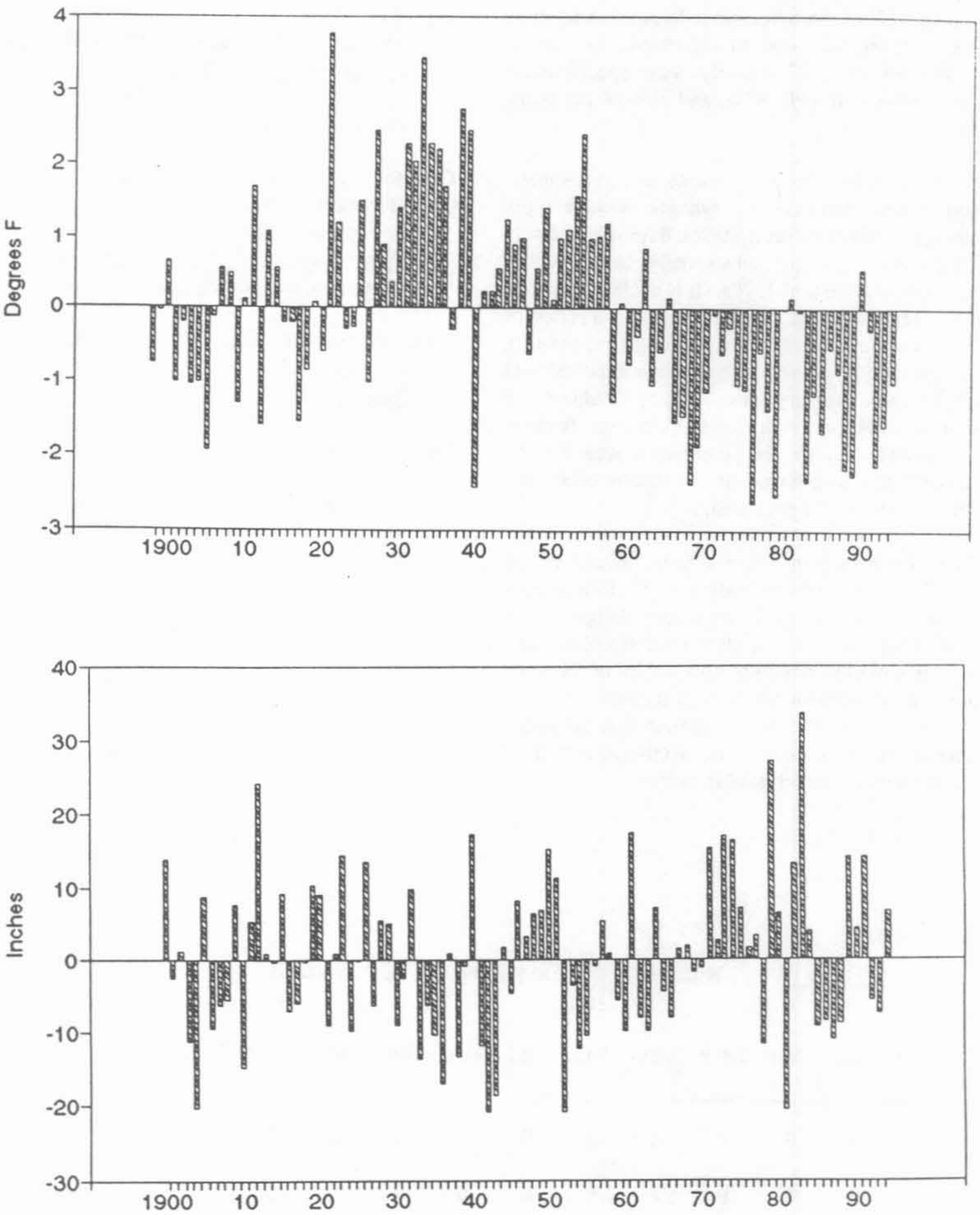

Figure 1. Annual temperature and precipitation departures, MSU, 1898-1994

