EGYPT WATER USE AND MANAGEMENT PROJECT

MID-PROJECT REPORT

VOLUME III

APPENDIX B
STAFF PAPERS

Section 4 of 4

by Egyptian and American Team

Cairo, ARE
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Mid Project Report
Volume III

Appendix B
Staff Papers
Section 4 of 4

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Staff Paper #41

THE COST OF DELIVERY OF IRRIGATION WATER

Raymond L. Anderson

Introduction

An irrigation system is a very complex organism designed to reduce the uncertainty that nature presents to human settlement in an inhospitable, arid environment. To succeed for any length of time, to capture and distribute available water and to control the amount of land placed under irrigation, farmers must develop self discipline and a high level of community organization. To do this for the length of time that farmers have irrigated lands along the Nile attests to a high degree of discipline and knowledge. But as times change, population grows and technology advances, irrigation communities also have to evolve new ways of operating to meet the increasing demands placed on them.

Modernization--building of large storage projects, rebuilding and lining main canals and restructuring and lining farm canals--requires new ways of delivering irrigation water and finding means to pay for reconstruction, operation, and maintenance. As with any project built by humans, it is possible to live only for a time on the labor and investment of past generations. Sooner or later, each generation of users must invest their labor, talents and capital in maintaining and improving the systems handed down to them by their fathers.

Charging money for the delivery of irrigation water is the traditional way that the costs of operating and maintaining the systems are met and the money to pay for capital investments in irrigation systems is raised.

Setting fees to cover the cost of irrigation water delivery is one of the difficult but very important functions of a well-run irrigation system. Irrigation farmers have long regarded water as free. And in many places such as the American West and Spain, the water is indeed free. It belongs to whoever captures it. But for an irrigation system to function effectively, it is necessary to raise money to pay the people who keep the records, deliver water, and repair and maintain the canals. Irrigators who pay their own costs also control conditions of water delivery. These costs are typically borne by the water users. Inasmuch as water supply is normally quite limited, the amount of water delivered to irrigators usually varies by size of farm, soil type and crops grown. Charges are normally levied according to the amount of water delivered--those who receive the most water pay the most money.

Water Fees

By fees is meant the money collected from farmers for the delivery of irrigation water. The level of fees or charges varies according to the level of development of the irrigation system that delivers water to farmers. A very rudimentary system with unlined ditches and few employees, delivering an undependable, erratic water supply, usually has lower charges than one that is well built, well maintained, has operating personnel, and delivers specified quantities of water to farmers at times needed by the crops.

In other words, fees charged for water typically reflect the level of service provided by the irrigation system. It should go without saying that a system that delivers adequate water on a dependable basis is much more valuable to farmers than one that delivers a poor water supply in a haphazard manner.

Since I know very little about irrigation in Egypt, it would be presumptuous to advocate changes in your systems without a fairly complete knowledge of how the systems operate. It might be instructive if I described in some detail how several systems in the U.S. and Spain go about the very difficult job of distributing water to irrigation farmers and what fees are charged for providing this service.

In most systems, American and Spanish, the water is diverted from streams into the irrigation works of the system. Water is diverted on the basis of long-established rights. Even when someone buys a right, the payment is to the holder of the water right rather than for water itself. In Colorado, not only is the water free, the river commissioner, the man who administers the diversion of water to the canals of the various right holders, is paid with public funds.

The systems that I will describe will be mostly farmer-owned mutual (cooperative) ditch companies. These companies are owned and operated by farmers served by the ditches. Farmers own shares of stock in the ditch company. The shares of stock determine the amount of water each farmer receives. The water delivered in a season is divided by the shares of stock, each share being allocated a proportionate share of the water supply. For instance, 10,000 A.F. divided by 500 shares of stock = 20 A.F. of water per share. A farmer owning five shares would be entitled to 100 A.F. of water during the season. Some systems require each stockholder to take a certain amount of water each time the canal is run. Others allow farmers to order water when they want delivery.

Another type of system includes government-sponsored and built irrigation systems (U.S. Bureau of Reclamation projects). These systems are usually called irrigation districts, and these typically deliver specified quantities of water to the land. The government builds the entire system and, in some cases, allocated lands to farmers. Farmers do not own shares, but a certain quantity of water is allotted per acre. Farmers typically can order water as needed because most of the supply is stored in reservoirs.

A third type of system is a government-sponsored project that builds reservoirs and delivers water to farmer-owned irrigation canals. The governmental function does not extend into the farmer-owned system. The government's only function is to deliver water as ordered by the farmer-owned companies. The Colorado-Big Thompson project is an example of this type of project.

