

WRC RESEARCH REPORT NO. 119

RECYCLING AGRICULTURAL RUNOFF

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FINAL REPORT

Project No. A-077-ILL

This project was partially supported by the U.S.  
Department of the Interior in accordance with  
the Water Resources Research Act of 1964, P.L.  
88-379, Agreement No. 14-31-0001-6014.

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WATER RESOURCES CENTER  
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January, 1977

## ABSTRACT

### RECYCLING AGRICULTURAL RUNOFF

The recycling agricultural runoff concept is the storage of excess water from agricultural land and using this water for irrigation of the same land when moisture supplies are low. Coincidentally, the system also recycles pesticides and nutrients, keeping them out of other parts of the environment. The claypan soils of Illinois appear to be best suited for water recycling when surface storage is used. Sandy soils are best suited to interstitial water storage.

A review and analysis of literature on irrigation, drainage, reservoirs, pesticides, and nutrients as it pertains to a recycling system is presented. Nutrient and pesticide recycling result in negligible cost or benefits to agricultural crops. There was insufficient information to determine the economic benefit to the environment of this recycling.

A model was developed relating irrigation and drainage to crop yield using intermediate variables of soil moisture and air temperature. The model predicted that an acre-ft. of storage would be required per acre of irrigated watershed. The model was not successful at predicting the increase in yield resulting from irrigation and/or drainage.

An example economic analysis reveals that under present conditions recycling agricultural runoff is not economically justifiable as a general practice in the claypan region of Illinois.

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Final report to the Office of Water Resources Research, Department of Interior on Annual Allotment Project A-077-ILL, January, 1977

KEYWORDS: \*irrigation/\*water reuse/farm ponds/\*impervious soils/\*Illinois/  
computer models

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## Foreword

This study was initiated through the interests of the center director, who discussed with the authors of this report the need to examine the utilization of water on agricultural lands. If we are to provide enough food for the world's growing population, scientists must find means to modify the weather, control floods through either structural or nonstructural measures, and clean up the environment. One important way to preserve our waterways is by reusing wastewater rather than discharging it. In agriculture, there is a need to reexamine land drainage to see whether it would be practical to capture and store drainage water so that it can be later put to beneficial use for irrigation. As a result, researchers are considering various alternatives for the handling of water on agricultural lands.

Because water is obviously a prime requisite for crop production, irrigation is practiced in drier climates. Illinois, however, is considered to have a semihumid climate with adequate rainfall for field crops, and irrigation is not practical except in areas with sandy soils. Nevertheless, the variability of precipitation in Illinois is such that annually there are small areas with insufficient rainfall for maximum agricultural production, and occasionally large areas are deficient in precipitation. Furthermore, some soils retain water for use throughout the growing season, while others hold a very short supply.

This study was carried on in a region where the soil has a low water capacity and crops are readily affected by drought. Given the assumptions of this preliminary investigation, the results are not as positive as one might expect. An experimental field program currently under way, however, will

provide empirical data on which to base decisions as to whether the recycling of runoff would be justifiable as a general practice in the many regions of the Midwest.

It is hoped that this study will encourage other researchers to address the situation and that investigations will continue in order to fully examine the potential value of conserving and recycling water for agriculture.

Glenn E. Stout  
Director  
Water Resources Center



## I. INTRODUCTION

### A. CONCEPTS IN RECYCLING RUNOFF

The recycling agricultural runoff concept is the storage of excess water from agricultural land and using this water for irrigation of the same land when moisture supplies are low. This process is widely practiced in subhumid areas. However, the scope of this project was limited to humid areas where moisture is plentiful on a year-around basis but is poorly distributed seasonally, causing surplus moisture conditions especially in the spring and deficient moisture conditions during the summer.

Water recycling also implies the recycling of materials dissolved in the water. This might include nutrients, pesticides, and salts. Superficially, it appears that this coincidental recycling would have both negative and positive effects. The reuse of nutrients would appear beneficial. On the other hand, recycling of pesticides would displace their effect both spatially and temporally making their reuse undesirable. Salt recycling would probably not cause a problem. Since the only water which would be irrigated onto the cropland would be runoff from the same land, there would be little accumulation of salt.

The removal and storage of seasonal surplus water and the reuse of this water to correct seasonal deficient water supplies imply a management of this water to optimize profit, either monetary or humanitarian. This optimized profit probably means an increase in yield brought about by improved field conditions. Improved field conditions

can result from an improved soil-plant environment directly due to moisture management. Indirectly, moisture management can improve trafficability which allows field operations to be performed on time which in turn improves the soil-plant environment.

Two water storage methods are considered within this research. One is the surface reservoir, the other is interstitial water storage in lower soil layers.

#### B. RESEARCH OBJECTIVES

The objective of this research is to determine the potential of agriculture runoff storage for serving as a source for irrigation and as a nutrient and pesticide trap. The scope of the project is limited to a review and analysis of the literature on various components of the runoff recycling system and a computer model to simulate the combination of some of these components. No field testing is included.

#### C. JUSTIFICATION OF RECYCLING AGRICULTURAL RUNOFF STUDY

Recycling agricultural runoff appears to have promise for increasing yield in some soils in humid regions. Undoubtedly, there will continue to be increased demand for food. This increased demand, on an international level, is simply the extra food needed to feed the extra mouths of an increasing population. On a national level, food is increasingly being looked to as a material to solve a balance of trade deficit.

Presently, there is not enough data available to design an optimum agricultural runoff recycling system. This is not to imply that there is not design information on drainage systems, storage reservoirs, or irrigation systems. Information of this type is plentiful. The missing information is that required to size the individual parts to form an integrated system and then to evaluate its increased production potential. As a specific example consider the problem of evaluating increased yield due to improved drainage. For one soil, information is available on the expected improvement in yield in fields which have been drained over fields which have not been drained if the fields are planted on the same day. For another soil, information is available indicating how much sooner a drained field would become trafficable so that it could be planted. And finally, information is available which suggest that an earlier planting date increases yield. However, there are no accepted methods for integrating the drainage effects of improved soil-plant environment, improved trafficability and earlier planting date so that the true yield increase due to drainage can be evaluated.

#### D. SOIL TYPES

##### 1. Claypan Soils

The shallow claypan soils of south central Illinois have much more promise of benefit from recycling agricultural runoff using surface reservoirs than other soils. These claypan soils have a shallow silt loam topsoil with an impermeable silty clay subsoil. The soil has slow to moderate surface drainage and very slow subsurface drainage. This soil makes an excellent candidate for studying recycling agricultural runoff for several reasons:

- a. This soil is representative of the soil in a large geographic area. There are nearly 5 million acres of shallow claypan soils in Illinois alone. See Figure 1.
- b. The soil is impermeable, making the construction of impoundments simple and inexpensive.
- c. The land is quite flat. Therefore, conventional drainage channels must be very large and expensive. This makes the alternative of storing agricultural runoff, rather than transporting it away, more attractive economically.
- d. The shallow topsoil with the impermeable subsoil means that crops develop only a shallow root system. Hence, even short dry periods, which are not uncommon during the summer, quickly deplete the moisture in the shallow root zone and cause severe crop damage. However, the potential for production in these soils is great, evidenced by the fact that during those rare years in which moisture is equitably distributed throughout the summer yields on these soils rival the best soils in the Midwest. These facts help make the economics of irrigation very attractive.
- e. And finally, storage reservoirs are the only practical method of obtaining irrigation water in the area. There are no aquifers in the area capable of supplying well water in sufficient quantities for irrigation.

## 2. Sandy Soils

In general sandy soils are not good candidates for the storage and reuse of water. Sand is very permeable and defies the storage of

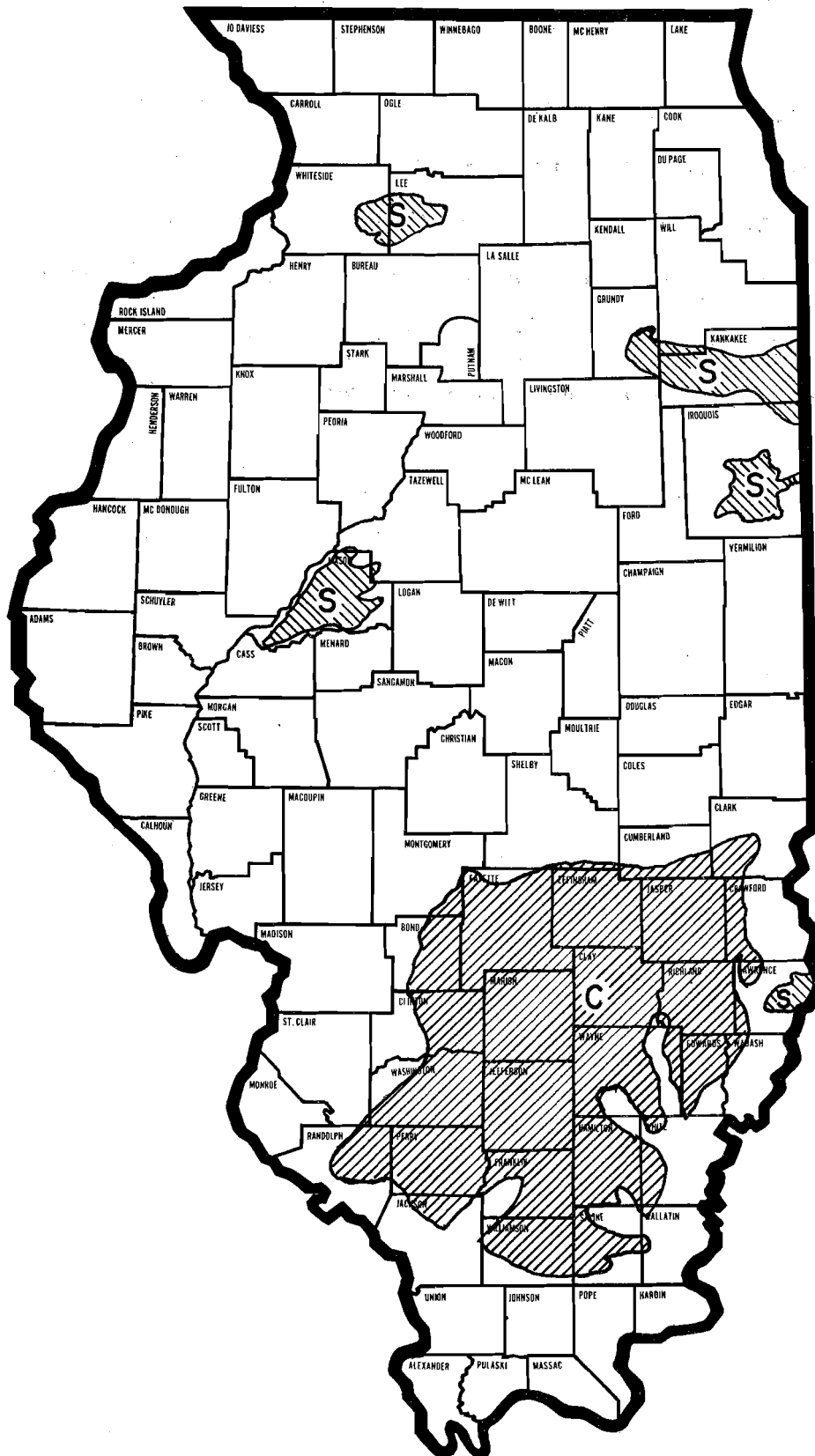


Figure 1. Location of sandy soils, S, and claypan soils, C, in Illinois.

water. Often, however, sand is found over an impermeable layer or a high water table, thus impeding the downward movement of water and allowing the possibility of interstitial water storage.

Interstitial storage has an advantage over surface storage because it does not use land surface area for storage. Additionally, the high permeability rate of sand allows the use of subsurface irrigation.

## II. SANDY SOILS

### A. SUBSURFACE IRRIGATION SYSTEMS

Figure 1 shows sandy soils in Illinois that have a low rate of overland flow. Agricultural runoff consists largely of seepage outflow. These soils occur along major stream valleys and are very responsive to irrigation. The groundwater under these soils can be used for irrigation in some cases where the aquifer is suitable for the development of wells. In other cases sandy soil is found over an impermeable layer and the natural condition of these soils is swampland or lake bed. Surface drainage ditches were installed to bring these soils into production. These generally are associated with a flat topography and a high water table that closely matches the water level in drainage ditches except immediately after high rainfall. This high water table and the high percolation rate meet two of the essential requirements for success of subsurface irrigation systems. Various nomenclatures have been used as these systems have gained some acceptance in about 200,000 acres of Illinois soils that meet this description. Two common terms applied to subsurface irrigation have been "controlled drainage" and "water table control." These terms have been descriptive of such systems because of the need to raise and lower the water table to meet alternate drainage and irrigation requirements for crops during the growing season. The effectiveness of such systems to agricultural

crops in the Midwest was demonstrated by Lembke and Sisson (1964) and to horticultural crops by Harris *et al.* (1962).

Illinois has a relatively small area suited to this practice when compared with the Netherlands, Florida and even other midwestern states such as Indiana. Nevertheless there are several advantages of this practice which make it very attractive (where it is adaptable) compared to other irrigation methods. Some of these advantages have been discussed by Criddle and Kalisvaart (1967, p. 913) and are:

1. It is effective on droughty soils having low water-holding capacities and high intake rates where other methods may be impractical from the standpoint of equipment and energy costs.
2. Labor requirement and equipment maintenance is low.
3. Special land preparation is not necessary.
4. Cultural operations interfere less with irrigation scheduling.

There are some problems with subirrigation systems in Illinois, however, that limit their effective use to a very narrow range of crops, soils, and management:

1. The system generally works best when it is needed least. That is, we generally have a high water table that can be controlled when there has been recent rainfall and consequently there is no crop stress.
2. It is necessary to reverse the process rapidly (maybe at a time when labor is not available) in the event of excessive rainfall.



3. When the water table is being held up, it is concave between drains and when it is being held down, it is convex as shown in Figure 2, thus requiring narrower drain spacings for close regulation than where the drain system is designed for drainage alone.

The authors will describe how such systems may be used to effectively recycle agricultural runoff and how they affect the downstream flow regime.

#### B. THE HYDROLOGY AND OPERATION OF A SUBSURFACE IRRIGATION SYSTEM

Where subsurface irrigation is practiced in Illinois, all of the land has been intensively drained by constructed ditches with very few tile systems. Tile systems have not been used because of the unstable nature of the sandy soils.

