Vol. 6: 71-78, 1996 | CLIMATE RESEARCH Clim Res | Published January 30

Influence of climate on design of systems for land application of wastewater

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ABSTRACT: Climate regimes and gradients strongly influence both spatial and temporal opportunities and constraints for disposal of wastewater by land application. Availability of long-term digitized daily weather data allows analysis of the design of such systems by modelling multiple years of daily operations at different locations with computer simulation. A 30 yr simulation of a 3800 $m^3 d^{-1}$ disposal plant in 5 locations in the southeastern United States demonstrates that the best design requires disposal field sizes ranging from 256 ha in the coastal and eastern parts of the region to 160 ha in western and inland locations. Results further indicate that a recommended-size system with a 24 ha storage pond 3.7 m deep should fail (overflow on at least 1 day of a month) no more than 3% of the time, a 20 ha pond no more than 17% of the time, and a 16 ha pond no more often than 20% of the time in all months and at all locations in the region. Conversely, these specifications should provide success (no overflow on any day of any month) in 97, 83, and 80% of the time, respectively.

KEY WORDS: Wastewater · Climate · Computer simulation · Design criteria

INTRODUCTION

As global population increases, environmental problems also increase and cause a growing need for new methods and management techniques for controlling human impacts. The uneven pattern of population distribution across the earth's land surface further accentuates many such problems. For example, between 40 and 50% of global population is now urbanized, and such massive accumulations of people on such little land area create large amounts of waste to be disposed.

An even more unequal distribution of population is found along coasts and rivers where over 75% of the total world population is situated. Initial advantages of settlement in these locations (transportation, water supply, sewage disposal, etc.) must now be balanced against increasing regulations regarding disposal of waste to surface waters. As regulations governing discharge to streams and coastal waters become more restrictive in all parts of the earth, the option of no-discharge disposal systems becomes attractive. These systems use land application of waste as the final stage to treat effluent.

In a land application system, wastewater is typically applied at a rate compatible with the infiltration rate of the soil or based on a crop's ability to utilize some nutrient such as nitrogen or phosphorus. However, varying climatic characteristics of specific regions require design considerations for land application that have been largely ignored or the bases for which have been unavailable.

Land application is well established and functions well in arid regions, but only a small portion of earth's population lives in these areas and the number is not increasing. As the technology spreads to more humid areas, design of systems becomes problematic. Since more than 50% of the earth's land surface is under humid climate types (tropical, temperate, and continental), and since the majority of earth's population lives in these climate regions, this problem has global significance. In the southern region of the United States, specifically, there is sufficient interest in employing the technology but insufficient data and experience to guarantee performance. Therefore this study

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concentrates on developing standards to ensure sustained performance of such systems in the climatic regimes found in that region.

Frequent rainfall coupled with high humidity creates an evaporation regime in the eastern and coastal portions of the southern region of the U.S. that inhibits the efficiency and viability of the land application disposal method. In contrast, the inland and western portions of the region have moisture-energy regimes that enhance the viability of the disposal methods. The bases of these variations across the region are climatological; therefore, a climatological analysis should provide design considerations regarding the capabilities of this disposal method across the region. This study proposes use of a simulated record of daily operation of a land application system to construct design criteria.

One of the operational problems confronting land application systems in humid climate regions is that the amount of effluent flow into the system increases when precipitation occurs, and at the same time the net water requirement of plants decreases. Extra storage and extra land area are thus needed, but the amounts required have not been established. Traditionally, average or extreme years have been used for design purposes, but this present system of design has proved inadequate. For example, a system in operation in the coastal portion of the southern region of the U.S. was designed with its application field size based on average annual evaporation and its holding pond size based on a single extreme precipitation event. The system was immediately unable to handle the design flow and failed. The failure of the system was attributed to its inability to function during long, continuous periods of daily rainfall, a condition that cannot be detected on the basis of averages and extremes of climate. Current technology enables use of actual daily data over extended time periods.

Ideally design should be based on a long-term history of system operations under the daily and annual variations of climate. These data do not exist at present, yet it is clear that, hypothetically, performance of these systems should be closely linked to climatic events. Therefore, computer simulation of daily performance of systems using true climatic data may provide a good option for quantifying design parameters. Such deductive results have value particularly in cases where design criteria are needed but are not available.