Regardless of the type of irrigation system, there are two major types of costs or charges that must be paid on all irrigation systems. These are:

Fixed costs. These occur whether the system is operated or not. Generally, fixed costs refers to the repayment of capital investment in the irrigation system and interest charges if these are associated with the projects. USBR projects pay no interest on the irrigation part of water projects. Capital investment can be for original construction or, more commonly, improvement and expansion of the system. Old, established systems may be in a situation where there are very low fixed charges. All borrowed capital has been repaid; only improvements need to be paid for.

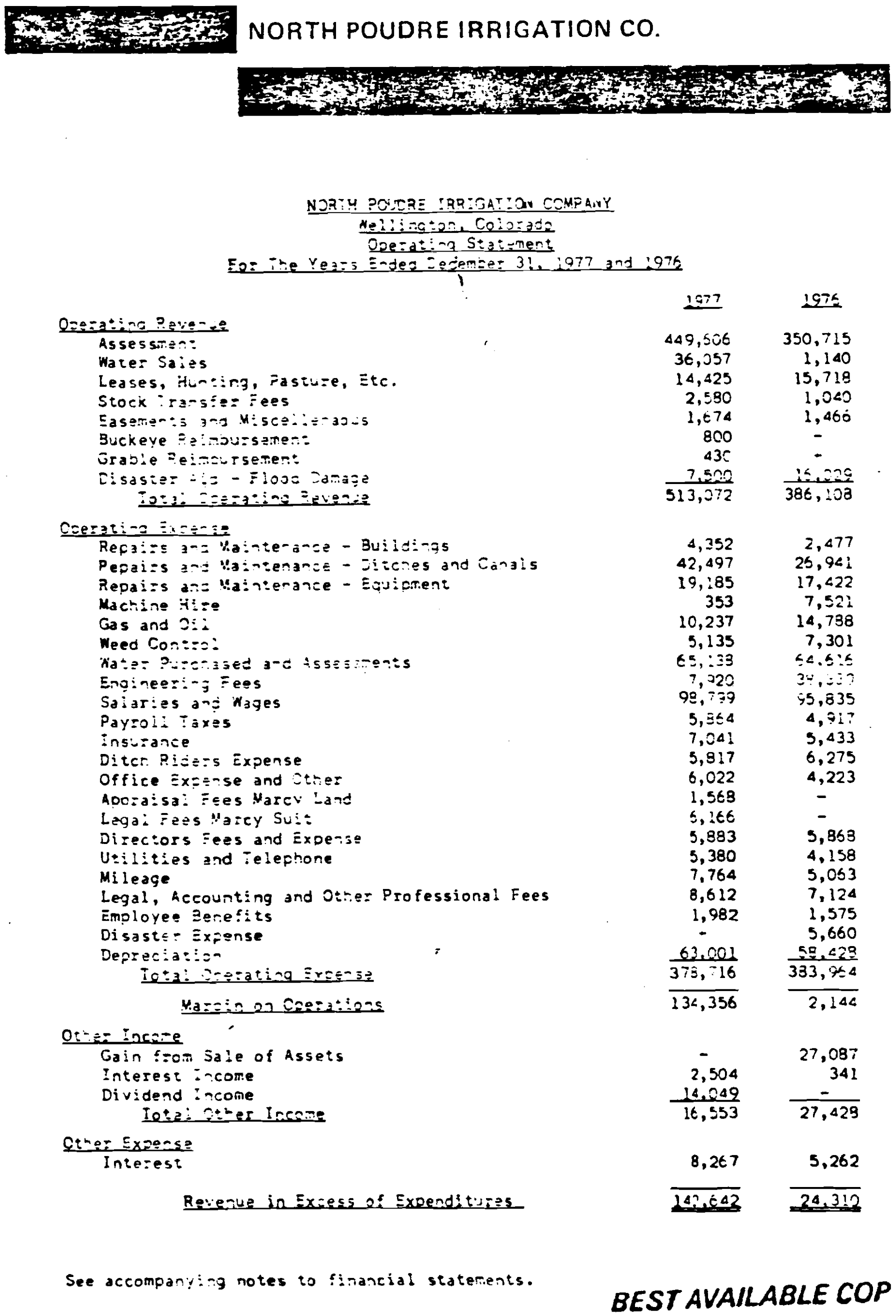
The other type of costs are variable costs, those expenses that are incurred from operating and maintaining the system (O & M costs). These include such things as wages of the ditch rider or ditch tender who handles water delivery to farmers, the superintendent who oversees operations and repairs on the system, and the secretary who takes water orders, collects fees, pays bills, and other workers on the system. Operation of equipment, labor, and materials used on the system must be paid. What the level of these charges are to the water users depends on how elaborate the delivery system is and the amount of services provided to the water user. If the farmers do much of the work to maintain and repair the system and only a few people are hired to work for the system, costs could be low. If the system is complex, with high maintenance costs and a large number of operating personnel, the costs would be higher.

