LAND APPLICATION OF MUNICIPAL WASTEWATER: DESIGN BASED ON CLIMATIC CRITERIA

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INTRODUCTION

Disposal of municipal wastewater is becoming an increasing problem as human populations increase and regulations governing discharge to streams and coastal waters become more restrictive. The option of no-discharge systems is becoming more attractive for many communities, especially in coastal regions where disposal opportunities are limited. These systems use land application of waste as the final stage to treat effluent. Typically, wastewater is 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, climatic characteristics of the coastal region require design considerations for land application systems that have been largely ignored or the bases for such have been unavailable.

The amount of effluent flow in a land application system increases when precipitation occurs, while at the same time the net water requirement of plants decreases. Therefore extra storage and extra land acreage is needed, but the amounts required have not been established. Additionally, frequent rainfall coupled with high humidity create an evaporation regime in the coastal region that inhibits the efficiency and viability of the land application disposal method. The bases of these problems are climatological; therefore, a climatological analysis provides design considerations regarding the capability of this disposal method in the coastal region.

The objectives of this research were to:

1) develop analyses that account for climatological constraints in design of land application methods of wastewater disposal in the coastal region;

2) demonstrate this approach at a location in that region; and

3) define design criteria with varying probabilities of failure for this 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 and Hudson 1980). Much of the literature has been devoted to determining the fate of the nutrients (Barbarick et al. 1982; Palazzo 1981; Thoma et al. 1993; Mancino and Pepper 1992). While design based on nutrient loading has been acceptable for arid climates, when this method of disposal is considered in coastal areas the water balance becomes the dominant portion of the design. Al-Omari (1989) examined probablistic design options of such a system based on five years of data in Texas, producing results in terms of field size and holding pond size.

The recent experience of a small coastal city serves to illustrate the need for considering climatic attributes in design of land application systems. The waste treatment facility of Pascagoula, MS was moved inland because the city population was growing and disposal restrictions were becoming stringent. The new facility used land application as the final disposal of the 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 Pascagoula system revealed that there is little scientific literature on which to base land application designs, especially in coastal regions. 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.

An improved approach to designing these land application systems could include running several years of actual daily weather data through a simulation of the system, determining the incidence and severity of failure, and testing design alternatives. Recent availability of digitized long-term daily weather records makes this a viable alternative.

METHODOLOGY

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. Regression analysis with SAS (1986) was used to determine prediction equations for that purpose.

In an M.S. thesis study conducted at Mississippi State University (Davis 1991), daily wastewater flow data for the period 1985-1988 were obtained from the following four treatment facilities: 1) McCullough Environmental Services, Jackson, MS; 2) Natchez Wastewater Treatment Plant, Natchez, MS; 3) Mississippi Gulf Coast Regional Wastewater Authority, Pascagoula, MS; and 4) Ernest E. Jones Wastewater Treatment Plant, Starkville, MS. Precipitation data stored on CD-ROM (Earthinfo 1992) for the same time period and same locations were obtained from observations of the Cooperative Network of the National Weather Service. The precipitation data were converted to the same volumetric measurement as wastewater flow (million gallons) 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, four years at each of the four locations, producing 16 prediction equations. Next, the four data sets for each of the four locations were combined for regression, producing four pooled prediction equations. Finally, all 16 data sets were combined with the variables being regressed to produce one overall pooled prediction equation. These 21 cases were compared to see which combination of variables yielded the maximum R2 value.

The R2 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 two days previous, and a base wastewater flow.

Simulation of Daily Water Disposal or Storage Requirements

Daily precipitation (P) and pan evaporation (E) data from Fairhope, AL were obtained from observations of the Cooperative Network of the National Weather Service stored on CD-ROM (Earthinfo 1992). This location was representative of the coastal zone atmospheric environment and had the most complete record of the climatic elements needed for the simulation. A factor of 0.8E was used to correct measured E to a more realistic estimate of evapotranspiration losses (ET) from well-watered grasses (Schwab et al. 1981). This daily climatic demand for water (ET) could be partially or totally satisfied by P. Therefore, on days with little or no P, there would be a water deficit (P-ET) which could then be satisfied by effluent. These would be the only days when disposal of effluent by field application could occur.