Consider the outflow of a typical drainage ditch to a major tributary. The hydrograph of flow during June appears as shown by the solid line in Figure 3. The most frequent type of subsurface irrigation structure consists of a dam across the drainage ditch with gates to control flow. These may be mechanized or they may consist of stoplogs which are removed manually. Let's consider the effect of water table control on water stage and flow rate immediately below such a structure. When more than adequate rainfall occurs during the early part of the spring season (February-May) all of the stoplogs are removed and there is no effect of the structure on stream flow as shown in Figure 3. After crops are planted in May, stoplogs are inserted and the water level is

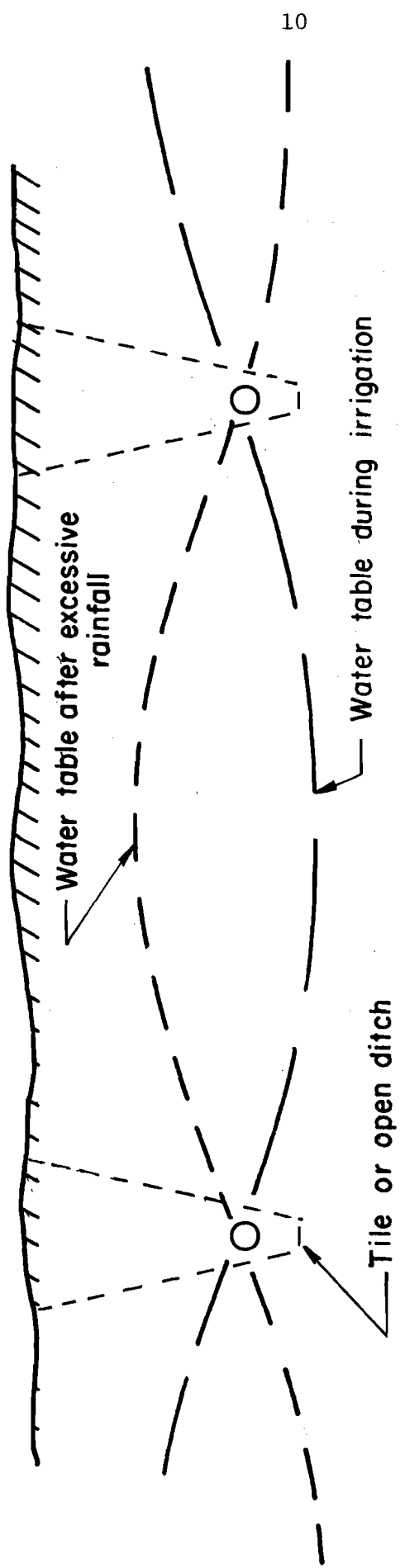


Figure 2. Comparison of water table shape during drainage and during subsurface irrigation.

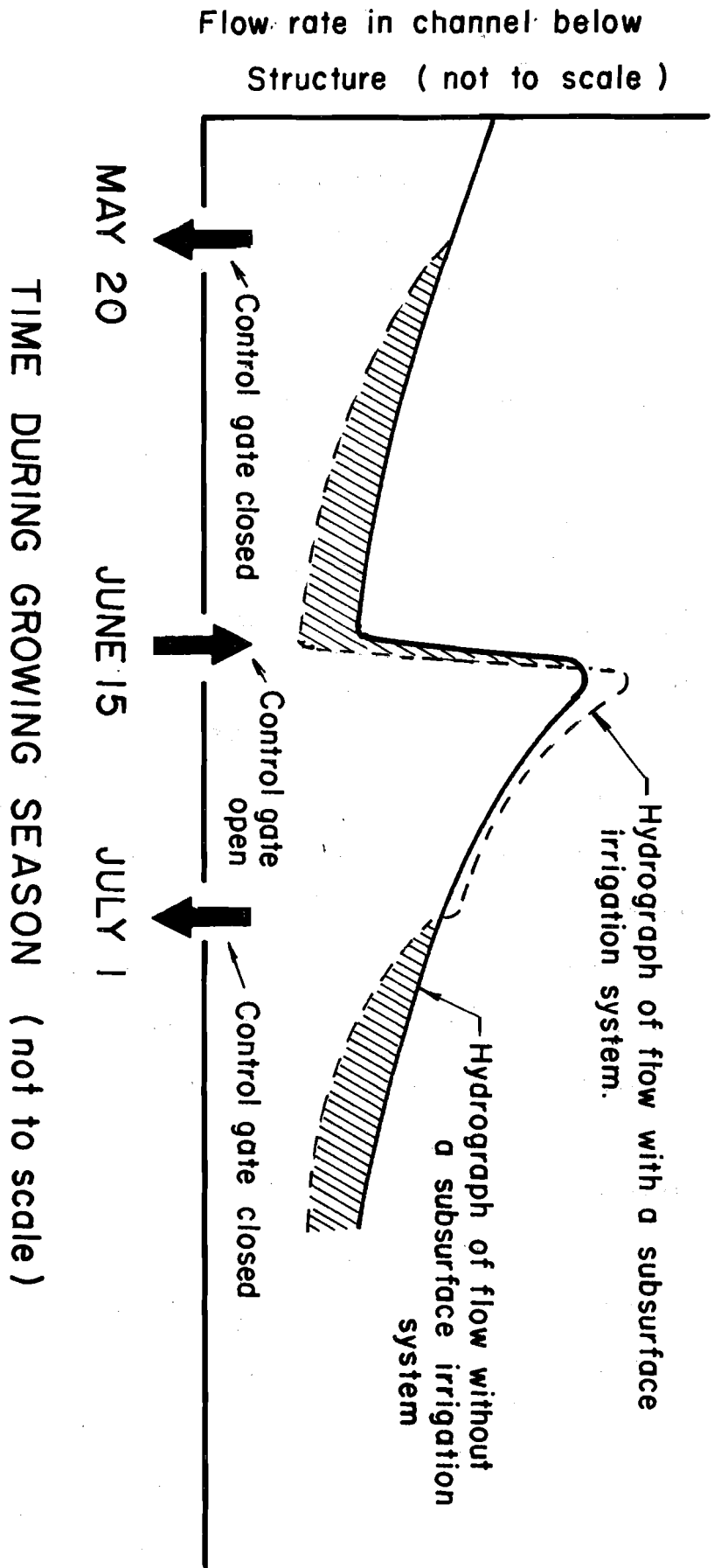


Figure 3. Comparison of hydrographs with and without a subsurface irrigation system.

raised upstream from the structure with a corresponding decrease in downstream flow. This is also shown in Figure 3. Some of the water is used to fill the channel, some fills the soil pores as the water table is raised, some water goes for increased evaporation and transpiration and the remainder percolates laterally and will probably enter the stream at some point below the gaging station. Of course, the efficiency of a subsurface irrigation system increases as a greater percentage of the decrease in downstream flow is used for transpiration of productive crops. The water table in the upstream fields develops a concave shape between ditches or drain lines as shown in Figure 2. It is obvious that the water table cannot be the same depth below the plant root system throughout the spacing between ditches. With a well designed system, the low point will permit adequate capillary rise into the plant root system while the high point should permit adequate aeration for the plant roots. It has been the authors' observation that for Illinois soils adapted to this type of irrigation practice this range should be between two feet and four feet during the time of the growing season that the crop has the greatest need for water. Lembke and Sisson (1964) have found that on soils typical to many of those adaptable to subirrigation in Illinois such a range in depth is possible with a concave water table between ditches at a spacing of 660 feet.

Now consider the effect of an unexpected large amount of rainfall in June after the water table has been raised to this concave shape. The water table will become horizontal and then begin to take on the convex shape shown in Figure 2. Sieben (1964) has taken 30 cm from the ground surface as a critical level in humid areas, above which crop damage is likely to occur. If the water control structure is well

managed, sufficient stoplogs will be removed to lower the shallowest part of the water table (between ditches) sufficiently to prevent crop damage due to poor aeration. Good weather forecasting and alert management become essential for the success of such an operation. In many cases for valuable horticultural crops, a reversible pump system is used to supplement the water control structure. The removal of stoplogs will cause an increase in the downstream stage. If the water control structure is operated effectively, the water stage and flow rate below the structure will increase more rapidly after a sudden excessive rainfall than it would had no structure been present, much in the same way that the flow below a flood control dam increases rapidly when water is released at the same time as a period of intensive runoff.

The flow rate then stabilizes and decreases to the point where stoplogs again are inserted in the water table control structure. It can be seen from Figure 3 that the difference between the base flow rate and the peak of flood hydrographs could be greater below a well managed control structure than had there been no structure at all.

The water table control system described here would necessarily be along a stream with an adequate supply of water. The system would also be adaptable to a situation where a pump would be used to recycle seepage water to the region behind the control structure. The shaded area of the hydrograph in Figure 3 represents the volume of water that will be used for agriculture. We conclude that peak flows from such systems will not be reduced and may even be increased while base flow will be diminished.

## III. IRRIGATION OF CLAYPAN SOILS

A. GENERAL CONSIDERATIONS

## 1. Variability of Yield

Crop production in claypan soil areas of Illinois is lower than in other areas of deeper, more permeable soil. It can also be shown that crop yields are more variable on the claypan, thus increasing risk in agriculture. Table 1 shows yields of corn in Effingham County compared with Mason County and Champaign County over a period of 10 years.

Table 1. Average corn yield in bushels per acre in three Central Illinois counties from 1950 to 1959.

	Champaign	Mason	Effingham
1950	52	41	42
1951	59	48	44
1952	62	51	44
1953	61	60	43
1954	61	47	19
1955	61	43	47
1956	78	69	61
1957	74	49	43
1958	75	73	45
1959	<u>64</u>	<u>48</u>	<u>55</u>
Average	65	53	44

Each of these counties has fairly uniform soils but each has a very different soil type from the others. Champaign County has mostly deep dark soils of recent glacial origin that have been drained artificially. Mason County has sandy soils that have been deposited by wind and water. Effingham County has claypan soils which have been deposited by a much earlier glaciation than those in Champaign County. While corn produced per acre was less in Effingham County, it can also be seen that there was greater variability in production. If we consider the percent variation between the highest and lowest yield over this 10 year period, it was 50% for Champaign, 45% for Mason and 105% for Effingham. Certainly a prospective farmer in Effingham County would be concerned about the risk in agriculture.

Many of the factors which influence the yields of crops on claypans are related to their response to the application of water and are important considerations in the recycling of agricultural runoff.

## 2. Infiltration Rate

The infiltration rate of claypan soils is very low, particularly after the first 20 inches of soil have become saturated. Runoff will occur unless rainfall or irrigation rates are low and not of long duration. The University of Illinois Irrigation Guide (1965) gives an infiltration rate of 0.5 inches per hour on soil with no cover, but many believe that this value should be reduced. The authors have found from field experience that sprinkler irrigation application rates should be no more than 0.3 inches per hour for 10 hour applications on a claypan soil.

### 3. Available Water Holding Capacity

Generally, by standard measurements, heavy textured soils have a high available water holding capacity for a given depth. Cisne silt loam was determined by Peters and Bartelli (1958) to have a water holding capacity of 5.1 inches in the first 21 inches. The standard measurement of available water is to determine water content between a  $-0.33$  atmosphere potential and a  $-15.0$  atmosphere potential. There is reason to question this definition when it is applied to claypan soils. Research has shown that while these limits are reasonable for coarse textured soils, they may result in values that are high on heavier textured soil conditions. For these heavier soils, the extraction of water by plants occurs over a wider range of soil water potential and soil hydraulic conductivity. Consequently, the amount available for a plant becomes a function of not only the soil water content but also the evapotranspiration rate. Denmead and Shaw (1962) observed that for corn on Colo silty clay loam soil in Iowa different available water capacities should be used with different evapotranspiration rates. They introduced the concept of a turgor loss point. They defined this for corn as the soil water content at which the transpiration rate fell below the potential evapotranspiration rate.<sup>1</sup> The turgor loss point for corn was found to be at a higher water content than the soil water content for visible wilting of the crop. The relationship between the water content in the root zone between  $-0.33$  and  $-15.0$  atmosphere potential and the turgor loss point

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<sup>1</sup> Potential transpiration rate is the transpiration rate of a plant when the soil water is at a potential of  $-0.33$  atmospheres.



was determined as a function of the potential transpiration rate for Colo silty clay loam and is shown in Figure 4. Denmead and Shaw (1962) found that any day on which the evapotranspiration rate and water content intersected below the curve in Figure 4 there was some stress on corn plants. Denmead and Shaw (1962) took dry matter accumulation measurements on plants that had been subjected to various periods and intensities of soil water stress. The number of stress days and the reduction in dry weight from control plants was determined for each treatment. A linear regression was fitted and it was found that the intercept was not significantly different from zero. This meant that with no stress days there was no reduction in yield. The slope of the regression line was close to the mean growth rate of the control plants.

Dale and Shaw (1965) found a relationship between nonstress days during the critical growth period and yield for corn. They found this critical period to be the nine weeks beginning six weeks before silking and ending three weeks after silking. The work of Dale and Shaw (1965) was based on measurements taken with corn on Colo silty clay loam soil in pots giving a restricted root system. We concluded that the stress day concept could be used to predict the available water holding capacity of claypan soils and crop yields during a given year.

#### B. ECONOMICS OF IRRIGATION

Acreage of irrigated agricultural crops in Illinois has always increased following dry years and decreased following several years of large amounts of rainfall. There has also been a long term increase

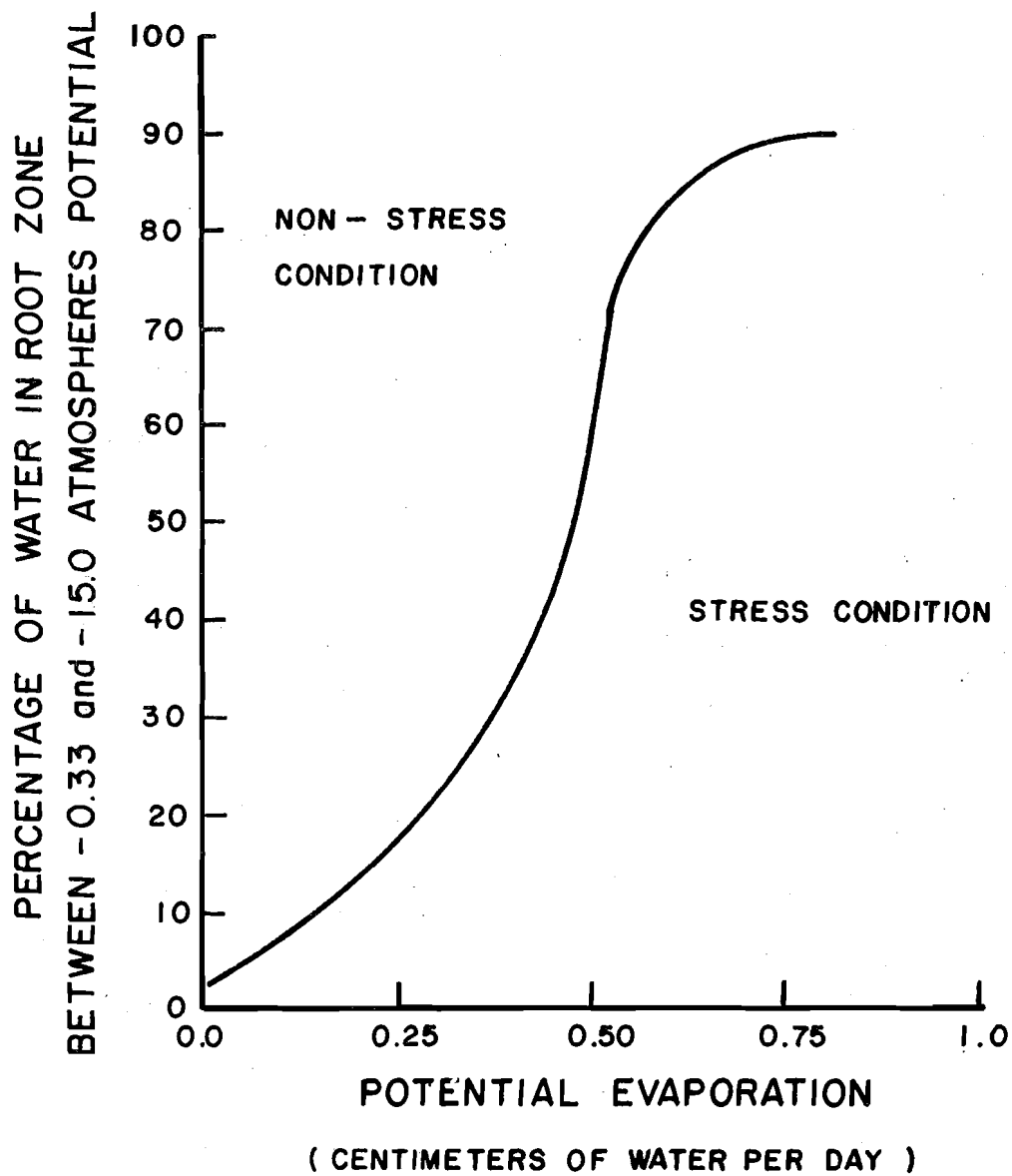


Figure 4. Estimated percentage of available water in root zone at the turgor loss point as a function of potential evaporation.

related to technology. Roberts (1951) made a study of irrigation and found that about 9,000 acres were irrigated in Illinois of which only about 13% were field crops. Drablos and Reiss (1969) found in a survey that improved technology accounted for a great part of the increase to 28,000 acres irrigated in 1966. Present estimates are that approximately 50,000 acres are irrigated in Illinois with the greatest portion being field crops irrigated from wells. Further developments of technology are responsible for part of the recent increase, but the economic potential for irrigation has made it more attractive in recent years.