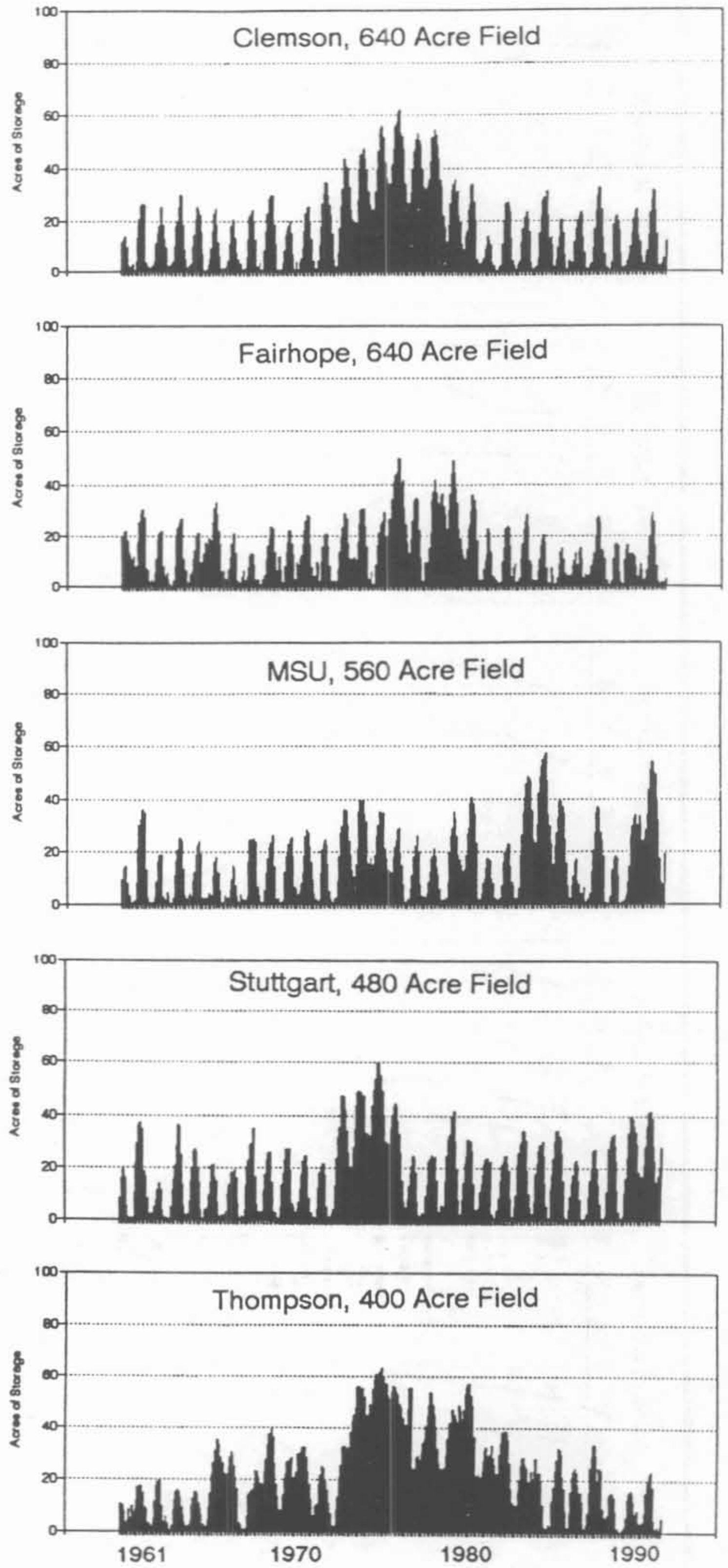

Figure 2. Monthly maximum cumulative storage required at 12' depth, with optimal system size at each site