Daily comparison of P-ET was conducted for the 30-year period. A simplistic procedure, cumulative summation of these daily values, provided patterns of climatic water consumption potential in this coastal environment. For perspective, patterns of the wettest, the driest, and the average year of the period were graphed. The average year was computed as the 30 P-ET values for each day of the year.

A computer model was developed to simulate the operation of a coastal land application disposal system on a daily basis over the thirty year period, 1961-1990. The model was run three times, using application field sizes of 600, 640, and 680 acres. A base wastewater flow of one million gallons/day (mgd) was assumed. Results were evaluated to determine design criteria for storage pond sizes at a depth of 12 feet 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 (mgd) using the equation

$$\text{Wday} = 1.0303 * B + 1.3983 * \text{Pday} + 0.7690 * \text{Pday-1} + 0.4931 * \text{Pday-2} - 0.0812$$

where

B = base wastewater flow
Pday = precipitation same day
Pday-1 = precipitation previous day
Pday-2 = precipitation two days previous

to account for the effects of P on the base flow. Next, the model calculated climatic water consumption capacity (ET) and determined days on which field application of effluent could occur. If daily P-ET 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-ET 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 ET 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 ET. Third, when P occurred it influenced the available ET for no more than one day; if daily P-ET was positive, that amount greater than zero was assumed lost to either runoff or to deep percolation by the beginning of the next day.

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 Record

Using the three simulated 30-year daily operation records, the maximum storage requirement for each month was retrieved and 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 what percent of the maximum quantities were exceeded in any given month with different application field sizes and different storage pond sizes.

RESULTS AND DISCUSSION

Results of the P-ET analysis document the regional potential for P to exceed ET on a cumulative, daily basis (Figure 1). In the wettest year (1978) and the average year (AVG), cumulative P-ET constantly rises through the entire year, producing net gains of water into the environment of about 50 inches and 20 inches, respectively. Only in the driest year of the period (1968) did cumulative P-ET fall through the year, and even then the net loss of water from the environment was minimal. Conceptually, this analysis indicates the climatic disadvantage of the coastal environment for the land application disposal method; that is, even in the period of highest evaporation, P is constant enough to continuously replace ET on a routine basis much of the time.

Results of the simulation using a 600 A field (600 A system) showed that, 90% of the time, monthly maximum cumulative storage could be held in a 65 A pond (Figure 2, Table 1). Simulation of the 640 A system showed that monthly maximum cumulative storage required a pond size of less than 37 A 90% of the time (Figure 3, Table 2). Results of the simulation of the 680 A system showed a requirement for a storage pond 35 A in size to contain the cumulative monthly maximum storage 90% of the time (Figure 4, Table 3).

Initial attempts to run a simulation of a 550 A system resulted in such spectacularly large storage requirements immediately that the simulation was halted. On the other hand, such little difference was found between the 640 A and 680 A systems that no further modelling was performed. Results of the simulations seem to indicate that the 640 A system is the best combination of amounts of land for disposal and for storage pond size in the coastal region. Further analysis was limited to that size system.

Probability of success of a 640 A system with storage ponds of 50, 40, and 30 A is shown in Figure 5. A 50 A storage pond provides success 99% of the time in all months. A 40 A pond provides success ranging from 99% in six months of the year to 90% in March. A 30 A pond provides success 99% of the time in October and drops to a low of 77% of the time in April. Probability of failure of the 640 A system is the inverse of the success rates. It can be seen that a 640 A system with a 40 A storage pond will be successful a minimum of 90% of the time in the coastal region.

SUMMARY

In the southeastern coastal 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.

Simulation using 30 years of weather data for a 1 mgd plant in the southeastern coastal region shows that the best design requires a 640 A application field and a 40 A storage pond 12 feet deep. These specifications prevent any failures in 90% of the years.