#### 1. Analysis of Irrigation Systems

Drablos and Reiss (1969) addressed the question: Will irrigation pay in Illinois? They concluded, after surveying 343 irrigation systems, that there was little doubt that irrigation has been quite profitable on farms where specialty crops, such as snap beans and cucumbers, were grown under contracts with canning or processing companies. For the systems irrigating corn, soybeans and other feed and grain crops, the profitability of irrigation depended on the response of crops and soils to irrigation and the management practices of the operator. They prepared Table 2, which compared the budget experience of 17 farmers on sandy soil who used irrigation to 17 who did not use irrigation. While Table 2 shows there was a yield increase attributable to irrigation, it also shows that for the average irrigating farmer added returns were only adequate to meet increased costs. On

Table 2. Size of farm, land use, and related variables on irrigating and non-irrigating farms in Mason County (1966 and 1967 averages) from Drablos and Reiss (1969).

	Irrigating farms	Non- irrigating farms
Number of farms.....	17	17
Av. acres per farm.....	523	461
Tillable acres.....	464	404
Soil productivity rating.....	44	46
Pct. of tillable land in:		
Corn and corn silage.....	52.9	41.5
Soybeans.....	19.5	24.9
Wheat and other small grains.....	8.8	15.7
Snap beans and other vegetables.....	9.0	0.1
Diverted acres and idle.....	4.8	5.6
Hay and pasture.....	5.0	12.2
Value of crop production, dollars.....	49,037	31,364
Per tillable acre, dollars.....	105.69	77.60
Crop yields, bu./A.		
Corn.....	107	88
Soybeans.....	27	30
Wheat.....	32	34
Value of feed fed per tillable A., dollars...	14.93	15.90
Av. mo. of all labor.....	18.3	15.9

Table 2 (continued)

Investment per tillable acre, dollars		
Feed, grain, seeds, and livestock	57	53
Machinery and equipment (inc. auto)...	59	29
Land and buildings.....	333	338
Total.....	449	420
Returns per tillable acre, dollars		
To unpaid labor, capital, and mgt.....	47.94	48.04
To capital and mgt.....	39.46	39.01
Per \$100 invested.....	8.78	9.28
Value of farm production per tillable acre, dollars.....	113.95	89.38
Farm costs per tillable acre, dollars		
Soil fertility.....	15.91	8.34
Buildings and fence.....	3.82	2.89
Machinery and auto:		
Depreciation.....	15.52	7.29
Electricity, gas, and oil.....	6.21	3.72
Repairs and auto expense.....	6.57	4.58
Hire.....	1.79	1.18
Total.....	30.09	16.77
Labor.....	11.98	11.97
Taxes.....	4.56	5.43
Seed and crop expense.....	6.82	3.59
Livestock and misc.....	1.32	1.37
Interest on capital.....	20.85	18.85
Total costs.....	95.35	69.21

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some farms, however, returns were greater than costs. Still they found no clear advantage for irrigation of agricultural crops in their study. Swanson and Jones (1966) used weather data and a yield response curve developed by Fulcher (1961) to determine the probabilities of returning various initial investments in irrigation equipment. They found that on Flanagan silt loam in Central Illinois irrigation did not compare to a corresponding investment in fertilizer and seeds.

Asopa and Swanson (1969) used available weather and crop production records in Illinois to estimate the water needs in order to maintain maximum corn yields in Illinois. They also studied the effect of supplemental irrigation on farm income using a regression model. They found that irrigation resulted in a moderate increase in average income and a slight reduction in the variance of income throughout a succession of years.

Lembke and Jones (1972) used a simulation model to study the annual net returns for different irrigation scheduling practices on two soils. They found that, for corn on a very sandy soil with only 0.8 inches of water per foot between  $-0.33$  atmospheres potential and  $-15.0$  atmospheres potential, there was an average return of \$18 per acre that could be attributed to irrigation. As the water content in this range increased to 1.2 inches per foot as would be common for a sandy loam soil, however, the average irrigation returns reduced to \$7 per acre, and with a silt loam soil there was no benefit for irrigation.

A recent analysis of irrigation costs by Schwab and Kidder (1976) in Michigan shows that an increase of \$110 or 40 bushels of corn per acre is the current "break even" return for an irrigation system if it is to be financed over a seven-year period. Perhaps \$125 or 50 bushels per acre additional return would be necessary to make irrigation a desirable investment alternative.

Why does irrigation of corn and other crops in Illinois continue to increase with such a pessimistic history of economic studies? One reason is that with the high price of skilled labor newer, more automated irrigation systems have become desirable investment opportunities. A second reason is that investment in irrigation equipment is not unlike the investment in more land in that it increases a farmer's production base and with the current inflation of land prices a capital investment in irrigation seems more attractive. Another reason for the increase of irrigation in Illinois is that much of the new irrigation in Illinois is not on land that is already productive but on sandy land that has been marginal and presently is being brought into production. Still another reason for farmers to use irrigation is to take the risk out of agriculture.

During 1976 an irrigation experiment was conducted at the University of Illinois Agronomy Substation at Brownstown, Illinois. Surface and sprinkler irrigation was compared to no irrigation for a corn crop on Cisne Silt Loam, a claypan soil. Two replications were made of each treatment. Table 3 shows the results of this study:

Table 3. Yield, bushels per acre, of corn under irrigation at Brownstown, Illinois. 1976.

	Sprinkler	Surface	No irrigation
Replication 1	145	162	50
Replication 2	<u>133</u>	<u>142</u>	<u>22</u>
	139	152	36

Based on the results of the 1976 study, irrigation was a profitable venture. Rainfall was far below normal during that year. From June 30 to July 20 there were 0.43 inches of rainfall. Weather records show that there is over a 90% probability of a greater amount of rainfall during this period. Certainly irrigation would have taken the risk out of Illinois agriculture in 1976.

## 2. Water Storage Costs in Illinois

The feasibility of recycling agricultural runoff will depend not only on irrigation costs and returns, but also on the feasibility of using land area for the storage of surface runoff. Some sites will have a greater potential for economic storage than others.

Dawes and Wathne (1968) conducted a study of the cost of reservoirs in Illinois. They determined the project cost for reservoir construction as:

$$P_c = 9161 S^{.54} + .49 S^{.87} K$$

where

$P_c$  = total project cost in dollars

$S$  = reservoir storage in acre-feet

$K$  = land cost in dollars per acre



In their study, Dawes and Wathne (1968) found, as shown by Equation (1), that large reservoirs are more economical than small ones. This economy of size was found to continue up to storage capacities of 40,000 acre-feet for most Illinois topography. This upper limit is greater than the size of most single farm runoff recycling reservoirs, thus making attractive the potential of several farmers sharing one storage reservoir. Dawes and Wathne (1968) did not refine their analysis for various physiographic subdivisions of the state.

## IV. DRAINAGE OF CLAYPAN SOILS

A. DRAINAGE REQUIREMENTS FOR CROP PRODUCTION

During the respiration process in the root system of growing plants,  $O_2$  is required and an excess of  $CO_2$  develops. Unless there is a good interchange of air between soil and atmosphere, an imbalance of  $O_2$  and  $CO_2$  will develop. A deficiency of  $O_2$  will result in a reduction of root respiration and total root volume, a decrease in the permeability of root membranes to water and plant nutrients, and the formation of toxic compounds in the plants and soil. An excess of  $CO_2$  can become toxic to the plant but it has generally been found in literature that such excesses are not as critical as a deficiency of  $O_2$ .

There are secondary effects of low levels of  $O_2$  in the soil. Among these are decreased mineralization of nutrient elements and reduced microbiological activity. One practical aspect of these secondary effects is the higher nitrogen fertilizer requirements on a poorly drained soil as described by Sieben (1964)

The limitation of oxygen is a major restriction for growth of plants on claypan soil because of the limited pore space available for aeration of the root system. Since plants need water as well as oxygen and since there is a very small root zone available in a claypan soil, very careful water management is required for optimum plant growth.

Since techniques for measuring aeration have not been applied to claypan soils, the aeration requirements for crop production have not

been defined. A technique that is simple and that reflects an integration of the conditions within the soil is desirable. One such technique is measurement of water table depth. In coarser textured soils the water table is easy to measure and can be monitored throughout the growing season to obtain an integrated effect on crop yield.

Sieben (1964) developed one technique for determining this integrated effect. He selected 30 cm below the soil surface as a critical water table level and then calculated the  $SEW_{30}$  value where:

$$SEW_{30} = \sum_{i=1}^n (30 - x_i) \quad (2)$$

and  $x_i$  = water-table depths below the surface during the growing season, cm., on day  $i$

$n$  = a day in the growing season where the first day is 1.

Sieben (1964) found that above certain levels of  $SEW_{30}$  there was a decrease in yield for cereal grain.

Unfortunately there is not a good relation between water table depth and aeration for claypan soils. When the water table drops there is a very little increase in aeration since much of the water is held at a negative potential and because water movement is very slow. The saturated zone above the water table is often referred to as the capillary fringe. While the capillary fringe may be as thin as two or three inches in a coarse textured soil, it might be the thickness of the entire rooting depth of the crop in a claypan soil. With this condition of saturation, subsurface drainage will not be of much help in water

management and it becomes necessary to utilize surface drainage and surface evaporation to achieve the necessary planting and tillage operations in the spring.

After crops are planted, since saturation occurs above the water table, aeration measurements rather than measurements of water table depth may give a more realistic picture of plant environment. Earlier methods of measuring soil aeration involved determination of  $O_2$  and  $CO_2$  contents of gas samples extracted from the soil. Williamson *et al.* (1965) found  $O_2$  contents of less than 4% in the soil air for wet conditions above the water table in coarse textured soils. No information is available in the literature for the optimum level of aeration in a claypan soil as this relates to crop growth.

Another method of determining the effect of drainage on plant growth is through yield measurements of crops with different levels of combined irrigation and rainfall. The many other factors that affect crop yield should be maintained constant in such a study. A five-year study of the effect of surface drainage on corn yield was conducted by Sisson and Galloway (1964) on Clermont Silt Loam, a claypan soil in Indiana. They compared land smoothing with bedding as surface drainage practices and found that land smoothing was the better practice using stand, uniformity of crop growth and yield as their criteria for comparison.

#### B. DRAINAGE REQUIREMENTS FOR TILLAGE OPERATIONS

In order to estimate field working days for a farmer, a relationship must be drawn between the moisture content of the soil and its capacity to undergo tillage operations. The terms tractionability

and trafficability have been used, often in a very general sense, to describe a soil's ability to be driven across or tilled. Thornthwaite and Mather (1955) wrote that tractionability is determined by the following four soil characteristics: bearing capacity, shearing strength, surface friction coefficient, and stickiness. The authors stated that tractionability includes far more than trafficability, which is a term that applies only to bearing capacity.

The bearing capacity of a surface is defined as the load per unit area which the underlying materials can support without being crushed or without settling enough to impede movement. Shearing strength is the resistance of the material to a tangential force. Surface friction is the resistance to relative motion of two bodies in contact, as determined by the character of the surfaces of the bodies and by the pressure that holds them in contact. Stickiness is described as the property of a soil causing it to stick to wheels, thereby making movement more difficult. Soils vary greatly in their properties, but moisture content is the determining factor in each individual soil.

Aldabagh (1971) defined trafficability as the capacity of a soil to withstand vehicular traffic. Trafficability is adequate if there is sufficient bearing capacity to support the vehicle and sufficient traction capacity to enable the vehicle to develop enough forward thrust to overcome rolling resistance. Traction failure can occur when there is adequate bearing strength, but bearing failure does not occur without traction failure. The author noted that soil moisture content is definitely the most important factor affecting trafficability.

Allman and Kohnke (1947) attempted to determine at what moisture tension soil is just dry enough to be plowed. They recorded field data on soil moisture content and the plowable condition of the soil. The decision on whether or not a soil was dry enough to be plowed was based on empirical observations. The wet plowing limit of a number of medium and heavy textured soils was found to be between pF 2.7 and pF 3.0, where pF = log of negative matric potential in ergs/dyne, pF 2.7 corresponds to a matric potential of about -500 centimeters of water, or -0.493 bar, and pF 3.0 corresponds to -1000 centimeters, or -0.983 bar. With sandy soils, the critical pF values were found to be lower, generally between 1.8 and 2.3.

Several researchers have empirically determined soil moisture criteria for tillage. These criteria are normally given as a certain percent of field capacity or percent of available soil moisture.

#### C. ECONOMICS OF DRAINAGE

Elliott (1974) developed a soil water balance model to predict days available for tillage in Illinois during spring months. He concluded that the model could be used by Illinois farmers as a planning aid in scheduling and selection of farm equipment and in choosing drainage systems. Wendte (1975) improved on Elliott's model to evaluate a timeliness benefit associated with earlier planting as a result of better drainage. Timeliness was defined by Hunt and Patterson (1968) as "that state of being opportune or optimum in field operations." A measure of timeliness is the cost accrued because a field operation is not completed on time. Drainage and weather are two important factors influencing timeliness in humid regions.