The U.S. EPA routinely uses models to develop standards for permits. In these cases, the models' results are first implemented, then are empirically adjusted as data become available from use. In a specific case of using a deductive model for developing industry standards, researchers (Wax & Pote 1990, Pote & Wax 1993) employed a computer simulation, similar to the one suggested for this study, to model daily operation of aquacultural ponds. They created a 30 yr simulated record of groundwater pumping requirements under 2 management options. Results showed up to 75% conservation of groundwater by using the recommended management method. Field tests subsequently conducted (Rodrigue & Pennington 1992) confirmed the relationships between climate data used in the simulation and system performance.

The objectives of this research were to: (1) develop analyses that account for climatological opportunities and constraints in design of land application methods of wastewater disposal in differing climatic settings across the southern region of the U.S., principally within the humid subtropical climate region; (2) apply this approach to 5 locations in the region, representative of the gradients in that climate region, for comparative purposes; and (3) compare optimal design criteria and probabilities of success at each location.

BACKGROUND

Three basic methods of land application (irrigation, infiltration/percolation, and overland flow) are common, with irrigation being the predominant method of choice (Deese & Hudson 1980). Much of the literature has been devoted to determining the fate of the nutrients (Palazzo 1981, Barbarick et al. 1982, Mancino & Pepper 1992, Thoma et al. 1993). While design based on nutrient loading has been acceptable for arid climates, when this method of disposal is considered in humid areas the water balance becomes the dominant portion of the design. A purely hydrologic model was used by Mather (1953) in determining the minimum land area needed to dispose of large amounts of industrial effluents in New Jersey, USA. Al-Omari (1989) examined probabilistic design options of such a system based on 5 yr of data in Texas, USA, producing results in terms of field size and holding pond size.

Pote & Wax (1995) 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. Specific problems identified were: (1) Increased flow rates occurred during precipitation events, the very time when the ground was saturated. While some of this may have been correctable, much was not. (2) Sizing of the irrigation system was based on average rainfall and evapotranspiration, not on daily occurrence records. (3) The capacity of the storage pond was based on expected irrigation frequency, and made no allowances for variations from the average climatological regime, for increased flow during rain, or for long periods of saturated soil.

Based on this one location, Pote & Wax (1995) 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 allowed 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 other climatic settings.

METHODOLOGY

Site selection

Five sites were chosen for the analyses. Selection was based on the following criteria: (1) availability of serially complete and homogeneous daily precipitation and evaporation records in digital format; and (2) spatial dispersion providing representation of the climatic gradients between the humid eastern and more arid western portions of the region, as well as the coastal (maritime) and interior (continental) portions of the region.

Based on the best possible combination of these criteria, the following sites in the U.S. were selected: Clemson, South Carolina; Fairhope, Alabama; State University, Mississippi; Stuttgart, Arkansas; and Thompson, Texas (Fig. 1).

Climatological data

Daily precipitation (P) and pan evaporation (PE) data for the period 1961 to 1990 were obtained from observations of the National Weather Service Cooperative Observation System stored on CD-ROM (EarthInfo 1992). While the P data were essentially useful straight from the storage medium, there were cases where data were missing for up to a month. In these cases, P data from the same date in the previous year, or from the next-nearest location on the same dates, were substituted to make the records serially complete. It is estimated that less than 0.5% of the P data were thus derived.

The PE data were much less complete and reliable. In order to produce a complete daily PE record for each location, the existing data were used to compute an average for each day, and that value was then substituted where daily values were missing. The daily values for each year were then graphed and inspected for anomalous high and low points, which were subsequently located in the data files. Adjustments were made to correct for the identifiable errors, such as accumulated values following a long string of missing observations or typographical or keying mistakes. If the observation in question appeared obviously wrong but no cause was readily evident, the average value for that day was substituted. It is estimated that less than 4% of the observations were adjusted in this fashion. The result of this tedious procedure, followed for all 30 years at all 5 locations, was a reasonably accurate and complete record of daily PE that could be used to quantify the daily climatic demand for water (E) in the southern region.