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Table 1. **Maximum monthly storage requirement in acres at 12' depth, 10 probability quantiles, for a 600 A system, based on 30 years of simulation.**

Probablity that storage pond area at 12' depth will be equal to or less than the indicated acreage

Month	99	90	80	70	60	50	40	30	20	10
J	67	60	38	32	28	23	20	18	17	12
F	75	61	43	37	32	29	25	24	20	17
M	80	64	42	39	35	32	30	27	23	17
A	77	62	41	37	36	32	28	26	20	13
M	76	57	40	32	30	27	22	20	12	8
J	73	58	36	26	21	19	18	13	7	2
J	63	53	23	19	17	16	13	10	4	2
A	64	48	23	18	17	16	11	8	4	2
S	59	42	24	19	17	16	11	5	3	2
O	57	39	24	19	16	14	6	4	2	1
N	53	45	26	19	14	12	8	7	4	2
D	60	53	31	26	22	17	15	12	11	7

Table 2. **Maximum monthly storage requirement in acres at 12' depth, 10 probability quantiles, for a 640 A system, based on 30 years of simulation.**

Probability that storage pond area at 12' depth will be equal to or less than the indicated acreage

Month	99	90	80	70	60	50	40	30	20	10
J	44	33	24	20	19	17	16	15	13	8
F	45	34	29	26	23	23	21	19	17	14
M	50	35	31	29	27	24	22	21	20	15
A	50	37	31	28	26	25	22	17	13	10
M	40	34	27	23	19	16	16	8	4	3
J	41	30	17	14	13	10	8	5	4	2
J	35	19	13	11	7	6	4	3	2	1
A	36	19	12	10	9	7	4	4	3	2
S	32	16	12	11	9	5	3	3	2	1
O	28	17	12	9	8	3	3	2	1	0
N	34	15	11	10	8	7	5	3	3	2
D	40	21	17	15	13	11	11	10	8	6

Table 3. Maximum monthly storage requirement in acres at 12' depth, 10 probability quantiles, for a 680 A system, based on 30 years of simulation.

	Probability that storage pond area at 12' depth will be equal to or less than the indicated acreage									
Month	99	90	80	70	60	50	40	30	20	10
J	36	27	19	19	18	15	15	14	12	9
F	37	34	25	22	21	20	19	18	17	12
M	41	35	27	25	24	22	20	19	16	14
A	40	34	26	23	22	21	20	15	14	4
M	36	27	24	16	15	13	11	5	4	2
J	30	21	12	10	9	5	4	3	2	1
J	30	12	8	7	6	4	3	2	2	1
A	31	11	10	8	5	4	4	3	2	1
S	25	13	8	6	5	4	3	2	2	1
O	22	15	8	5	3	3	2	2	1	0
N	27	10	8	6	6	5	4	3	2	1
D	33	15	14	12	10	10	10	9	8	5

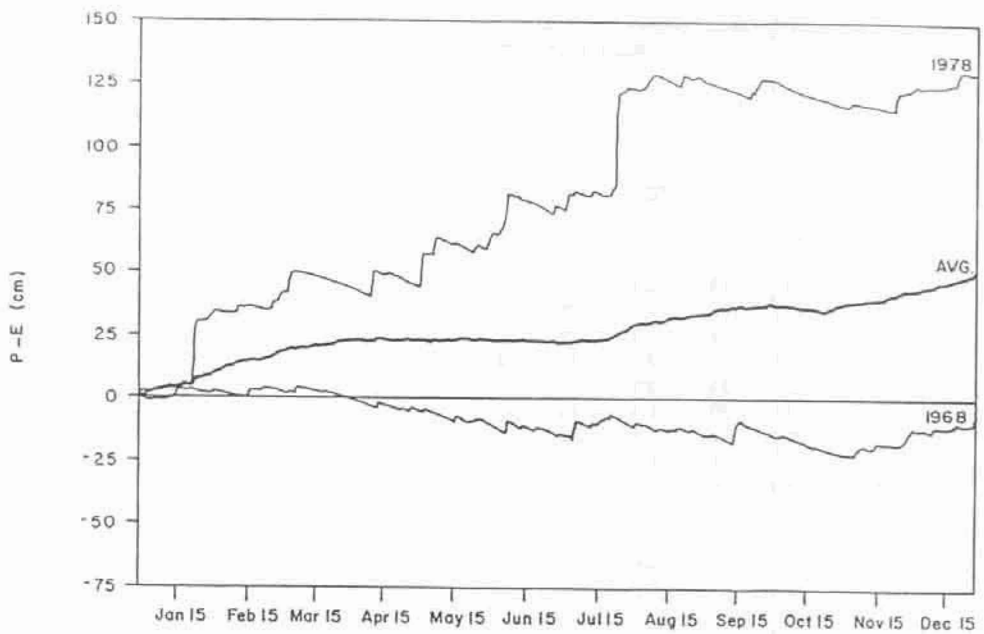

Figure 1. Cumulative P-ET, daily, Fairhope, during the wettest year (1978), the driest year (1968), and the average year (AVG).