Typical expenses of an irrigation system include:

- Fixed costs
    - Repayment of loan
    - Interest on loans
    - Taxes
    - Depreciation on equipment
- Variable costs (maintenance and operating expenses) O & M costs
    - Maintenance
        - Labor
        - Material
        - Repair of equipment
    - Operation of equipment
    - Permanent employees (salaries, wages, other costs)
        - Superintendent
        - Secretary
        - Ditch riders and tenders
        - Reservoir tenders
    - Office expenses
        - Telephone
        - Attorneys
        - Social Security tax
        - Office machines
    - Other
        - Car and truck maintenance
        - Two-way radios, etc.

This is a partial list of expenses of running a canal system and as in any business, they constitute the cost of operation. Table 1 shows an accounting of fees and expenses of a mutual ditch company in Colorado.

Table 1--Statement of income and expenses of the North Poudre Irrigation Company, northeast Colorado, for the years 1976, 1977, and 1978

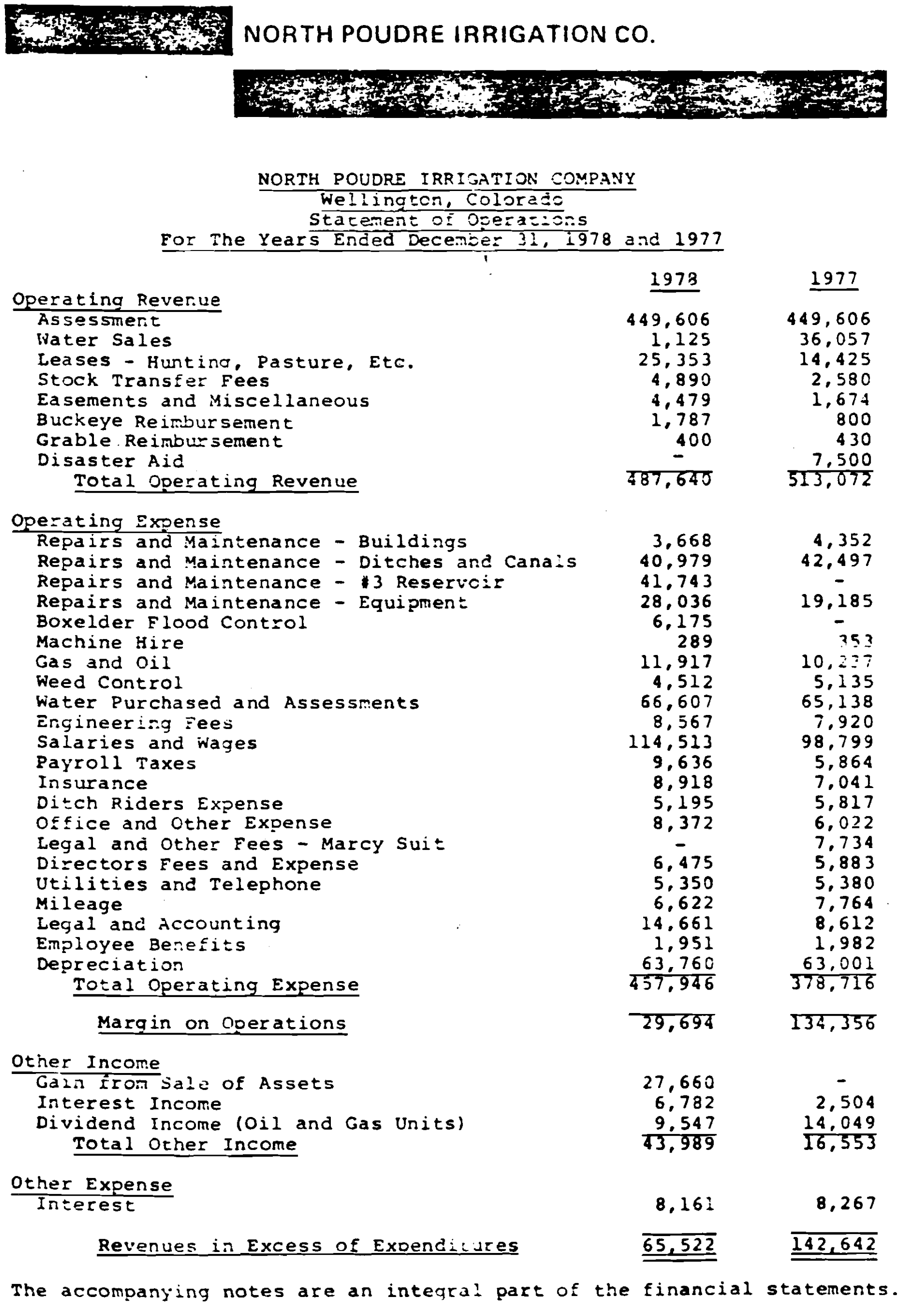


NORTH POUDRE IRRIGATION CO.

NORTH POUDRE IRRIGATION COMPANY
Wellington, Colorado
Operating Statement
For The Years Ended December 31, 1977 and 1976

	1977	1976
Operating Revenue		
Assessment	449,606	350,715
Water Sales	36,057	1,140
Leases, Hunting, Pasture, Etc.	14,425	15,718
Stock Transfer Fees	2,580	1,040
Easements and Miscellaneous	1,674	1,466
Buckeye Reimbursement	800	-
Grable Reimbursement	430	-
Disaster Aid - Flood Damage	7,500	16,029
Total Operating Revenue	513,072	386,108
Operating Expense		
Repairs and Maintenance - Buildings	4,352	2,477
Repairs and Maintenance - Ditches and Canals	42,497	26,941
Repairs and Maintenance - Equipment	19,185	17,422
Machine Hire	353	7,521
Gas and Oil	10,237	14,788
Weed Control	5,135	7,301
Water Purchased and Assessments	65,138	64,616
Engineering Fees	7,920	38,339
Salaries and Wages	98,799	95,835
Payroll Taxes	5,864	4,917
Insurance	7,041	5,433
Ditch Riders Expense	5,817	6,275
Office Expense and Other	6,022	4,223
Appraisal Fees Marcy Land	1,568	-
Legal Fees Marcy Suit	6,166	-
Directors Fees and Expense	5,883	5,868
Utilities and Telephone	5,380	4,158