In humid regions, where available working days frequently limit the timely conduct of field operations, penalty costs associated with untimely conduct of field operations are usually measured by how planting before or after some optimum day influences yield.

The relationship between the planting date of corn and yield in the corn belt has generally shown a favorable response to early plantings up to late April. Aldrich and Leng (1965) and Graffis *et al.* (1975) found that the benefits of early planting are: a longer growing season, greater vegetative growth during cooler weather, earlier silking, more efficient use of available soil water and earlier harvesting. Pendleton and Egli (1969) carried out a planting experiment for corn on Flanagan silt loam soil in central Illinois and found that yields decreased linearly with planting dates after April 30 at a rate of 1.6 bushels per day.

Wendte (1975) used the research results of Pendleton and Egli (1969) to obtain a timeliness cost, but he also introduced the concept of the earliest possible planting date with prior available field work days.

A timeliness penalty was calculated based on the economic loss of the market value of yield decrease less the reduction in cost of seed, fertilizer, harvesting, hauling and drying. Using price assumptions of Hinton (1975) for the next five years, Wendte (1975) calculated the timeliness penalty for each earliest possible planting date after April 30 for given drainage criteria.

Wendte (1975) also determined the drainage cost to achieve a reduction in timeliness penalty for various soils. The poorest drained

soil that Wendte (1975) studied was Elliott silt loam with a permeability of 0.5 inches per hour. Using subsurface drainage and costs based on 1975 data, he arrived at an optimum drain spacing of 80 feet and a maximum net timeliness benefit of \$47 per acre.

Schwab *et al.* (1976) found that the net benefit of a tile drainage system on heavy soils in Ohio was \$42 per acre when the crop produced was corn. This compares closely to the value determined by Wendte for heavy soil.



## V. RECYCLING CHEMICALS IN RESERVOIRS

Runoff water from agricultural land contains both pesticides and nutrients. These chemicals may be dissolved, suspended, or attached to soil or crop residue particles which are suspended in the runoff water. These chemicals will be trapped in the storage reservoir with the water. Some of the chemicals will leave the reservoir with overflow water, some will be irrigated back onto the crop, some will be released to the atmosphere, and the remainder will accumulate in the reservoir. Recycling agricultural runoff will help keep these chemicals out of natural waterways and will increase their concentration on cropland. The overall result is a combination of costs and benefits.

### A. PESTICIDES

#### 1. Mechanisms for Costs and Benefits of Pesticide Recycling

It is hardly conceivable that recycled pesticides would have any benefit to crops they were applied to. To be effective pesticides must be applied at a specific concentration and at a specific time. The reduced concentration and the time lag in recycling would make them worthless. There is one benefit of pesticide recycling. It helps keep the pesticides out of natural waterways. Pesticides in waterways have allegedly been the cause of many reported fish kills and supposedly many more unreported fish kills and other cases of less dramatic ecological damage. However, there are no estimates of the economic benefits which could be derived by trapping these pesticides and reducing their concentration in stream flow from agricultural land.

There are numerous conceivable ways in which recycled pesticides could be damaging. The term pesticide includes herbicides, insecticides, and fungicides as well as less common groups of chemicals. It is conceivable that any of these pesticides could be of harm to man or other consumers of a crop if the pesticide were recycled onto a crop near harvest time. A possibility of damage to the crop itself exists if a herbicide were recycled onto a crop at a different time of development than it was originally intended. For example, damage might result if a pre-emergence herbicide were recycled onto a crop after the crop emerged. As another example, there is the possibility of damage if a herbicide, originally applied to a resistant crop, were recycled to a susceptible crop. This type of damage might result where one crop follows another or with the runoff from two crop fields being recycled through the same reservoir.

All these examples are possibilities of harm resulting from recycling pesticides. However, after personal communications with prominent pesticide scientists (Metcalf [1976], Slife [1976], and Hiltibran [1976]), the authors have concluded that it is unlikely that any serious, unavoidable danger exists from any of these mechanisms. The greatest danger would lie with the situation where a herbicide was applied to a resistant species, such as corn, and runoff water was recycled to a susceptible species, such as soybeans, resulting in damage to the soybeans. The danger here is not unavoidable, however. A simple solution would be to produce only one crop species at a time on land serviced by each recycling reservoir.

Similarly, there is little serious danger of a pre-emergent herbicide damaging an emergent plant through recycled water. For spring planted crops such as corn and soybeans, irrigation water is not likely to be applied until long after the crop has emerged because drought is usually not a problem early in the growing season.

## 2. Literature Review of Pesticide Research

### a. Monitoring Research

The principal reason pesticide recycling is not a problem to crop production is that runoff from agricultural watersheds contains only a small portion of the pesticide applied. A study by Hamon (1975) at the Northern Appalachian Experimental Watershed shows that a 1.12 kg/ha atrazine application lost only 5.7% of the herbicide in runoff. A 2.24 kg/ha simazine application lost only 3.8%, and for a 4.48 kg/ha application of sevin only 5.77 g were washed off during the entire cropping season.

Miller *et al.* (1967) reported that a 1.12 kg/ha application of parathion to a cranberry bog resulted in 750 ppb in irrigation ditch water. Within 96 hrs. the concentration had decreased to 5 ppb. In another study Averitt (1967) added 4.48 kg/ha 2,4-D to a natural body of water. A 689 ppb concentration resulted after one day. Eleven ppb remained after 31 days.

These are but a few examples of the large amount of data available concerning the concentrations of pesticides in surface waters.

However, this data is not as useful as it might seem. First, there are hundreds of pesticides presently in use and there are thousands of unique combinations of crop, climate, topography, etc., situations under which these pesticides might be applied. No successful way has been devised to extrapolate pesticide residue data to new pesticides or new application situations. Second, pesticide residue concentration data is useless without data concerning the biological significance of these concentrations. Biological repercussions are also pesticide and site specific and are undoubtedly as difficult to extrapolate to new situations as are predictions of pesticide concentration in the water.

b. Prediction Model Research

Donigian and Crawford (1976) of Hydrocomp, Inc., under a grant from the U. S. Environmental Protection Agency Environmental Research Lab at Athens, Georgia, have attacked the first of these problems. They realize that it is impossible to collect residue data for each pesticide under all conditions. Therefore, they are developing a computer model called ARM which, given information about a particular pesticide and a specific site, can predict the amount of residue contained in runoff water. The ultimate goal of the continuing ARM model development effort is the establishment of a methodology and a tool for the evaluation of the efficacy of management practices to control the loss of sediment, pesticides, nutrients, and other nonpoint pollutants from agricultural lands. A brief review of this work is in line here since it represents the most comprehensive attempt to date to predict nonpoint pesticide pollution.

Except for the possibility of wind erosion, the movement of pesticides from the crop land to the aquatic environment has two mechanisms: being transported by runoff water directly and by attachment to sediment which is in turn removed by runoff. Either method then can only occur during runoff-producing events. The status of the soil moisture and the pollutant prior to the event is a major determinant of the amount of runoff and pollutants that leave the land during the event. The ARM model then is divided into several major components. The LANDS component simulates the runoff from the watershed. The SEDT component simulates the sediment production of the watershed. The ADSRB component simulates the pesticide adsorption/desorption to soil particles and the amount of pesticide dissolved in the water. DEGRAD determines the pesticide degradation. And NUTRNT simulates nutrient transformations when the model is used to predict nutrient pollution.

The hydrology subprogram, LANDS, derived from the Stanford Watershed Model, is the heart of the ARM model. It is basically a moisture accounting procedure using inputs of precipitation and evaporation. Parameters within the mathematical functions are used to characterize the land surface and soil profile characteristics of the watershed. These parameters must be selected, tested, and modified when LANDS is applied to a new watershed.

The sediment loss simulation was derived from work by Moshe Negev at Stanford University. The ARM model includes only sheet and rill erosion. Sediment loss is simulated with two algorithms, one determining the detachment of soil fines by raindrop impact, the other determining the pickup and transport of the soil fines.

Once the hydrology and sediment production of a watershed have been simulated, the adsorption/desorption of the pesticide onto sediment particles determines the amount of pesticide loss which will occur. The ADSRB subprogram determines the amount of available pesticide which attaches to sediment particles and is lost in erosion and the amount which is lost in solution in runoff water.

The amount of pesticide available for removal during a runoff event is dependent on the application rate and the attenuation of the pesticide. Attenuation processes of volatilization and degradation by microbial, chemical, or photochemical means often account for the great majority of the applied pesticide removed from the soil environment. It is known that these attenuation processes are affected by soil moisture, soil temperature, soil pH, etc. However, the relationships are not sufficiently well developed for use as prediction tools. A volatilization model derived from work by Farmer and Letey was included in the DEGRAD subprogram but was not used because of the lack of field data for testing purposes. The DEGRAD subprogram assumed a simple first order decay to estimate the attenuation process.

The ARM model was calibrated and tested at two watersheds near Watkinsville, Georgia. One watershed is a natural watershed; the other is a terraced watershed with a grass waterway. They received identical management during the 1973 test year including: minimum tillage, planted to soybeans, and application of herbicides paraquat, diphenamid, and trifluralin at the rates of 1.1, 3.4, and 1.1 kg/ha, respectively. However, trifluralin was not simulated because of a lack of reliable laboratory data. Paraquat is totally adsorbed by the soil and

can only be transported with the sediment. Diphenamid can be transported both on sediment and in solution in runoff.

After comparing recorded and simulated results from the two watersheds, the authors concluded that the runoff and sediment loss simulations reasonably represented the observed data. However, the pesticide simulations showed considerable deviations from recorded values. This was especially true for diphenamid. The authors further concluded the results demonstrate the need to further investigate the processes of pesticide degradation and pesticide-soil interactions.

The importance of these conclusions to the recycling agricultural runoff study is that the state-of-the-art is not sufficiently developed to allow prediction of the pesticide contained in runoff water, much less the amount of pesticide which would be returned to the field in recycled runoff. This is demonstrated by the fact that the ARM model:

- 1) requires site specific calibration of its hydrologic and sediment yield subprograms
- 2) can be used on very few pesticides because of a lack of laboratory data
- 3) cannot reasonably predict loss of pesticides on which laboratory data is available because of a lack of information about attenuation processes and adsorption-desorption functions

## B. NUTRIENTS

### 1. Mechanisms for Costs and Benefits of Nutrient Recycling

Recycling nutrients has two beneficial aspects. First, these nutrients are retained for use in crop production. The nutrients dissolved in the reservoir water could be used by irrigation onto cropland. An alternative use for crop production would be to use these nutrients to grow aquatic crops in the storage reservoir. Aquatic production will be discussed in detail in a later section. Second, these nutrients would be prevented from entering and eutrophying natural waterways. Present agricultural practices allow nutrients, either dissolved or suspended in the runoff, from heavily fertilized agricultural land to enter watercourses. This is termed nonpoint source agricultural pollution. Eutrophication, partly caused by agriculture, has direct costs associated with cleaning the water for domestic and industrial use and with lost revenues from recreation. In addition there are indirect or nonmonetary costs associated with the aesthetic aspects of eutrophication.

The possible disadvantages of nutrient recycling are, first, the possibility of plant damage due to applying the nutrients to the plant itself rather than to the ground. This would only be a problem if sprinkler irrigation was used. It should be pointed out that the possibility of damage is very slight, especially in light of the low nutrient concentration that would be expected and the relatively high nutrient concentrations which have been used successfully in the



foliar application of nutrients by sprinkler irrigation. A second possible problem would be difficulties arising from the eutrophication of the storage reservoir. Filamentous algae growth could conceivably cause difficulties with the irrigation system.

Information about the quantification of nutrients from cropland runoff is in two categories. The first is information on the amount of nutrients in runoff water. This information is useful for evaluating the potential for environmental improvements through the use of reservoirs for runoff trapping. The second category is information about the concentration of nutrients in reservoirs. This information is useful for evaluating the potential for decreased fertilizer cost due to nutrient concentrations in the irrigation water from the reservoir.

## 2. Nutrients in Runoff

The models which have been developed to predict nutrient balances are concerned primarily with determining the nutrient concentration and total nutrient loss through surface runoff. The ARM model (Donigian and Crawford, 1976), discussed in detail in the section on pesticides, also has a subprogram, NUTR, which predicts nutrient loss from erosion, surface washoff, leaching, and biological conversion. However, numerous assumptions were necessary for model development, and the model has not yet been compared with field data. Further development of the model is expected.

Other nutrient models include the work by Dutt *et al.* (1972) at the University of Arizona. This model was developed from data from irrigated land in arid regions and would be difficult to adapt to humid regions without extensive field evaluations.

Another model developed by Hagin *et al.* (1974) is designed to predict complete nitrogen and phosphorous balances for agricultural land. The model takes into account changes in reaction rates caused by temperature, pH, moisture and oxygen levels. The model has not been compared with field data.

Frere *et al.* (1975) of the Agricultural Research Service have developed the Agricultural Chemical Transport Model, ACTMO. The nutrient portion of the model has not been tested on field data.

None of the above models is generally accepted for predicting nutrient losses in runoff. Field data may provide some indication of expected nutrient losses. As a first approximation, consider the nitrate levels in the Vermilion and Sangamon Rivers in Illinois. These rivers drain heavily agricultural regions which are highly fertilized. Metcalf (1970) reported their 1966-69 nitrate concentration averaged 38.0 and 32.6 ppm respectively.

A study was conducted by Asmussen and Sheridan (1976) near Tifton, Georgia, on the Little River watershed. This 32,751 ha watershed is approximately 37% cropland. The remainder is woodland and grass. During 1975 the average  $\text{NO}_3\text{-N}$  concentration in the runoff was 0.18 ppm. This amounted to 178. g/ha  $\text{NO}_3\text{-N}$  from the watershed. During the same period the watershed reached a rainfall input of 261. g/ha of  $\text{NO}_3\text{-N}$ . The ortho-phosphorus load from the watershed was 119. g/ha-yr.

Tile drainage must not be overlooked as a means for transporting nutrients from cropland. Baker *et al.* (1975) made a four-year study of tile drainage water quality in central Iowa.  $\text{NO}_3\text{-N}$  averaged 14.6 kg/ha-yr for the period 1970-73. Annual phosphorus losses were negligible.

The three studies mentioned above are useful in that they provide an indication of the range of nutrient levels which might be expected in runoff from humid croplands. However, these studies were on permeable soils. Kissel *et al.* (1976) made a study of nitrogen losses in runoff from Houston Black Clay, a swelling clay soil with a relatively low permeability. This study was made in the blackland prairie of Texas with watersheds cropped to a rotation of grain sorghum, cotton, and oats. For the entire five-year study, the mean concentration of  $\text{NO}_3\text{-N}$  in runoff was 2.6 ppm  $\text{NO}_3\text{-N}$ . The mean loss of  $\text{NO}_3\text{-N}$  was 3.2 kg/ha-yr. Losses of sediment-associated N were about 5 kg/ha-yr.