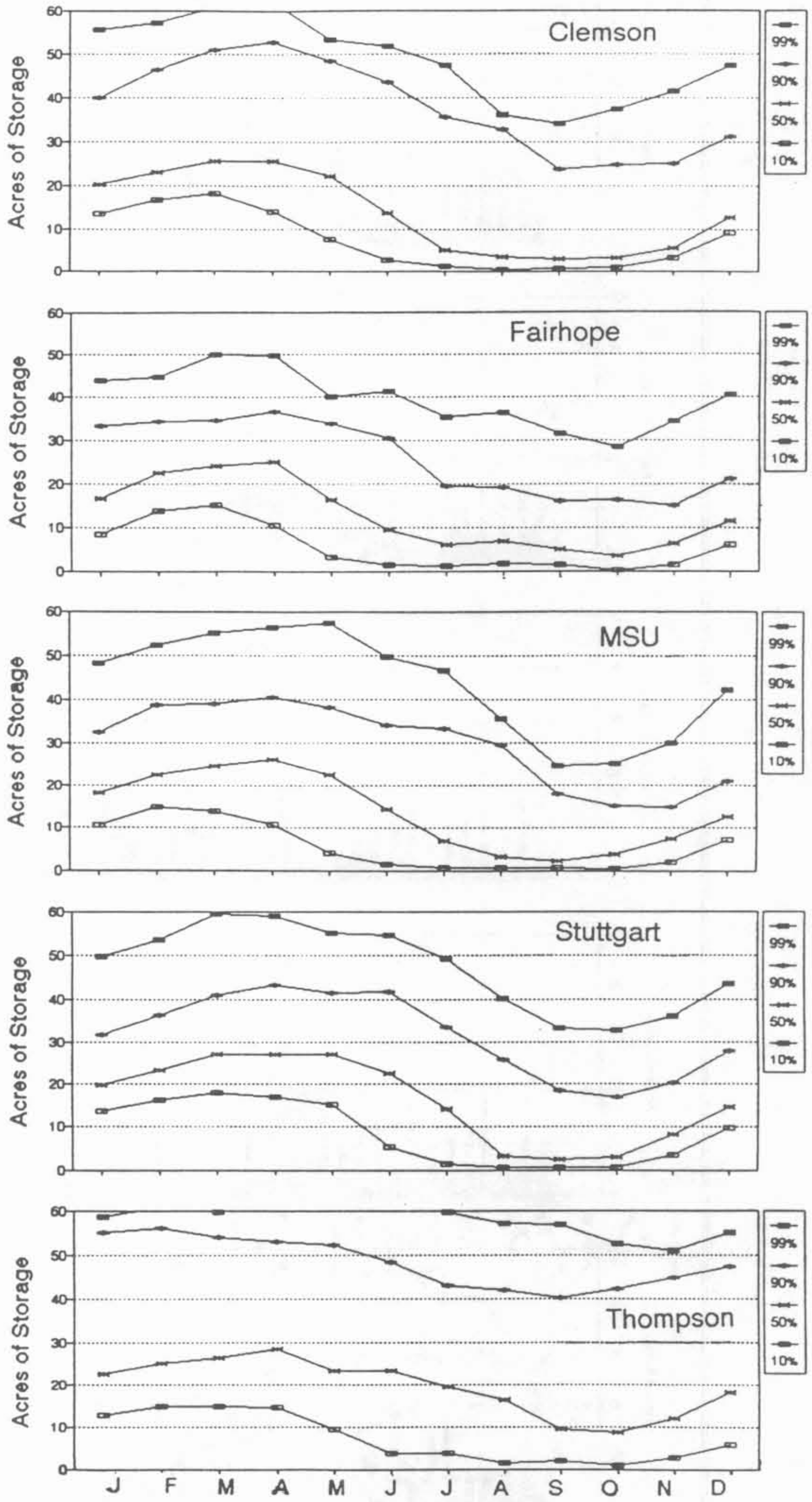

Figure 3. Monthly maximum cumulative storage required to prevent failure, 12' depth, four probability levels, optimal system size at each site