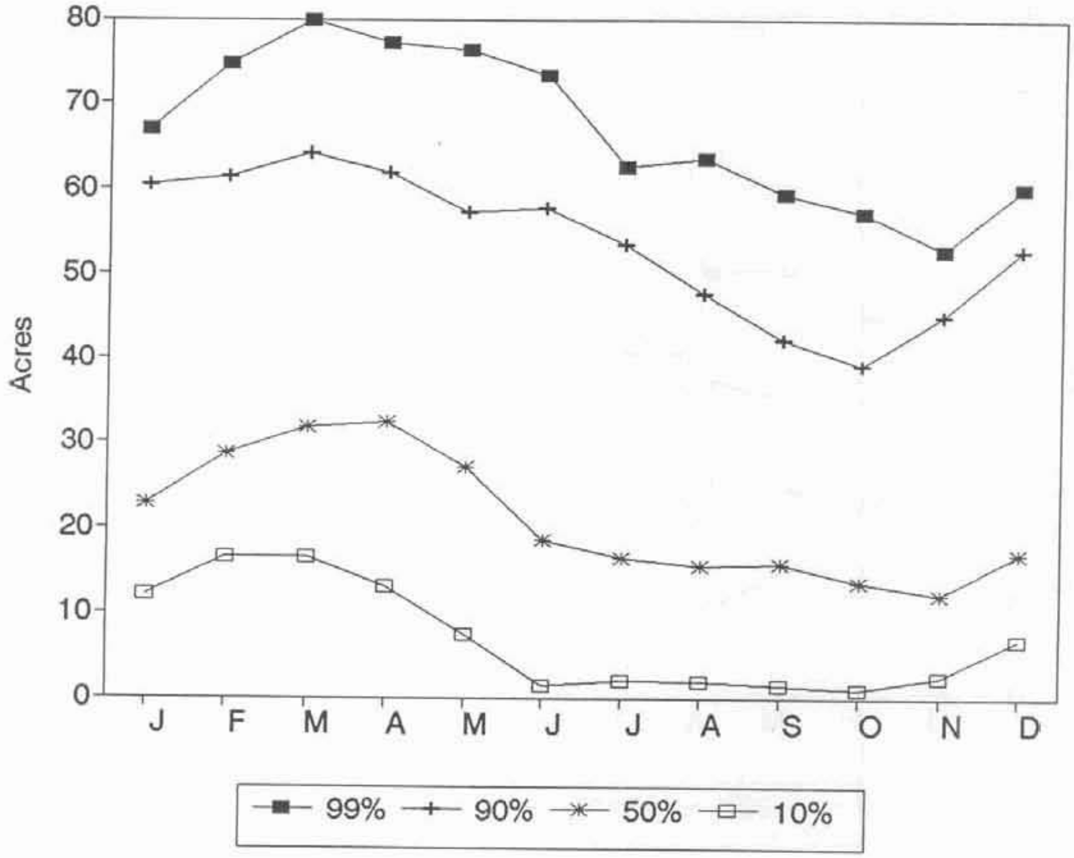

Figure 2. Monthly maximum cumulative storage required at 12' depth, 600 acre system, at four probability levels.