The claypan soil of central Missouri is similar to the claypan soil of south central Illinois. Heinemann (1975) reported soluble N losses from this soil during 1973 ranged from 9 to 36 lb/A from no-till corn and 11 to 42 lb/A from conventionally tilled corn. N applications ranged from 87 to 324 lbs/A on both tillage treatments. Losses from no-till and conventionally tilled corn were 10.5 and 11.0 lbs/A when applications were near the optimum rate of 155 lbs/A.

### 3. Nutrients in Reservoirs

Studies reporting nutrient concentration in runoff water give an indication of the amount of nutrients which leave cropland. But,

this information is not a good indication of the amount of nutrients which might be returned to the cropland by irrigating captured runoff water. Only one study was found which attempted a nutrient balance on a small agricultural reservoir. Gill *et al.* (1976) made a nutrient balance study of three agricultural watersheds in northern Mississippi. Gill *et al.* estimated the nutrients received by each of the watersheds since their construction, a time range of 15 to 19 years. They also measured the amount of nutrients contained in sediment. They found that an average of 24% of the nitrogen and 53% of the inorganic phosphorus received by the reservoirs was in the sediments of the reservoirs. The higher percentage of phosphorus was not surprising because phosphorous compounds are less soluble and are usually transported attached to soil particles. The nutrients not in the sediment were assumed to have either passed through the reservoir, been lost as gases from biological decomposition, or not reached the reservoir as predicted. If the latter occurred, then the percentage of nutrients trapped in the sediment would be higher. In either case, the nutrients trapped by the sediments generally could not be applied back to cropland through irrigation water.

The best indication of the amount of nutrients available for irrigation back on cropland was found in a study of pond water quality in a claypan soil in Washington County, Illinois, made by Dickey and Mitchell (1975). The watersheds studied were predominantly in Cisne-Hoyleton and Bluford-Wynoose soil association areas. These soils are typical of the soils throughout the claypan region of southern central Illinois. Four cultivated watersheds were studied. Figure 5 shows the average monthly trends in nitrate nitrogen for the four

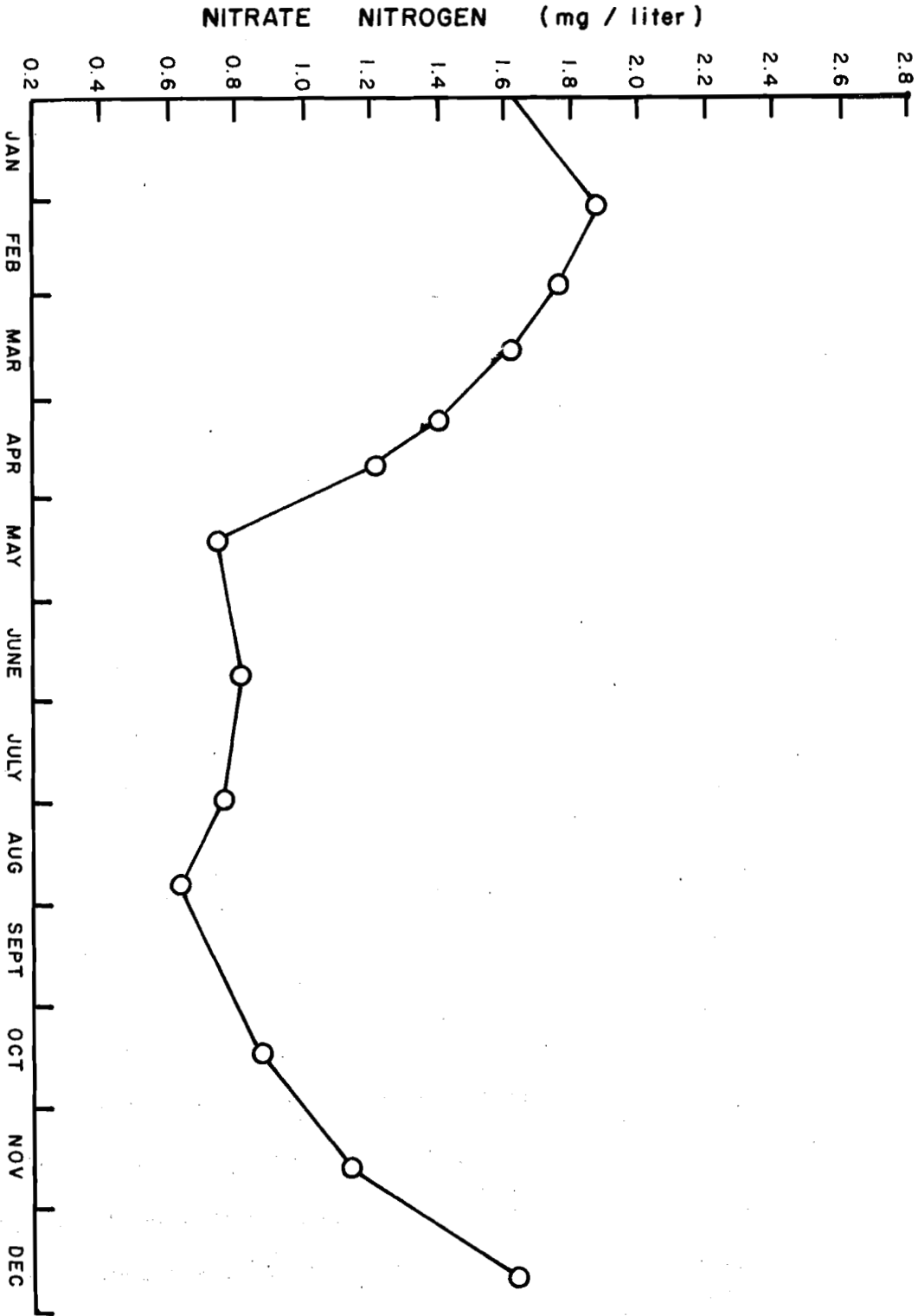


Figure 5. Nitrate nitrogen concentrations of four ponds in cultivated watersheds located in the claypan region of Illinois. 1971.

watersheds. Note that the  $\text{NO}_3\text{-N}$  concentrations are highest in the winter months when they cannot be utilized in irrigation water.

$\text{NO}_3\text{-N}$  concentrations during the summer are only about 0.7 ppm.

A yearly irrigation amount of six inches with this concentration of nitrogen would provide only about one pound of nitrogen per acre, a negligible amount.

## VI. MULTIPLE USES OF RESERVOIRS

The portion of the land which is used as a surface reservoir obviously cannot be used for the production of traditional crops. This does not mean that the reservoir area could not be as productive, or even more productive, than it could be for growing corn.

### A. RECREATION

One productive use which could be made of these reservoirs is recreation. No studies have been made on the return which could be realized from the recreational uses of a large number of small reservoirs required to irrigate south central Illinois. Many small privately owned reservoirs do obtain a sizeable income from fishing and other recreation. However, these reservoirs are few and are usually located near urban areas. Recreational income data from these reservoirs could not be extrapolated to predict income from the proposed irrigation reservoirs. In addition, recreational use of the water would most likely be made during the summer, the same time the water would be in short supply due to irrigation. Still another consideration would be the additional lost cropland to provide public access to the reservoirs. In short, recreation does not appear to be a viable alternative use of reservoir area except in special cases.

### B. AQUACULTURE

Aquaculture, i.e., the production of aquatic crops, might provide an alternate use of reservoir land. At present the only

aquatic crop grown commercially in fresh water reservoirs in the U.S. is fish. Practically all fish farmed in Illinois and the Midwest are for sport purposes. These fish are sold for stocking in other reservoirs to provide fishing. The sport market for fish is so relatively small it would be unrealistic to assume that more than a few of these irrigation reservoirs could be used for the production of sport fish.

The production of food fish could conceivably utilize large amounts of reservoir area. Food fish are those which are produced for direct processing, either into human food, animal food, or fish meal. Food fish are not being produced in Illinois ponds at present except on a very small scale. However, recent experimental work by Buck (1976) at Forbes Lake near Kinmundy, Illinois, has shown that food fish production does hold some hope for the near future. During a 170-day period (May to October) in 1975 Buck produced a remarkable 2,971 and 3,834 kg of fish per hectare in two separate earth ponds. The ponds received no artificial circulation or aeration. The nutrient source was swine manure. Buck's fish production system still has some serious defects. Yearly production is highly variable. Also, some of the exotic species Buck used to obtain these high yields are now restricted for private use in Illinois and most other American states until further research identifies their effect on the natural aquatic environment. Nevertheless, Buck's work does indicate the very large potential available for food fish production which could utilize large areas of reservoirs.



Aside from the problems of the fish production procedure itself, there are the problems of making this production system work cooperatively with an irrigation system. The major problem is that the growing season of the fish, the summer, is the time when the water level in the reservoir will be low because of water usage for irrigation. Additionally, some years the reservoir might be emptied for irrigation. This does not mean that the two systems are incompatible. It only means that management decisions would have to be made. For example, it could be decided to construct the reservoir large enough that it would be emptied by irrigation only on a large recurrence interval, or it could be decided to stock the fish so that they might be carried on a small pool size, or perhaps harvest the fish before pool size becomes too small. A management decision might even be to not irrigate the corn in order to save the fish crop, depending on the relative value of the two crops. Although aquaculture may one day provide an alternate use for irrigation reservoirs, the authors conclude that at present it is not a suitable alternative.

## VII. WATER BALANCE AND YIELD MODEL

A water balance model was developed to predict soil moisture conditions in claypan soils which in turn were used to predict corn yields. The water balance model included a recycling reservoir and irrigation and drainage systems so that their effects on soil moisture and, therefore, crop yield could be evaluated. It was necessary to develop a new crop yield model because other models considered did not have provisions for either a recycling reservoir or a drainage system.

### A. REVIEW OF YIELD MODELS

Runge (1968) studied how maximum daily temperature and rainfall interact at various times during the growing season and affect corn yield on deep loam soil in central Illinois. Runge developed three regression models for predicting percentage change in corn yield as a function of temperature and precipitation occurrences above or below average for two- or eight-day periods during the growing season. The three models produced dissimilar results. Results from two of the models were averaged for prediction purposes.

Changnon (1969) predicted corn yields in Illinois using a regression equation relating weather data and dummy technological variables to corn yields. The model was used to predict the increase in yield due to irrigation. The model did not take drainage into consideration but did account for soil type by dividing the state into 12 geographic regions. Each region had its own regression equation. The model showed that for one region, which included part of the claypan

soil area, 4.8 inches of irrigation water per year would increase yield 37 to 49 percent in 4 of 20 years.

Fulcher (1961) also used a regression equation for predicting corn yield on Flanagan silt loam soil in Illinois. The equation used nitrogen application, plant population, and soil moisture in the period from 7 days before to 10 days after anthesis. The model was developed using two years' data from irrigated and not irrigated plots. Swanson and Jones (1966) used this model to estimate the economics of irrigating corn in the Urbana, Illinois, area. They concluded that irrigation was not economically feasible for that area.

#### B. WATER BALANCE MODEL

A water balance model was developed to predict daily soil moisture and storage reservoir pool size as a function of rainfall, temperature, pan evaporation, drainage spacing and irrigation. The water balance is divided into two systems. These two systems are the soil system and the reservoir system. These two systems are schematically illustrated in Figures 6 and 7. These systems were updated every day in the model by increasing the amount of water in storage in each system by the algebraic sum of the inputs and outputs.

##### 1. Soil Water System

The soil system was defined as a 19-inch layer of permeable soil over an impermeable layer. A subsurface drain line was assumed to be at the permeable layer interface. The drain spacing was a variable in the model.

The soil was assumed to have two regimes of water: the drainable water and the available water. The drainable water is that which can be removed by subsurface drains or by evapotranspiration.

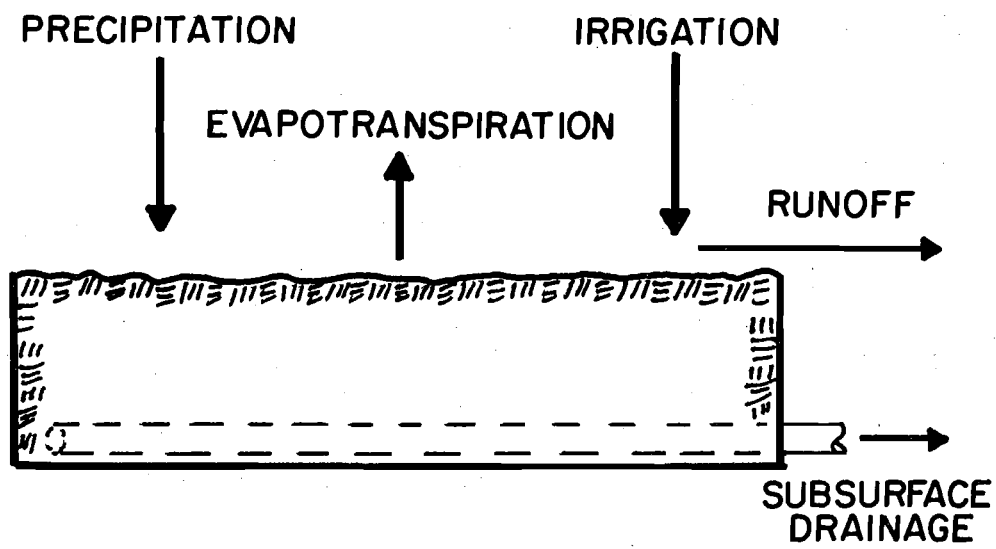


Figure 6. Inputs and outputs of the soil system in the water balance model.

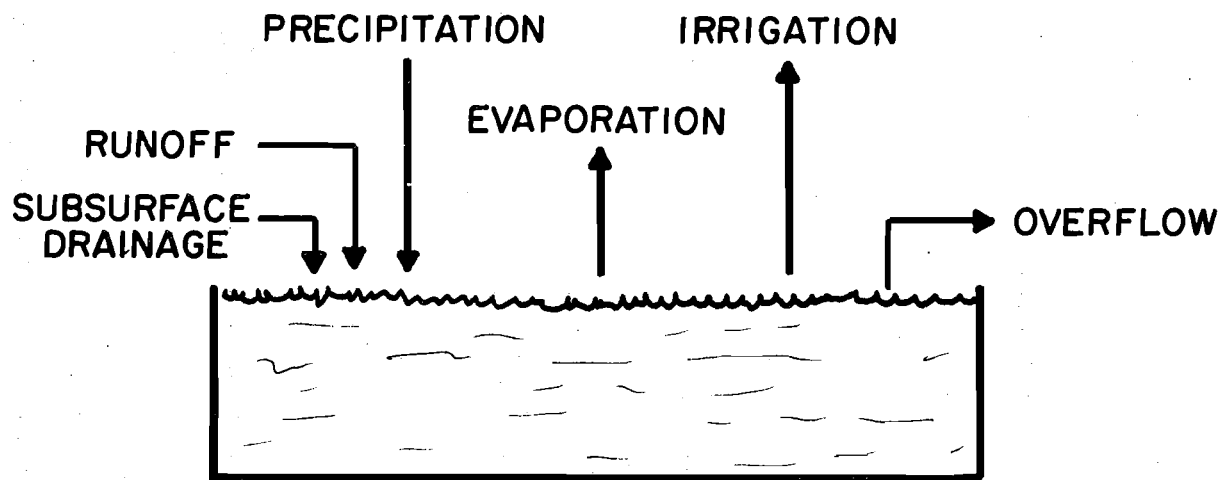


Figure 7. Inputs and outputs of the reservoir system in the water balance model.