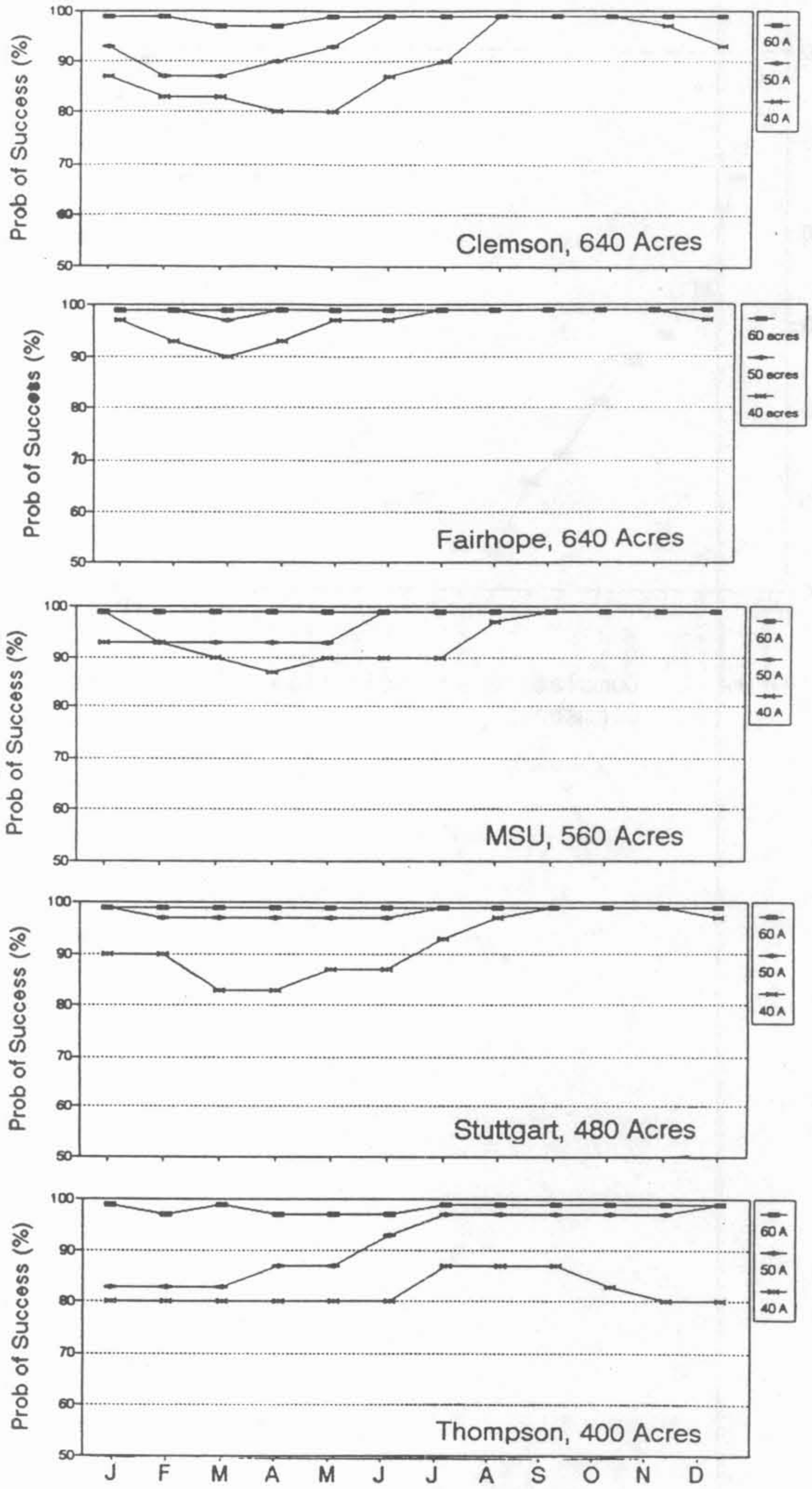

Figure 4. Probability of success by months, varying storage pond sizes, 12' depth, optimal system size at each site