Mileage	7,764	5,063
Legal, Accounting and Other Professional Fees	8,612	7,124
Employee Benefits	1,982	1,575
Disaster Expense	-	5,660
Depreciation	63,001	58,428
Total Operating Expense	378,716	383,964
Margin on Operations	134,356	2,144
Other Income		
Gain from Sale of Assets	-	27,087
Interest Income	2,504	341
Dividend Income	14,049	-
Total Other Income	16,553	27,428
Other Expense		
Interest	8,267	5,262
Revenue in Excess of Expenditures	142,642	24,310

See accompanying notes to financial statements.



NORTH POUDRE IRRIGATION CO.

NORTH POUDRE IRRIGATION COMPANY
Wellington, Colorado
Statement of Operations
For The Years Ended December 31, 1978 and 1977

	1978	1977
Operating Revenue		
Assessment	449,606	449,606
Water Sales	1,125	36,057
Leases - Hunting, Pasture, Etc.	25,353	14,425
Stock Transfer Fees	4,890	2,580
Easements and Miscellaneous	4,479	1,674
Buckeye Reimbursement	1,787	800
Grable Reimbursement	400	430
Disaster Aid	-	7,500
Total Operating Revenue	487,640	513,072
Operating Expense		
Repairs and Maintenance - Buildings	3,668	4,352
Repairs and Maintenance - Ditches and Canals	40,979	42,497
Repairs and Maintenance - #3 Reservoir	41,743	-
Repairs and Maintenance - Equipment	28,036	19,185
Boxelder Flood Control	6,175	-
Machine Hire	289	353
Gas and Oil	11,917	10,237
Weed Control	4,512	5,135
Water Purchased and Assessments	66,607	65,138
Engineering Fees	8,567	7,920
Salaries and Wages	114,513	98,799
Payroll Taxes	9,636	5,864
Insurance	8,918	7,041
Ditch Riders Expense	5,195	5,817
Office and Other Expense	8,372	6,022
Legal and Other Fees - Marcy Suit	-	7,734
Directors Fees and Expense	6,475	5,883
Utilities and Telephone	5,350	5,380
Mileage	6,622	7,764
Legal and Accounting	14,661	8,612
Employee Benefits	1,951	1,982
Depreciation	63,760	63,001
Total Operating Expense	457,946	378,716
Margin on Operations	29,694	134,356
Other Income		
Gain from Sale of Assets	27,660	-
Interest Income	6,782	2,504
Dividend Income (Oil and Gas Units)	9,547	14,049
Total Other Income	43,989	16,553
Other Expense		
Interest	8,161	8,267
Revenues in Excess of Expenditures	65,522	142,642

The accompanying notes are an integral part of the financial statements.