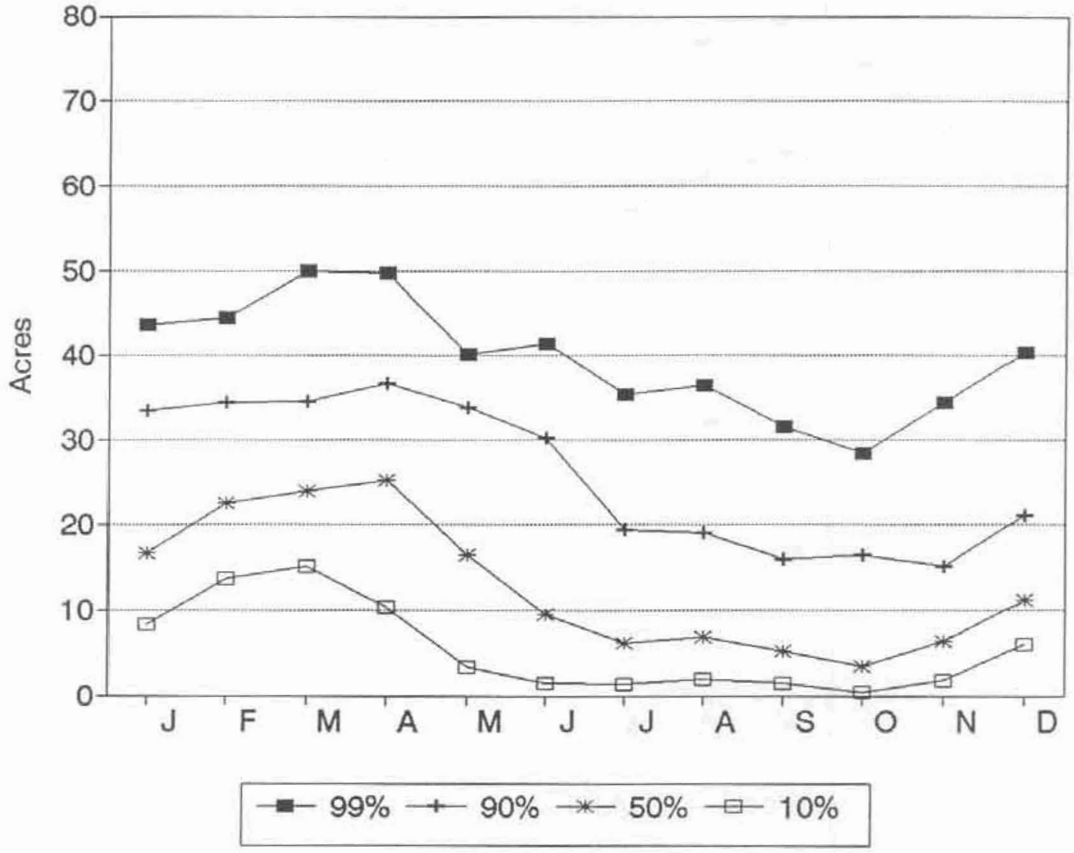

Figure 3. Monthly maximum cumulative storage required at 12' depth, 640 acre system, at four probability levels.