The available water must be removed by evapotranspiration. The amount of drainable water is indicated by the height of the water table above the subsurface drain.

The National Cooperative Soil Survey (1975) reports that for Cisne series soil the permeable top layer extends to a depth of 19 inches and has an available water capacity of 0.20 to 0.24 inches of water per inch of soil. The permeability below 19 inches is less than 0.06 in./hr. The model uses 19-inch permeable soil depth and an available water capacity of 0.22 resulting in a total of 4.18 inches of available water at field capacity.

The drainable water capacity, i.e., drainable pore space, was assumed constant and was estimated by the relationship between drainable pore space and hydraulic conductivity reported by Dylla (1966) as follows:

$$f = 0.1151 \log_{10} K + 0.1005 \quad (3)$$

where

$f$  = drainable pore space (given as a fraction of the total soil volume) for a range between 0.05 and 0.35

$K$  = hydraulic conductivity (in./hr.)

The National Cooperative Soil Survey (1975) reports that for Cisne series soil the permeability is 0.06 to 0.6 in./hr.. The model uses a permeability of 0.5 in./hr. The resultant drainable pore space is 0.0659.

Daily inputs and outputs were added to the two water regimes systematically. Water inputs of precipitation or irrigation were made to the available water capacity until it was full. Excess water was added to the drainable water capacity. Evapotranspiration was taken

from the drainable water capacity until it was dry, the remainder was taken from the available water capacity. Subsurface drainage can, of course, only come from the drainable water capacity. Runoff came from neither soil moisture regime; instead it was proportioned from the precipitation before it entered the soil. Each soil water input and output is discussed in further detail below.

Precipitation was the daily precipitation records from Effingham, Illinois. Evapotranspiration was calculated from an equation, similar to that given by Pierce (1960), as follows:

$$AE = UPE \times L \times D \times R \quad (4)$$

where

AE = daily actual evapotranspiration (in./day)

UPE = unadjusted daily potential evapotranspiration (in./day)

L = daylight-hours correction factor

D = soil-dryness correction factor

R = rainfall correction factor

The correction factors R, D, and L are given as decimal reductions so they can all be multiplied together with UPE to obtain AE.

UPE was estimated using the method of Thornthwaite (1948) and the graphical aids of Palmer and Havens (1958). The calculations may be summarized as follows:

1. Obtain the long-term mean monthly temperatures (degrees Fahrenheit) for Urbana, Illinois, from U.S. Environmental Data Service (1974).
2. From Palmer and Havens (1958) obtain the appropriate monthly heat index corresponding to the mean temperature for each of the 12 months and sum them to obtain the annual heat index.

3. For the annual heat index obtain weekly values of UPE as a function of mean daily temperature from Palmer and Havens (1958).
4. Obtain daily values of UPE by dividing weekly values of UPE by 7.0.

The values of UPE obtained in Step 4 represent the potential moisture loss for one day having 12 daylight hours. The daylight-hours correction factor L is used to adjust UPE for daylight lengths longer or shorter than 12 hours. Taken separately, UPE times L yields the value of daily potential evapotranspiration. L is the day length divided by 12. Duffie and Beckman (1974) calculate day length with:

$$T_d = \frac{2}{15} \cos^{-1} (-\tan \phi \tan \delta) \quad (5)$$

where

$T_d$  = day length, hrs.

$\phi$  = latitude

$\delta$  = declination

The declination can be approximated by

$$\delta = 23.45 \sin 360 \left( \frac{284+N}{365} \right)$$

where N is the day of the year.

The rainfall correction factor R, developed by Pierce (1960), was used to adjust UPE for the influence of cloud cover and humidity on days with measurable precipitation. R was taken as 0.5 on days with rainfall greater than 0.01 inch.

D is the correction factor for the degree of soil dryness. D was assumed to be 1.0 when the water table was within the permeable top layer of soil and/or when there was available water in the soil.

D was 0.0 when the drainable water and the available water supplies were depleted. It was assumed that if the water table was within the 19-inch permeable top soil layer the capillary fringe would keep the soil surface moist. Therefore, when this condition existed, evaporation was assumed to take place only from the water table and not from available soil moisture. Since the entire soil profile had to be at field capacity before the water table could be raised and since evaporation took place only from the water table when it was within 19 inches of the surface, the soil profile could not start drying out until the water table had been lowered below that depth.

This assumption was used because several researchers have presented results which support it. Keen (1927) demonstrated the limited influence of evaporation on the water table for depths of 35, 70, and 85 centimeters (12, 28, and 33 inches) for a coarse sand, fine sand, and heavy loam soil, respectively. Veihmeyer and Brooks (1954) found a sharp reduction in annual evaporation when water-table depth changes from 1.0 foot in a fine sand to 1.5 feet in a silt loam. Laliberte and Rapp (1965) found that with tile drainage evaporation was no longer influenced by the water table when it reached a depth of 1.5 to 2.0 feet. Penman (1948) found that a water-table depth of 10 inches in a bare soil cylinder kept the soil surface moist except during extended periods without rainfall. Gardner and Fireman (1957) concluded that if the water table is lowered below 2 or 3 feet evaporation is influenced only slightly by the water table. Aldabagh



and Beer (1975) found that if the water table was kept below a depth of 1.5 to 2.0 feet, the soil surface would be dry enough to permit spring plowing.

Irrigation was set at 1.0 inch per application and was applied each day between June 1 and August 31 if the available soil moisture content was 2.5 inches or less. In the event there was insufficient water in the reservoir for a 1.0-inch irrigation, whatever water was in the reservoir was irrigated uniformly over the field. In all cases an irrigation efficiency of 1.0 was assumed.

The Soil Conservation Service (SCS) method of predicting surface runoff was used in the simulation model. The equation for predicting surface runoff is given by the U.S. Soil Conservation Service (1972) as follows:

$$Q = \frac{(I - 0.2S)^2}{I + 0.8S} \quad (6)$$

where

Q = direct surface runoff (in.)

I = storm rainfall (in.)

S = maximum potential difference between rainfall and runoff, starting at the time of the storm's beginning (in.)

The term S is further defined as follows:

$$S = \frac{1000}{CN} - 10 \quad (7)$$

where

CN = an arbitrary curve number varying from 0 to 100

The curve number CN depends on infiltration rate of the soil, antecedent

moisture condition, land use, surface cover, time of the year, and conservation practices.

By substituting the appropriate curve number for the antecedent moisture condition into Equation (7), the value of  $S$  can be determined. When rainfall exceeds the value of  $0.2S$  (called initial abstraction  $I_a$ ), direct surface runoff can be calculated by substituting  $S$  into Equation (6) along with the amount of rainfall, and solving for  $Q$ .

Runoff also occurred when the two soil water regimes were full of water. Any infiltration in excess of the amount required to fill the available water capacity and the drainable water capacity was included in the runoff. This is equivalent to surface draining pools of water from saturated ground.

Subsurface drainage was calculated by multiplying the change in water table height by the drainable porosity and subtracting the contributions of precipitation and evapotranspiration. Daily water table heights were calculated using the van Schilfgaarde drainage equation as given by Young and Ligon (1972). This equation gives the height of the water table  $Y_N$  at the end of the  $N$ th time period based on the height of the water table from the previous day  $Y_{N-1}$  as follows:

$$Y_N = \left[ Y_{N-1} + \frac{A}{f} (e^{1/A} - 1) P_N \right] e^{-1/A} \quad (8)$$

where

$Y_N$  = water-table height above the tile axis midway between tile lines at the end of the  $N$ th time period (in.)

- $P_n$  = net accretion rate in the Nth period (in./day)  
 N = time interval (days)  
 $A = fFCS/K$  (days) (9)  
 f = drainable pore space  
 S = drain spacing (ft.)  
 K = hydraulic conductivity (ft./day)  
 C = the ratio of the average flux between the drains to the flux midway between the drains  
 F = the value of an infinite series which is a function of  $r/S$  and  $d/S$   
 r = drain radius (ft.)  
 d = depth to an impermeable layer below the drain axis (ft.)

The parameter A has dimensions of time and describes the geometry of the drainage system as well as the physical properties of the soil. As seen from the relationship given above, A is a function of drain radius, spacing, depth to an impermeable layer below the drain axis, hydraulic conductivity, and drainable pore space.

The drainable pore space f is dimensionless and is expressed as a fraction of the total soil volume. The value of f is assumed to remain constant for a given soil regardless of moisture content.

The factor C as used above is a shape factor for the water table which was first introduced by Bouwer and van Schilfgaarde (1963). It accounts for the change in the shape of the water table during draw-down. According to Bouwer and van Schilfgaarde, C can generally be selected as unity.

F is an infinite series which was tabulated by Tokosz and Kirkham (1961). As can be seen by the equation given below, F is a function of drain radius r, spacing S, and depth to the impermeable layer d.

$$F = \frac{1}{\pi} \left[ \ln \frac{S}{\pi r} + \sum_{m=1}^{\infty} \frac{1}{m} \left( \cos \frac{2m\pi r}{S} - \cos m\pi \right) \left( \coth \frac{2m\pi d}{S} - 1 \right) \right] \quad (10)$$

The symbol  $P_N$  is the rate the excess water is added to the soil profile. It represents that part of the precipitation occurring in the Nth time period which moves through the soil profile and is added to the water table. The rate of excess moisture addition is constant and is assumed to take place over the entire length of the Nth time period. Before  $P_N$  can have a value greater than zero, the moisture content of the soil must be at or greater than field capacity.

## 2. Reservoir Water System

The reservoir inputs and outputs are shown in Figure 7. The subsurface drainage, runoff, precipitation, and irrigation are defined and described in the soil water balance section.

The reservoir surface was assumed to be one tenth the size of the cropland area for the purpose of proportioning the precipitation and evaporation from the reservoir surface.

The daily evaporation from the reservoir was determined from the daily pan evaporation records from Effingham, Illinois. Reservoir

evaporation was assumed to be 78% of pan evaporation. Reservoir evaporation was estimated for dates when pan evaporation was not available from the average monthly reservoir evaporation values reported by Roberts and Stall (1967).

Daily net inputs into the reservoir in excess of that required to fill the reservoir to its maximum capacity were assumed to overflow from the reservoir and leave the soil and reservoir systems. The maximum reservoir capacity was a variable in the model.

### 3. Water Balance Simulation Results

The model was used to predict the effect of size of storage reservoir on the probability that it would go dry. The model used climatological data from Effingham, Illinois, for the years 1951 to 1971 and simulated irrigation of the crop using various size reservoirs. The reservoir size was specified by the number of inches of water it would hold from the entire watershed. For example, a 2-inch reservoir could hold enough water at one time to cover the entire watershed with 2 inches of water. It was assumed that the entire watershed was irrigated cropland. Reservoir size was varied from 1 inch to 15 inches. Figure 8 shows the result of the simulation.

Figure 8 shows the percentage of years in which the reservoir would go dry at least once during the irrigation season as a function of the reservoir size. The watershed was simulated as having drain

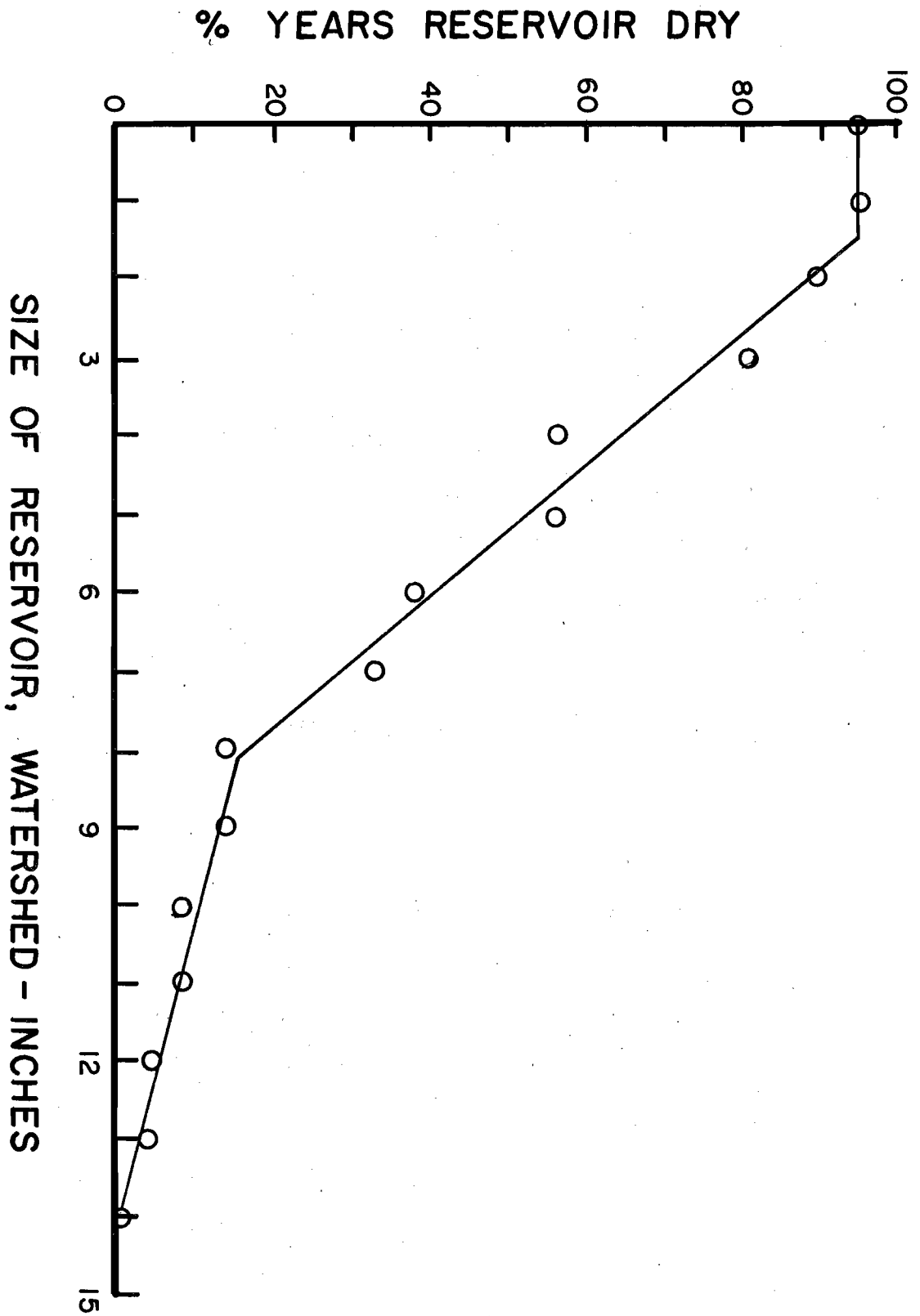


Figure 8. Irrigation dependability as a function of reservoir size with no subsurface drainage.

lines spaced every 500 ft, which is practically equivalent to no subsurface drainage. The data show that with a 1-inch or smaller reservoir the storage reservoir was empty and irrigation water was lacking sometime during about 95% of the years. The data also show that 14 inches of storage are required to prevent the reservoir from going dry at any time during the 21-year period simulated.