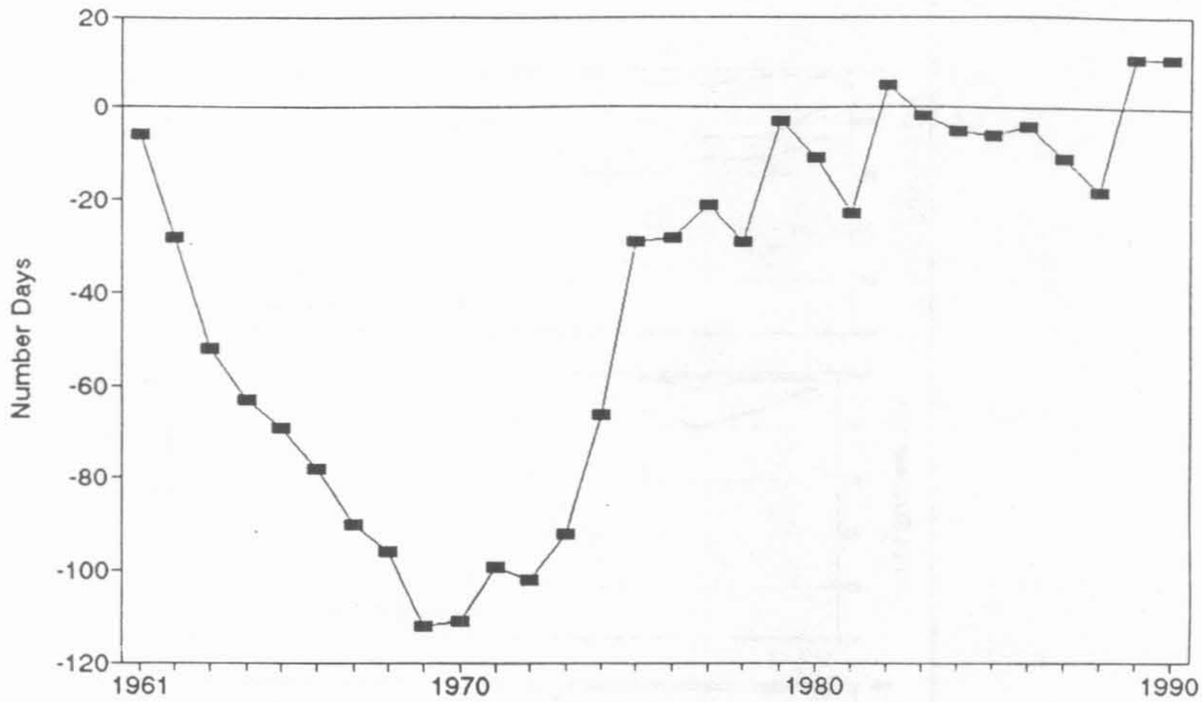

Figure 5. Cumulative precipitation days, departure from normal, Clemson

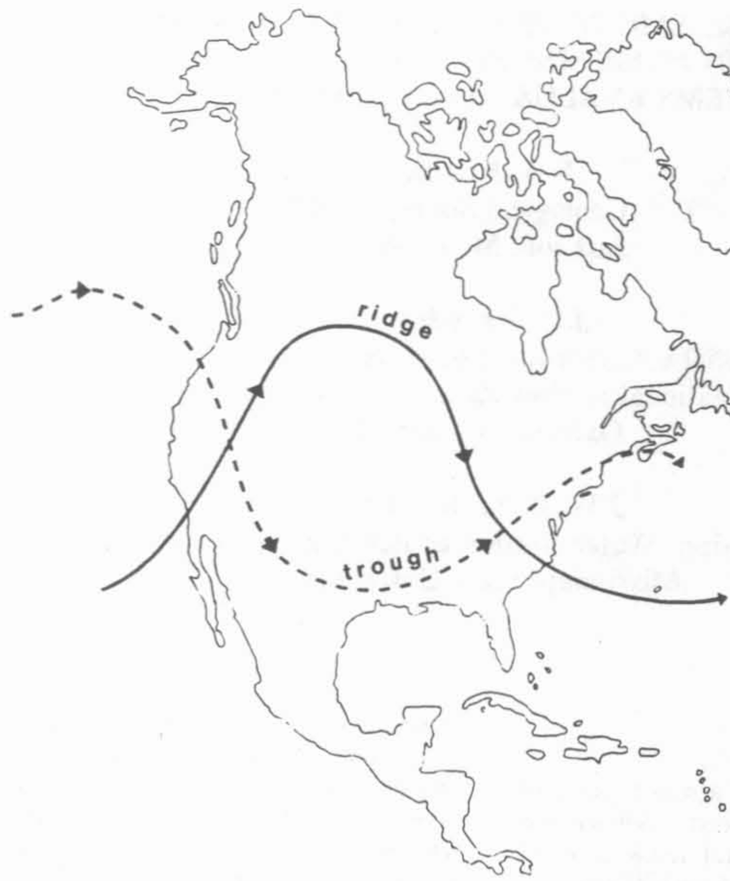

Figure 6. Upper air flow patterns inhibiting or enhancing precipitation events in the southeast