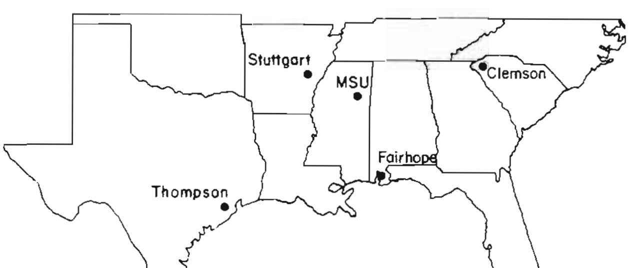

Fig. 1. Location map showing the 5 sites in the study region

Determining daily water balance

Estimation of *E*. PE is not directly comparable to true evaporative loss (E) from a large saturated surface, such as a freshly irrigated field or a lake or pond. Large surfaces of water and pans have differing degrees of exposure to wind and sun. Therefore, a correction coefficient is generally used to correct measured PE to a more realistic estimate of actual E.

In early studies (Schwab et al. 1955) a constant coefficient of about 0.7 was used to convert PE to E from large reservoirs. However, in more recent years it has been determined that the relationships vary from month to month and possibly from location to location (Kohler et al. 1955, 1959, Ficke 1972, Hounam 1973, Yonts et al. 1973, Ficke et al. 1977, Farnsworth & Thompson 1982, Farnsworth et al. 1982, McCabe & Muller 1987).

Boyd (1985), in a study conducted on a small, shallow pond near Auburn, Alabama, found that pan-to-pond coefficients ranged from 0.72 in March to 0.90 in September, with an average of 0.81 for all months. Because the environment in which these coefficients were determined is in the region under study, a factor of 0.8 was used in this study to correct the measured *PE* data to more realistic estimates of *E*. Table 1 shows, for spatial comparison, the range of *E* values thus determined from *PE* records for the 5 sites in this study.

Estimation of daily wastewater flow as influenced by precipitation. The available literature on infiltration and interception in municipal waste treatment systems leaves little doubt that effluent flow increases during periods of rainfall. Most of the literature is related to prevention of the phenomenon, but this study required the development of a predictive model that would quantitatively link rainfall events to increases in flow rates. Pote & Wax (1995) describe how regression analysis with SAS (1986) was used to determine prediction equations for that purpose.

In their study, daily wastewater flow data for a 4 yr period were obtained from 4 treatment facilities along with precipitation data for the same time period and same locations. The precipitation data were converted to the same volumetric measurement as wastewater flow (m^3 d^{-1}) for comparison and statistical analysis. An average, or base dry weather flow, was determined for each of the wastewater data sets.

Initially, 16 data sets were individually regressed, 4 years at each of the 4 locations, producing 16 prediction equations. Next, the 4 data sets for each of the 4 locations were combined for regression, producing 4 pooled prediction equations. Finally, all 16 data sets were combined with the variables being regressed to produce 1 overall pooled prediction equation. These 21 cases were compared to see which combination of variables yielded the maximum R^2 value.

The R^2 value for the overall pooled equation, 0.96, was the highest, indicating that the variables chosen to predict wastewater flow were good estimators and that the model should be applicable to any location and any year. The combination of variables that resulted in the best prediction was precipitation for the same day, precipitation from the previous day, precipitation from 2 d previous, and a base wastewater flow.

Table 1. Summary of average annual *E* rates, southern region of U.S. (cm)

Location	*E*
Clemson, South Carolina	107
Fairhope, Alabama	109
State University, Mississippi	117
Stuttgart, Arkansas	124
Thompson, Texas	134

Simulation of daily water disposal or storage requirements

The daily climatic demand for water (*E*) could be partially or totally satisfied by *P*. Therefore, on days with little or no *P* at any of the 5 sites, there would be a water deficit (negative *P–E*) which could then be satisfied by effluent. These would be the only days when disposal of effluent by field application could occur at any of the sites.