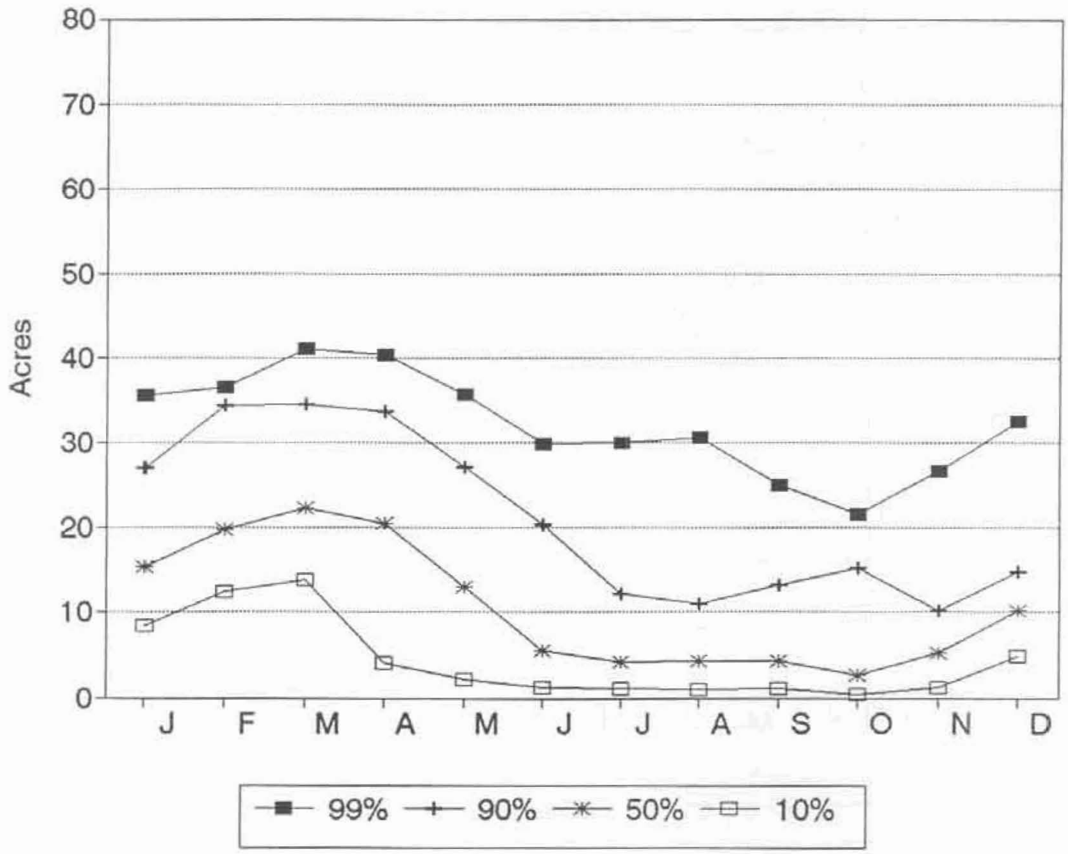

Figure 4. Monthly maximum cumulative storage required at 12' depth, 680 acre system, at four probability levels.

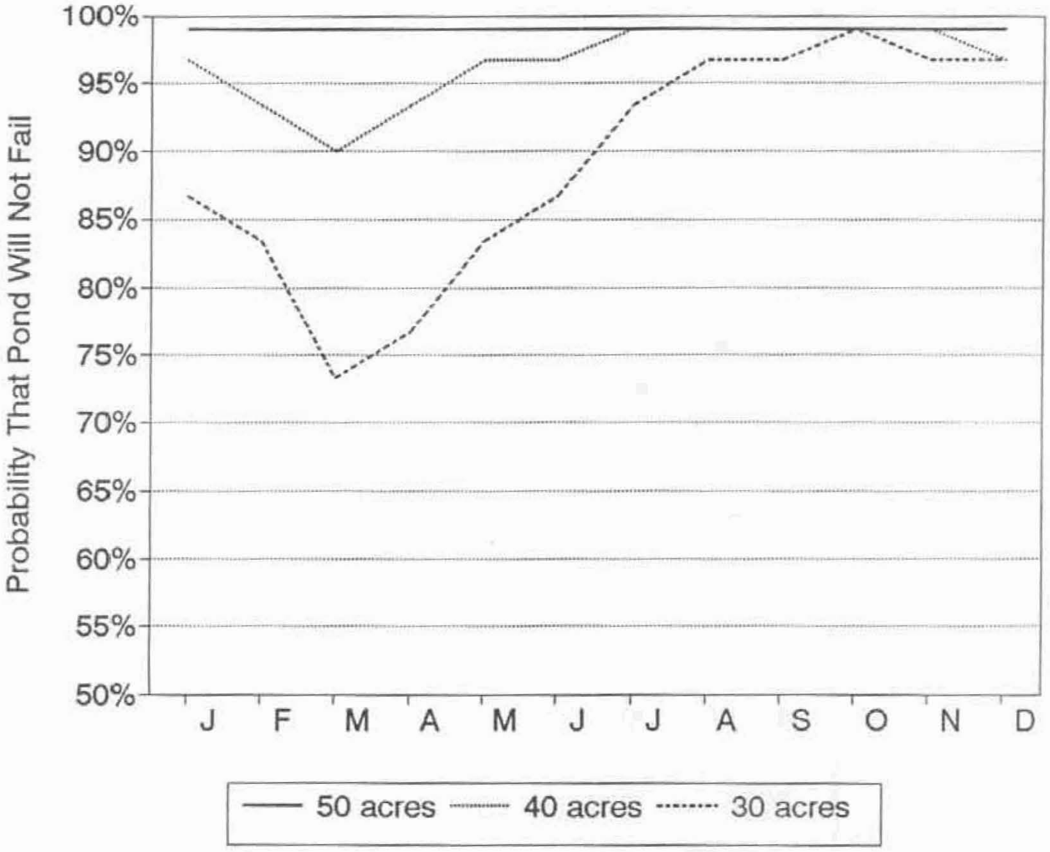

Figure 5. Probability of success by months, 640 acre system, with varying storage pond sizes at 12' depth.