Approximately 10 inches of storage would be required to keep the reservoir from going dry except in one out of 10 years. Approximately 8 inches of storage would be required to keep it from going dry except in one out of five years.

Figure 9 shows the results of another simulation. This simulation was exactly the same as the one illustrated in Figure 8 except that subsurface drainage was added. Drain line spacing was 10 feet. Ten feet was chosen because of a subjective decision that narrower spacings could not be economically feasible.

Figure 10 is a comparison of the data from Figures 8 and 9. This comparison clearly shows that, in order to maintain a given irrigation dependability, more reservoir storage is required if the land is subsurface drained than if it is not subsurface drained. This result occurs because the subsurface drainage system removes part of the stored water from the soil causing it to need more irrigation later in the year. This does not mean that nondrained crops would necessarily have a better crop dependability. A higher level of irrigation dependability means lower risk of crop failures from drought. On the

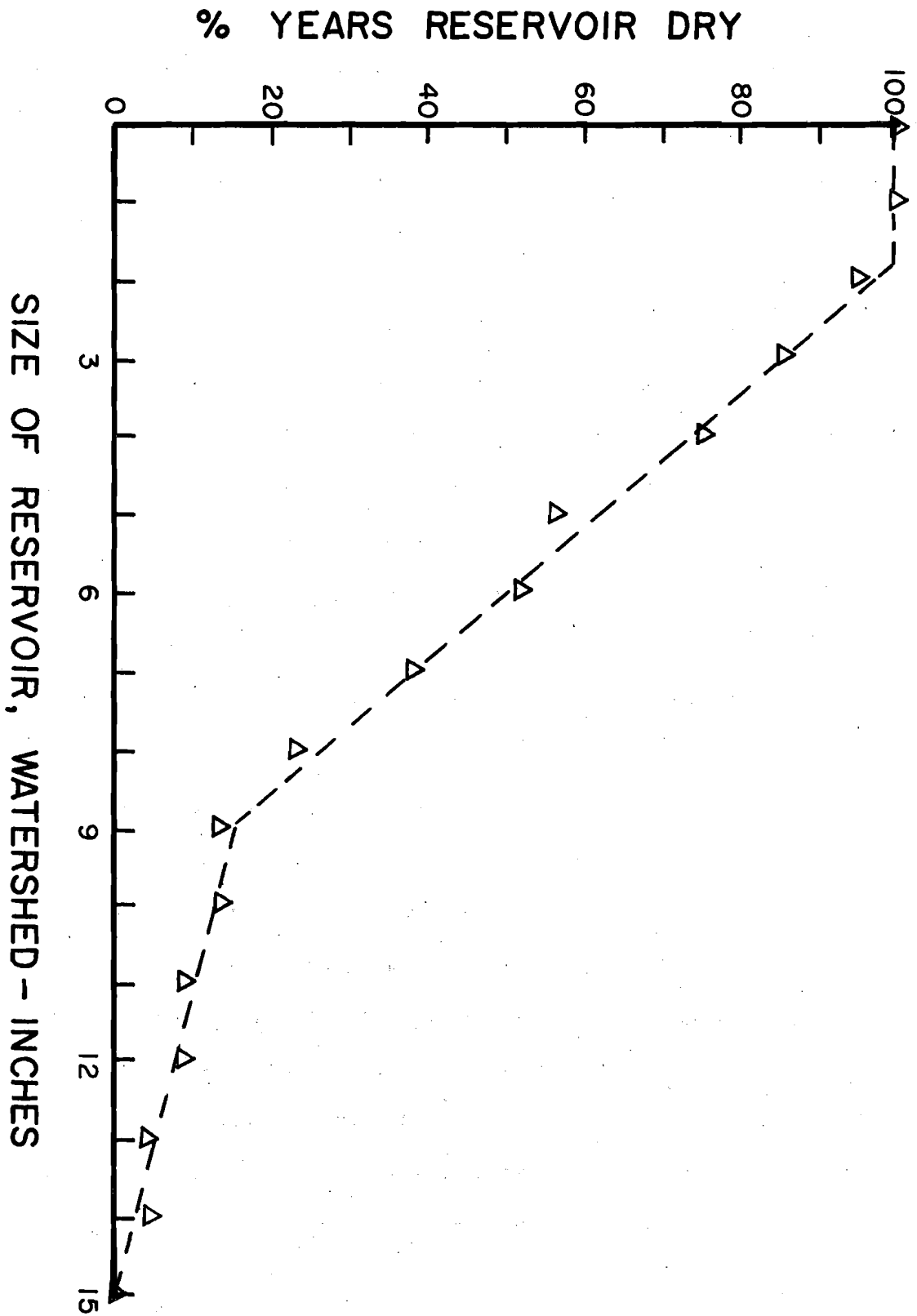


Figure 9. Irrigation dependability as a function of reservoir size with subsurface drainage.



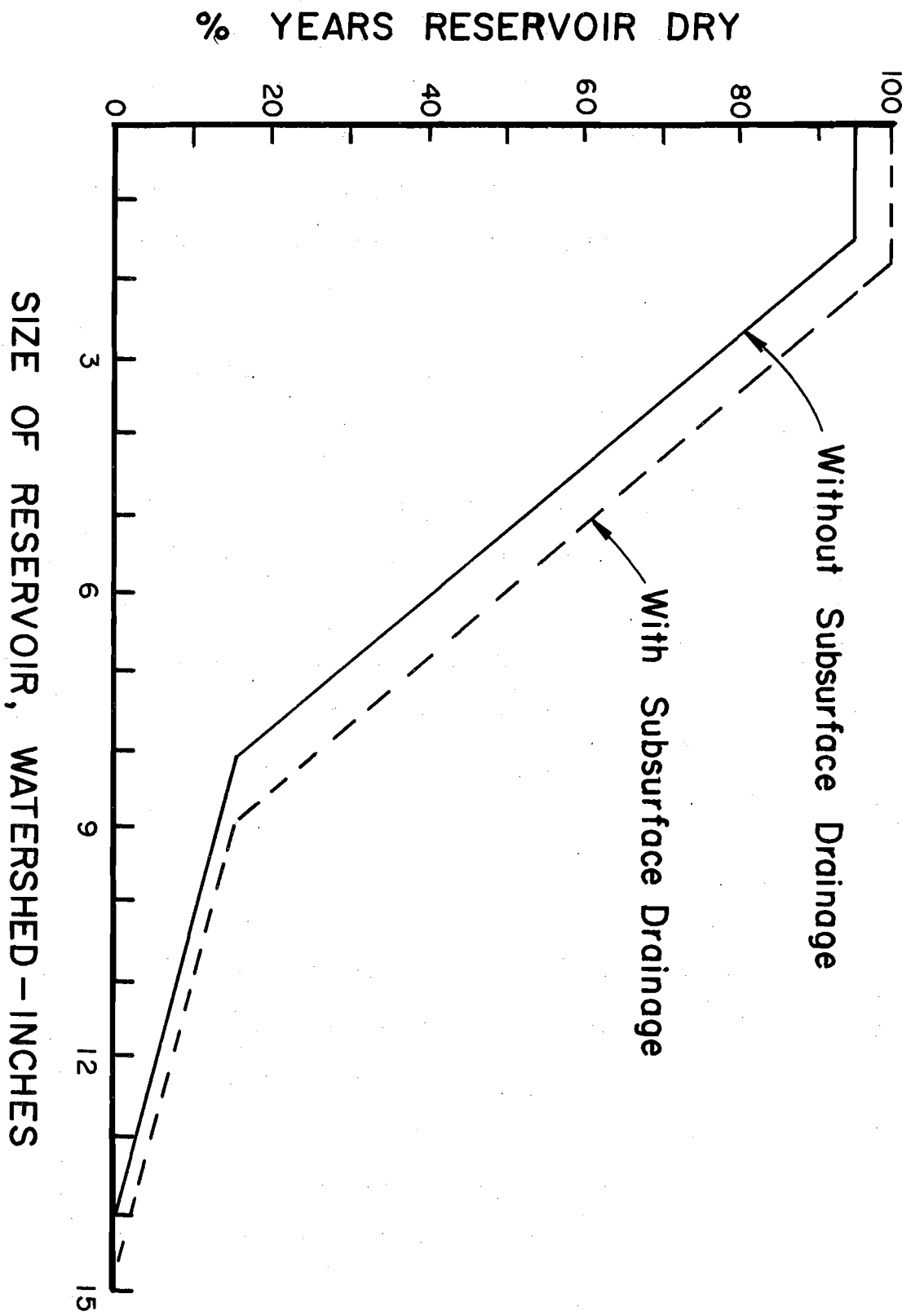


Figure 10. Comparison of irrigation dependability with and without subsurface drainage.

other hand, a higher level of drainage means lower risk of crop failure from root inundation, low soil temperature, poor trafficability, etc.

In order to determine the real value of high irrigation dependability or good drainage it is necessary to know their interdependent effect on corn yield. The next section describes this part of the model.

### C. YIELD PREDICTION MODEL

Irrigation dependability and subsurface drainage along with weather, technology, and numerous other less important factors determine corn yield for a given set of soil factors. Irrigation, subsurface drainage, and weather are principally related to yield through the factors of soil moisture and temperature. The model under development relates soil moisture and air temperature to crop yield.

#### 1. Model Development

The model is briefly described as follows. The water balance model was used to generate the soil moisture and average daily temperature data that would have been expected in Effingham county, Illinois, a county that has largely claypan soils. The data was generated using no irrigation and no drainage. A multiple regression equation was then developed to relate the soil moisture and temperature data to the Effingham county average crop yields which were corrected to a standard technology level. The water balance model was

then used to simulate the daily soil moisture if drainage and/or irrigation were used in a runoff recycling system. Finally, the regression equation was used to predict the new crop yields resulting from the changed daily soil moisture.

Two critical times during the development of the plant are planting and anthesis. The moisture and temperature levels at these times are very important. Therefore, the primary variables used in the regression equation for the prediction of yield were average soil moisture and average maximum temperature for the planting period and for the anthesis period. The planting period was defined as the month of May. The anthesis period was defined as the month of July.

The general form of the multiple regression equation was as follows:

$$\begin{aligned}
 Y_t = & C_0 + C_1 M_1 + C_2 M_1^2 + C_3 M_2 + C_4 M_2^2 + C_5 M_1 M_2 \quad (11) \\
 & + C_6 M_1^2 M_2 + C_7 M_1 M_2^2 + C_8 M_1^2 M_2^2 + C_9 T_1 \\
 & + C_{10} T_2 + C_{11} T_1 M_1 + C_{12} T_2 M_2
 \end{aligned}$$

where

$Y_t$  = Effingham County annual corn yield, corrected to 1970 technology level, bu/ac.

$M_1$  = Average available soil moisture during planting period as predicted by water balance model

$M_2$  = Average available soil moisture during anthesis period as predicted by water balance model

$T_1$  = Average daily maximum temperature during planting period as recorded at Effingham, Illinois

$T_2$  = Average daily maximum temperature during anthesis period as recorded at Effingham, Illinois

$C_i$  = Constants

Annual corn yields for Effingham county were modified to account for the general increase in corn yields which had occurred in the last several years due only to an increase in technology such as better crop varieties and better fertilizer practices. The actual corn yields were approximated by a best fit straight line as shown in Figure 11. The line represents what the corn would yield if average weather conditions had existed for each year. The difference between the yield predicted by the straight line for a given year and the actual yield was assumed the result of yearly weather conditions, namely, soil moisture and temperature. The equation for the straight line is:

$$Y_p = -75.4 + 2.23 N \quad (12)$$

where

$Y_p$  = predicted yield for average weather conditions

$N$  = number of year, i.e. for 1970,  $N = 70$

The actual annual yield was corrected to the technology level of 1970 using the following equation:

$$Y_t = Y \frac{Y_{p70}}{Y_p} \quad (13)$$

$Y_t$  = Yield corrected to 1970 technology level

$Y$  = Actual yield

$Y_{p70}$  = Predicted 1970 yield for average weather conditions

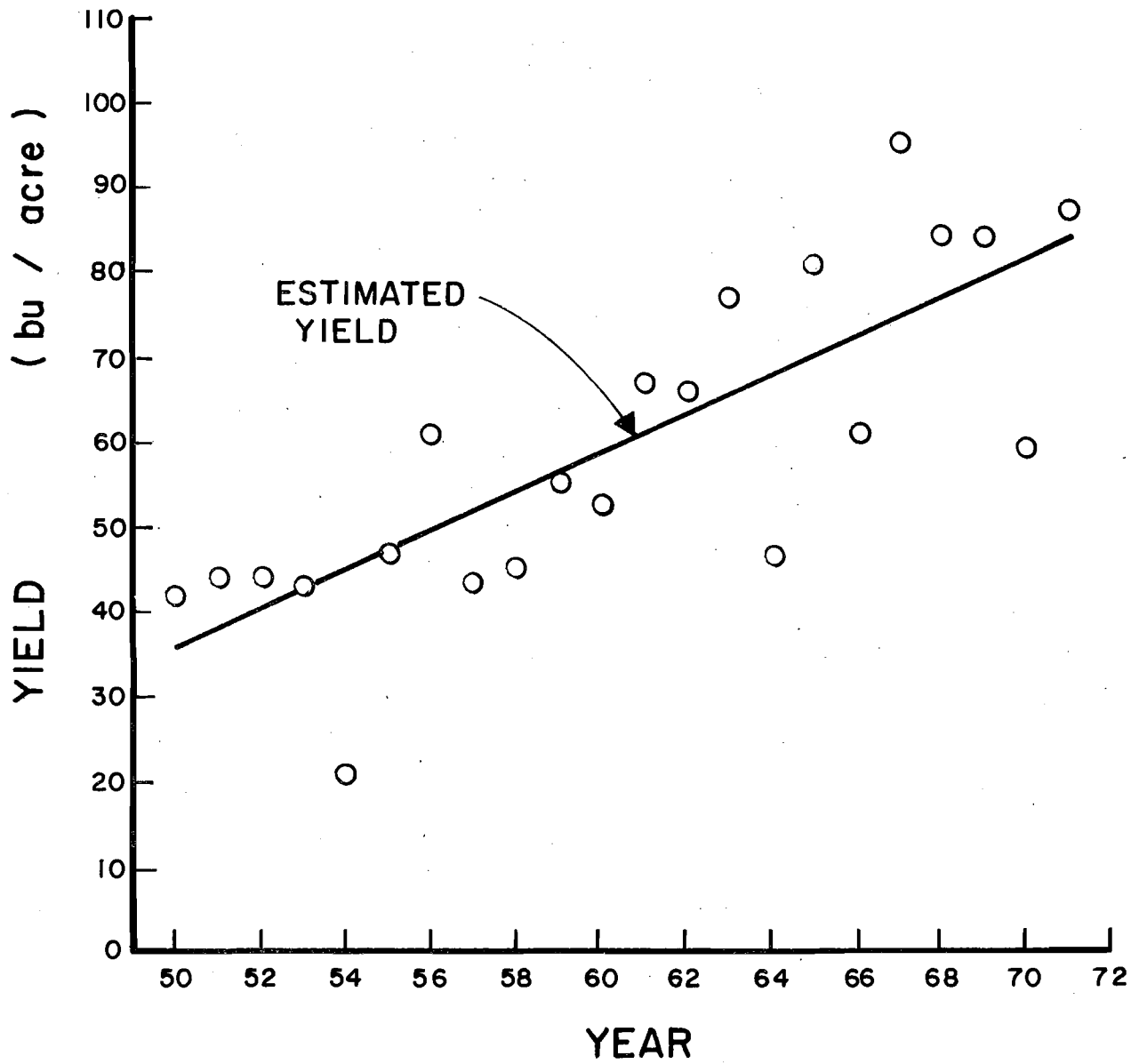


Figure 11. Yield and estimated yield based on average weather conditions for Effingham County.