Daily comparisons of *P–E* were conducted for the 30 yr period at all sites. A simple procedure, cumulative summation of these daily values, provided comparative patterns of climatic water consumption potential at each site. For perspective, patterns of the wettest, the driest, and the average year of the period were graphed for each location. The average year was computed using the 30 *P–E* cumulative summation values for each day of the year.

A computer model was developed to simulate the operation of a land application disposal system on a daily basis over the 30 yr period 196 to 1990. Holding pond and application field size were the major dependent variables in the model. The model was run numerous times at each site, using varying application field sizes to find the minimum workable size. Minimum workable field size was defined as a system in which the field was around 10 times larger than the size of the holding pond. Holding ponds at all 5 sites were similar in size. After thus determining a minimum field size, the model was run additional times with field size increasing by 16 ha each time.

Each simulation was named for the application field size in the model; thus there were 256 ha models, 240 ha 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. A base wastewater flow of 3800 m^3 d^{-1} was assumed at each site. Results of each simulation were evaluated to determine design criteria for storage pond sizes at a depth of 3.7 m, and to assess the probability of success and failure for the various storage pond sizes.

For each day, the model first calculated daily wastewater flow (W_{day}) in m^3 d^{-1} using the equation

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

where B = base wastewater flow; P_{day} = precipitation same day; P_{day-1} = precipitation previous day; P_{day-2} = precipitation 2 d previous. This accounted for the effects of *P* on the base flow (Davis 1991). 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 m^3 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 any 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 3.7 m 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 because they become potentially available to the plants by root uptake only. 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 1 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 5 sites.

Consumption of wastewater by infiltration (I) was not addressed in the model. This makes the model more conservative and more accurate for low infiltration soils. The model could easily be adapted to account for I, but much of the soil's capacity for I may be required for irrigation and P alone. Furthermore, accurate and detailed soil infiltration rates for each soil type would be required.

Analyses of simulated records

Using a minimum of four 30 yr daily operation simulations at each of the 5 sites as described above, a recommended optimal system size was determined for each of the sites. The maximum storage requirements for each month of the 30 yr 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 (no overflow on any day in a month) of a range of holding pond sizes (24, 20, and 16 ha with a depth of 3.7 m) at each location. The results of these analyses at each location were compared to show the impact of climate on the design of land application systems across the region.

RESULTS AND DISCUSSION

Cumulative $P–E$

Results of the $P–E$ analyses document the potential for the climate to consume land-applied wastewater on a cumulative, daily basis across the southern region (Fig. 2). This spatial analysis demonstrates the climatic gradients and differences, in terms of $P–E$, from the coast to the interior and from east to west across the region, creating climatic advantages or constraints for land application disposal systems.

For example, the coastal-inland gradient is evident in the differences shown between Fairhope and

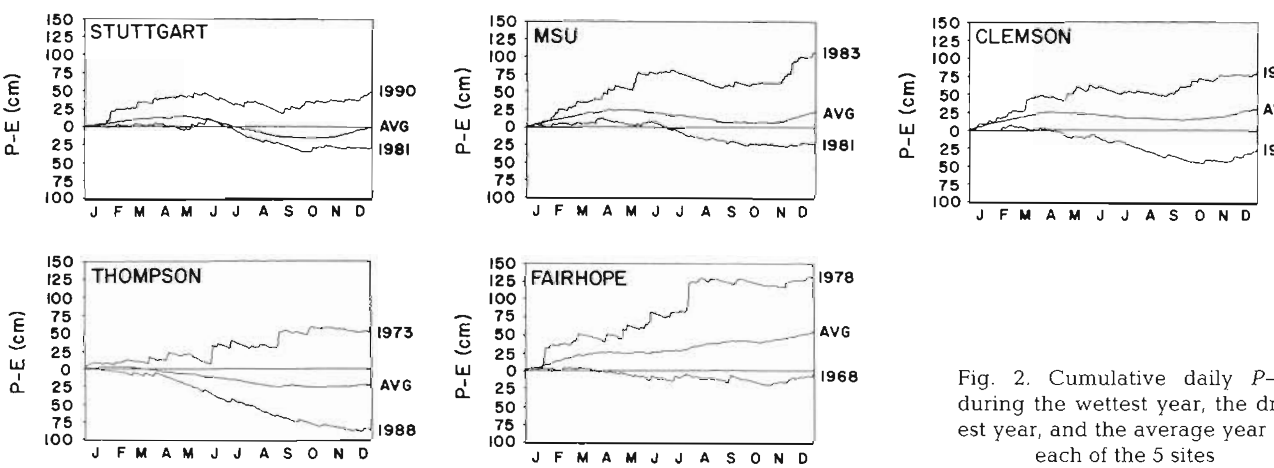

Fig. 2. Cumulative daily $P–E$ during the wettest year, the driest year, and the average year at each of the 5 sites

Stuttgart. In the average year, the inland location ends at zero while the coastal location ends with a positive 50 cm. In the wettest years, cumulative $P–E$ constantly rises through the entire year at both sites, producing net gains of water into the environment of only about 50 cm in the inland area but about 130 cm in the coastal area. Only in the driest years of the period did cumulative $P–E$ fall through the year, ending at −30 cm for the inland site but only at −8 cm for the coastal site, a minimal net loss of water from the environment. Conceptually, this analysis indicates the climatic disadvantage of the coastal environment but the climatic advantage of the inland areas of the region for the land application disposal method. That is, even in the period of highest evaporation, P is constant enough to continuously replace E on a routine basis much of the time in the coastal areas, yet the opposite is true in the inland portions of the region.

The east-to-west gradient is evident in the differences shown between Clemson and Thompson. In the average year, the western location ends at −25 cm while the eastern location ends with a positive 25 cm. In the wettest years, cumulative $P–E$ constantly rises through the entire year at both sites, producing net gains of water into the environment of only about 50 cm in the west but about 76 cm in the east. Only in the driest years of the period did cumulative $P–E$ fall through the year — ending at −90 cm for the western site but only at −25 cm for the eastern site, a minimal net loss of water from the environment. This analysis shows the climatic advantage of the western over the eastern portions of the region for the land application disposal method.

Recommended system sizes

The iterative simulation process resulted in the following recommended system sizes for each location: (1) Clemson, 256 ha; (2) Fairhope, 256 ha; (3) State University, 224 ha; (4) Stuttgart, 192 ha; and (5) Thompson, 160 ha. The decreases in system sizes by latitude from the coast to the interior and by longitude from east to west once again emphasize the climatic gradients across the region (Fig. 3). Fig. 4 shows the maximum storage requirements for each month of the 30 yr period as established from the results of the selected optimal simulation at each site. Note that all the recommended systems can meet maximum storage requirements with holding ponds around 24 ha, but that the majority of maximum storage requirements can be met with a 16 ha pond. The analyses showed that those years with an excessive number of rain days or with extended wet periods needed the larger holding pond capacity.