$Y_P$  = Predicted yield for average weather conditions,  
not corrected for technology

The results of these calculations are shown in Table 4.

A stepwise multiple regression analysis was used to determine the coefficients,  $C_i$ , in Equation (11) using the technology corrected yield data from Table 4. The optimization criterion for the regression analysis was minimum residual sum of squares.

The resulting equation was:

$$Y_t = -11.0 + 48.8 M_1 - 12.5 M_2^2 - 53.1 M_1 M_2 + 0.901 M_1^2 M_2^2 + 16.0 T_1 - 8.71 T_2 - 3.68 T_1 M_1 + 2.28 T_2 M_2 \quad (11a)$$

A comparison between the actual corrected yields and the yields predicted by Equation (11a) is shown in Table 5.

## 2. Model Results

The water balance simulation model was then used to generate the soil moisture conditions which would have occurred under different combinations of irrigation and drainage. The yield prediction equation, Equation (11a), was used to predict the yields which would result under the simulated moisture conditions. The irrigation and drainage combinations studied were:

- 1) no irrigation and no drainage
- 2) irrigation with no drainage
- 3) drainage (drain spacing = 10 ft.) with no irrigation
- 4) irrigation with drainage

Table 4. Comparison of actual, predicted (for average weather), and technology corrected yields.

<u>YEAR</u>	<u>ACTUAL YIELD</u>	<u>PREDICTED YIELD</u>	<u>CORRECTED YIELD</u>
50	42	36.1	93.9
51	44	38.3	92.7
52	44	40.6	87.5
53	43	42.8	81.1
54	21	45.0	37.7
55	47	47.3	80.2
56	61	49.5	99.4
57	43	51.7	67.1
58	45	53.9	67.4
59	55	65.2	68.1
60	53	58.4	73.2
61	67	60.6	89.2
62	66	62.9	84.7
63	77	65.1	95.5
64	47	67.3	56.4
65	81	69.6	93.9
66	61	71.8	68.6
67	95	74.0	103.6
68	84	76.2	89.0
69	84	78.5	86.4
70	59	80.7	59.0
71	87	82.9	84.7

Table 5. Comparison of technology corrected actual yields and yields predicted from soil moisture and temperature data using Equation 11a.

<u>YEAR</u>	<u>CORRECTED YIELD</u>	<u>PREDICTED YIELD</u>
51	92.7	90.0
52	87.5	79.3
53	81.1	100.1
54	37.7	45.6
55	80.2	78.9
56	99.4	83.3
57	67.1	70.6
58	67.4	79.3
59	68.1	74.9
60	73.2	80.9
61	89.2	84.7
62	84.7	90.2
63	95.5	81.1
64	56.4	51.8
65	93.9	85.8
66	68.6	61.7
67	103.6	87.4
68	89.0	85.6
69	86.4	83.4
70	59.0	74.2
71	84.7	79.6



The results are shown in Table 6.

Statistical analysis of the data in Table 6 shows that yield is not significantly improved either by drainage alone or by irrigation alone. Irrigation plus drainage significantly improves yield at the 95% confidence level. At the 95% confidence level the improvement in yield with irrigation plus drainage as predicted by the model is 0.46 bushels per acre per year. One should not conclude that this is the true increase in yield which could be attained by drainage and irrigation. Instead, it is concluded that the model is not able to adequately simulate the growing conditions and subsequent yield of the corn.

#### D. DISCUSSION OF WATER BALANCE AND YIELD MODEL RESULTS

The model was designed to produce two important results. The first was the increase in yield which should be expected on claypan soil with the addition of an irrigation system or a drainage system or both. The second was an indication of the required size of a surface storage reservoir to provide a dependable irrigation source. This information is critical in order to make an extensive economic analysis of a runoff recycling system.

The model was not able to reasonably predict yields which would result from the addition of irrigation and/or drainage systems to claypan soils. The model predicted a decrease in yield as a result of subsurface drainage alone. This is contrary to all other experimental evidence found in this study. The model predicted very

Table 6. Comparison of predicted yields for combinations of drainage and irrigation.

YEAR	YIELD (bu/acre)			
	NO IRRIGATION NO DRAINAGE	IRRIGATION NO DRAINAGE	NO IRRIGATION DRAINAGE	IRRIGATION DRAINAGE
51	90.0	88.6	178.5	175.5
52	79.3	77.3	41.6	83.0
53	100.1	81.5	89.2	77.5
54	45.6	67.1	13.7	56.
55	78.9	75.5	79.8	89.6
56	83.3	83.3	83.3	83.1
57	70.6	70.5	71.6	71.6
58	79.3	79.3	78.8	78.8
59	74.9	78.6	58.2	147.2
60	80.9	80.5	81.8	79.6
61	84.7	77.7	75.9	73.0
62	90.2	87.2	93.2	93.0
63	81.1	77.0	56.2	78.4
64	51.8	99.1	59.7	178.5
65	85.8	85.8	99.5	98.4
66	61.7	70.3	54.9	67.6
67	87.4	81.2	87.4	79.4
68	85.6	76.6	61.6	68.5
69	83.4	83.4	79.4	79.4
70	74.2	83.1	74.1	102.3
71	79.6	78.1	74.4	81.7
Average	78.5	80.1	75.8	92.5

little increase in yield due to irrigation alone. Again, this is contrary to all other experimental evidence found in this study. From this evidence it was concluded that the model was unable to predict reasonably expected yields. The failure of the model may have been its inability to simulate a water balance, or its inability to predict yields from the water balance data, or perhaps both. There is reason to suspect that the water balance model may be reasonably accurate. That analysis will be presented later. This leaves the conclusion that the regression equation was not able to predict yields from the soil moisture and temperature data.

The failure of the yield regression equation may be attributed to the fact that the weather data used to simulate the soil moisture data was from the Effingham weather station while the yield data used to develop the regression equation was the average county yield. Given the variability of storms during the growing season it is probable that the weather station data did not adequately represent the rainfall received by the average corn field.

Another possibility for error was the correction of yields for technological advances. It was assumed that technology increased at a linear rate. Some technology, such as the introduction of hybrid varieties, may have caused yields to increase rapidly in a very few years, causing the technology trend to be more nearly like a step function than a linear function.

Still another possibility for error was that the reported county average yield data did not adequately represent the true

average yield. Data indicate that during years with unfavorable weather conditions a substantially fewer number of crop acres were reported. Presumably, these acres not reported were acres not planted or perhaps not harvested because of unfavorable weather conditions. If these assumptions are valid, it means that only yields from the better cropland were reported during poor years while yields from all cropland, including marginal cropland, were reported during good weather years. The model did not correct for this reporting discrepancy.

The accuracy of the water balance model is relatively difficult to judge. The information it produces which is used for yield prediction is soil moisture data, and long term records of soil moisture in claypan soils are not available. However, the water balance model is also used to predict the relationship between a reservoir's size and its dependability as an irrigation source. Evidence that this prediction is reasonable adds credibility to the model since soil moisture is directly related to irrigation.

Recall that the water balance model predicted that approximately 12 inches of storage would be required to keep the reservoir from going dry except in 10% of the years. This compares favorably with a U.S. Soil Conservation Service (1969) estimate that 1.5 ft. of reservoir storage is required per irrigated acre in humid areas. The SCS estimate did not discriminate between soil types.

An equation referenced by Schwab (1976) may be used to estimate the water yield from a watershed. The equation is

$$Y = 5.04 \log A - 0.56 (\log A)^2 - 3.98 \log T \quad (14) \\ - 0.15 (\log A) (\log T) + 3.89$$

where

Y = annual yield, in.

A = watershed area, acres

T = return period, years

Assuming a watershed of 80 acres is used to supply water to irrigate itself, and assuming a return period of 10 years, the equation results in a water yield of 7.17 inches. The water balance model predicts a needed irrigation amount in excess of 7.0 inches with a recurrence interval of seven years. The two recurrence intervals should be reasonably close but are not exactly comparable because Equation (14) does not take into consideration storage capacity or soil type and the equation was developed for Ohio, not central Illinois. Nevertheless, the equation results do show that a watershed in a humid area should yield sufficient water for its own irrigation, as predicted by the model.

## VIII. EXAMPLE COST ESTIMATE

A meaningful example cost estimate can include only the costs and benefits of a recycling reservoir and an irrigation system. It does not include costs or benefits associated with nutrient recycling, pesticide recycling, or drainage. Nutrient or pesticide recycling are not included because evidence indicates that they have a negligible economic effect. Drainage is not included for two reasons. First, no means were found to predict the interactive effect on expected yield when both irrigation and drainage systems are used. Second, since drainage systems can be installed without a recycling system, their benefit can be analyzed independently of the recycling system. This does not mean that the benefit of a drainage system will be the same with or without the recycling system. A drainage system would have more benefit with the recycling system than without because the drainage system could remove excess water in instances where heavy rainfall follows irrigation. However, as stated before, this interactive effect has not been quantified.

If the method of Dawes and Wathne (1968) is used to determine the reservoir cost and the method of Schwab and Kidder (1976) is used to determine other irrigation costs, an estimate can be made of the returns needed from a Runoff Recycling System to justify the investment.

Consider Equation (1) with a storage of 100 acre-feet and a land price cost of \$500/acre.

$$P_c = (9161) 100^{0.54} + (0.49) 100^{0.87} (500)$$

$$P_c = \$123,600$$

Increasing  $P_c$  to 1976 construction costs using the method suggested by Dawes and Wathne (1968),  $P_c = \$150,000$  or \$1500/acre-ft. cost of storage. Assuming a reservoir life of 50 years and an interest rate of 8%, the capital recovery factor is 0.082 and the annual cost per acre for the reservoir is \$120.

Using the method of Schwab and Kidder (1976) to calculate the cost of irrigation for 100 acres of corn with a traveler type sprinkler,

Distribution hose, sprinkler and winch	\$10,635
Pipe line	
3,300 ft. of 6 in. main @ \$2.15/A. = \$7,095	
660 ft. of 6 in. lateral @ \$1.65/ft. 1,090	
600 ft. of 6 in. main from lake to field @ \$2.15/ft. <u>1,290</u>	
	9,475
Gasoline motor and pump, 500 gpm	6,550
Tractor share for irrigation	<u>1,000</u>
	\$ 27,660

and we have an investment of \$277/acre.

If we consider annual costs for irrigation equipment as 20% of investment costs, annual equipment fixed cost is \$55/acre.

Using Schwab and Kidder's estimates of added irrigation costs and adapting these to the 103 bushel-per-acre increase experienced at the 1976 Brownstown irrigation study cited earlier in this report, we have the following estimate of costs:

## Added cropping costs because of irrigation

Increase plant population by 5000 seeds using seed cost of \$40/80,000 seeds		\$2.50
Additional fertilizer		
N 44 lb. @ 15¢/lb.	\$6.60	
P 20       30¢	6.00	
K 10       9¢	<u>.90</u>	13.50
Added harvesting, hauling and drying cost of 103 bu. @ 25¢/bu.		25.75
Loss of land due to required equipment paths 8% x \$50/acre cash rental		<u>4.00</u>
Total		\$35.75

## Variable costs for irrigation

Fuel for irrigation - gasoline @ 40¢/gal. with pumplload of 60 HP pumping 500 gal./min. requiring 5.4 hours/acre for 6 acre-in. of water		\$15.23
Labor for irrigation - 1 hour/set for 10 acres Thus 6 sets = .6 hours/acre @ \$4/hour		2.40
Irrigation repairs and service - 4¢/acre in./\$1000 investment		<u>6.75</u>
Total		\$24.38

If we assume that there are no added drainage costs and summarize the added costs for recycling runoff:

Reservoir storage cost	\$120
Annual equipment fixed cost	55
Added cropping cost	36
Variable cost	<u>24</u>
Total	\$235



The break-even price of corn with the 1976 increase in yield of 103 bu./acre due to irrigation was

$$235 \div 103 = \$2.28/\text{bu.}$$

This is a reasonable expected price on today's market. We can conclude that with a yield increase such as the one that occurred in 1976 at Brownstown recycling agricultural runoff is a sound agricultural practice. Unfortunately, considering the history of crop yields in this area as shown in Table 1, 1976 yields without irrigation were lower than usual. A yield increase of 50 bushels per acre would be more likely from a long-term standpoint and would not give a farmer the economic incentive necessary to recycle agricultural runoff for corn production.

Other crops than corn were not considered in this study, and it is entirely possible for such high value crops as strawberries, apples or other fruit crops which are adapted to the claypan soil area of Illinois to produce a return from irrigation that would be greater on an average year.

## IX. CONCLUSIONS

Recycling agricultural runoff is not an economically acceptable practice for corn in the claypan regions of Illinois under present conditions. The cost of building, maintaining, and operating a reservoir and irrigation system are greater than the benefit of expected yield increases. Exceptions to this would be where topographic features make the construction cost of a reservoir much less than normal. One acre-ft. of storage is required for each acre irrigated.

The coincidental recycling of pesticides and nutrients causes only negligible costs and benefits. The low concentration of these chemicals have very little effect on field crops. The recycling system also helps keep these chemicals out of other parts of the environment where even low concentrations may cause considerable change in a delicately balanced ecosystem. However, there are no estimates of the economic benefit, if any, of preventing this ecological change.

Irrigation is possible only with a recycling reservoir as a water supply. Therefore, an economic analysis of irrigation alone is no different from that of a complete recycling system. In 1976 irrigation increased yield in claypan regions of Illinois by 103 bu./acre. However, 1976 was an exceptional year and normal expected increases in yield are 50 bu./acre. With a 103 bu./acre increase in yield corn prices would have to be \$2.28/bu. to break even.

Drainage can be installed and evaluated independently of a recycling system. This study was not conclusive as to what degree of drainage was most economical.

No estimates of the interactive effect between irrigation and drainage were found in the literature. The model developed in this study to find this effect was not successful.

Future research should be centered around determining what degree of drainage is most economical and determining the interactive effect between irrigation and drainage.

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