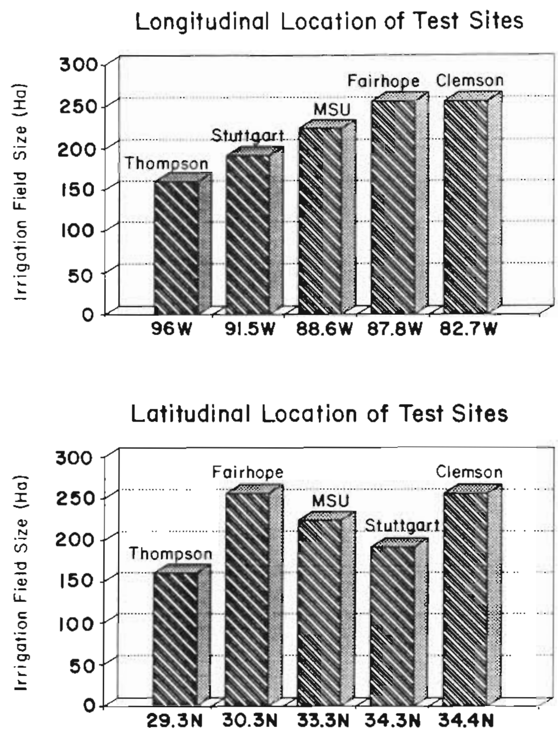

Fig. 3. Optimal system size by latitude and longitude

Storage requirements at selected probability levels

Results of the simulation using the optimal system size at each location showed that, 99% of the time, monthly maximum cumulative storage could be held in a 24 ha pond at all locations, with the exception of 2 months (March and April) at Clemson and 4 months (February, April, May, and June) at Thompson — the extreme locations in the region (Fig. 5). At the 90% probability level, monthly maximum cumulative storage required a pond size of less than 24 ha at all locations in all months. Maximum storage requirements at this probability level again occurred at Clemson and Thompson. Monthly maximum cumulative storage requirements were similar for all locations at the 50% probability level, with a 12 ha pond meeting requirements at all sites in all months.

Probability of success with selected holding pond sizes

Probability of success (no overflow on any day of the month) of the recommended system sizes at all sites with varying storage pond sizes 3.7 m in depth is shown in Fig. 6. A 24 ha storage pond provides success a minimum 97% of the time in all months at all locations. Once again, only the extreme east and west locations do not manifest virtually complete success (99%

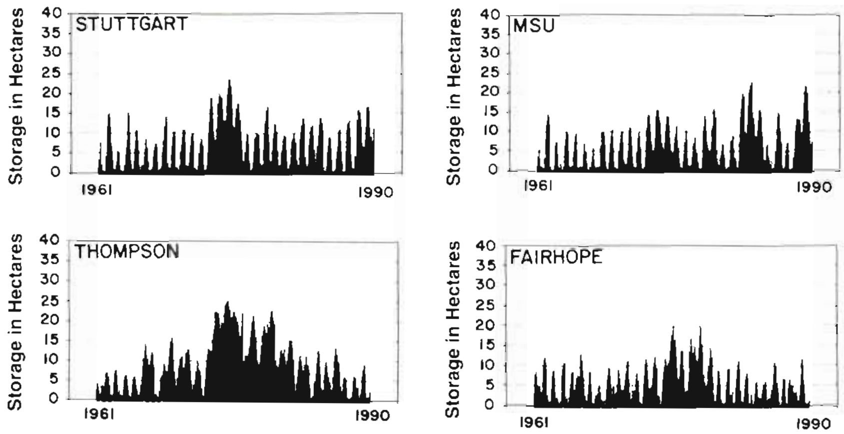
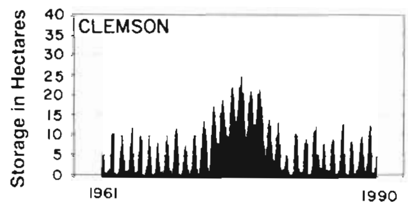

Fig. 4. Maximum cumulative storage required during every month of the entire 30 yr simulation (in ha at 3.7 m depth) with optimal system size at each of the 5 sites

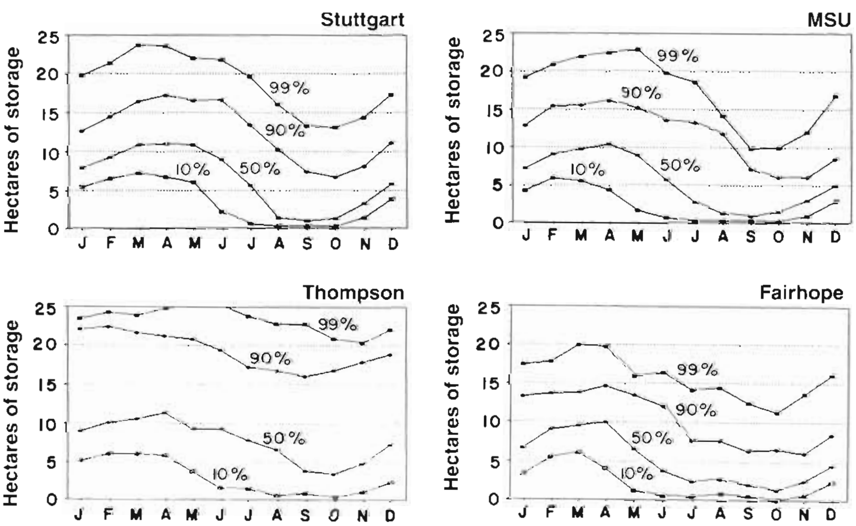
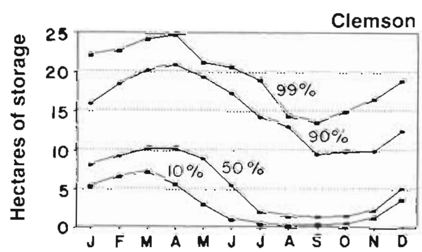

Fig. 5. Monthly maximum cumulative storage required to prevent failure (in ha at 3.7 m depth), at 4 probability levels, with optimal system size at each of the 5 sites

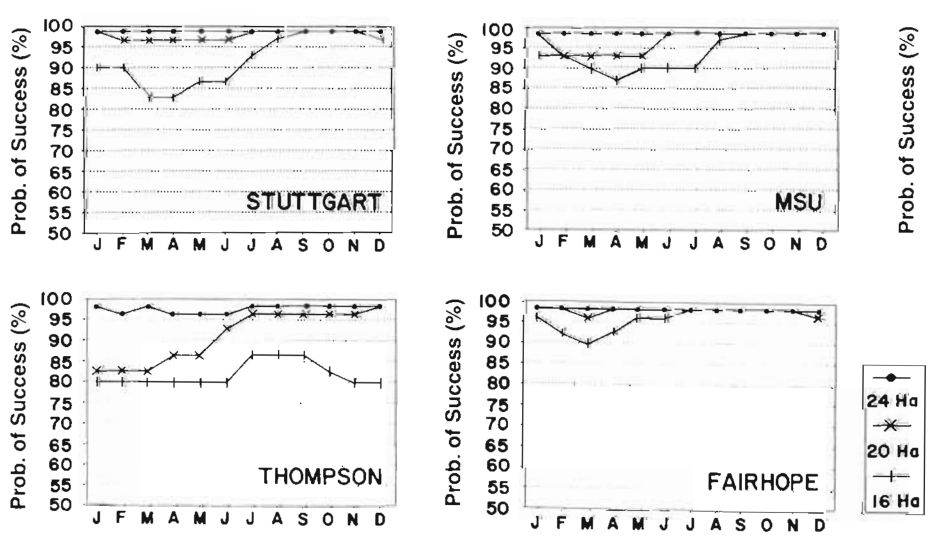
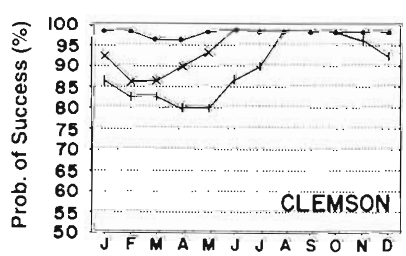

Fig. 6. Probability of success by months, for varying storage pond sizes (in ha at 3.7 m depth), with optimal system size at each of the 5 sites

probability) with a 24 ha storage pond. A 20 ha pond provides success ranging from 83 to 99% of the time at the eastern and western extremes of the region, whereas that pond size assures system success from 93 to 99% of the time at the other locations. A 16 ha 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 Fig. 6 that the eastern and western extremes consistently exhibit the greatest variability of success with all 3 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.

SUMMARY

To account for climatic variability and climatic gradients across the southern region, design of land application systems requires a climatological analysis of the day-to-day water balance. The availability of long-term digitized daily weather data offers the opportunity to test the design of such systems by simulating multiple years of operation at sites in geographically diverse portions of the region.

Simulation using 30 yr of weather data for a 3800 m^3 d^{-1} plant in 5 locations in the region shows that the best design requires system sizes ranging from 256 ha in the coastal and eastern parts of the region to 160 ha in western and inland locations. Furthermore, results show that a recommended-size system with a 24 ha storage pond 3.7 m deep should fail (overflow on at least 1 day of a month) no more than 3% of the time, a 20 ha pond no more than 17% of the time, and a 16 ha 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.

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Editor: V. Meentemeyer, Athens, Georgia, USA

Manuscript first received: May 23, 1995
Revised version accepted: September 12, 1995