Mutual Irrigation Companies

An example of the way water fees are assessed on the North Poudre Irrigation Company in Colorado is shown in table 2. Under a mutual irrigation company, only those farmers owning shares in the company will receive water. Even though a canal could serve a farm, those who do not own shares will not be served. The amount that each share must pay of the major expenses borne by the company is listed, the time that payments must be made is indicated as well as the interest charged on delinquent accounts. Note that company policy states that fees due must be paid before water is delivered to any farmer. This company purchases part of its water supply from the Colorado-Big Thompson project, the rest it diverts from the river.

A brief survey of water charges by mutual irrigation companies for 1978 and 1979 is shown in table 3. The cost of water to farmers ranges from slightly over \$1 per acre-foot to a little over \$8/AF. Water delivered by the C-BT system, the USBR project that supplies supplemental water, costs about \$2/AF plus a delivery charge in the company of \$1 per AF = \$3/AF. Data from Arizona show water delivery charges for surface irrigation systems ranging around \$6/AF.

One critical problem is how to bill the water users. This could be on an acreage basis or a water delivery basis. Most of the successful mutual irrigation companies issue shares of stock to water users (irrigators) to establish each water user's interest in the irrigation system. Issuing shares has two very strong points to recommend it.

1. It determines the entitlement of the irrigator to the water supply. If a water user holds 5 percent of the stock in the system, he is entitled to 5 percent of the water supply.
2. Shares of stock also determine the proportion of cost to be paid by the water user. If the irrigator owns 5 percent of the stock, he

Table 2--Water assessments and other fees charged to stockholders of the North Poudre Irrigation Company, 1978 and 1979

Charge Dollars	Recommended Budget for 1978 Items per share
7.00	For water assessments
18.00	For operation and maintenance and weed control
2.00	For loan retirement
2.00	For new equipment
6.00	For right-of-way acquisition
10.00	For reservoir rehabilitation
45.00	

$30.00 per share due and payable April 1, 1978, interest @ 1.5 percent per month charged after May 1, 1978.
$15.00 per share due and payable October 1, 1978, interest @ 1.5 percent per month charged after November 1, 1978.

Total amount owing must be paid prior to water delivery.

Total assessments of $45.00 per share due April 1, 1978, on two shares or less.

* * *

	Recommended Budget for 1979 Items per share
7.00	For water assessments
9.25	For operation and maintenance and weed control
2.00	For loan retirement
2.75	For new equipment
4.00	For right-of-way acquisition
10.00	For reservoir rehabilitation
45.00	

$30.00 per share due and payable April 1, 1979, interest at 1.5 percent per month charged after May 1, 1979.
$15.00 per share due and payable October 1, 1979, interest at 1.5 percent per month charged after November 1, 1979.

Total amount owing must be paid prior to water delivery.

Total assessments of $45.00 per share due April 1, 1979, on two shares or less.

Table 3--Irrigation company water charges, cost of water to farmers, Cache La Poudre River, Colorado, 1978 and 1979

Company	Assessment per share		Yield per share	Fees charged per A.F.	
	1978	1979		1978	1979
	Dollars		Acre-feet	Dollars	
Arthur Ditch Company	6	5	4 +	1.50	1.25
Lake Canal	--	45	41.0	--	1.10
Larimer & Weld Irrigation Co.	--	10	42 (?)	--	.24
New Cache La Poudre Irrigating Co.	25	35	24.2	1.04	1.45
New Mercer	80	110	30.23	2.64	3.64
North Poudre Irrigation Co.	45	45	5.5	8.18	8.18
Pleasant Valley and Lake	110	80	55.0	2.00	1.45
Water Supply and Storage Co.	460	400	107.0	4.30	3.74

will have to pay 5 percent of the cost of operating the system.

Irrigation Districts

Irrigation districts do not issue shares of stock as do mutual irrigation companies. Instead, water service is based upon land being included within the boundaries of an irrigation district. The revenue to operate irrigation districts is typically derived from a tax on each irrigated acre and a charge or fee for each acre-foot of water delivered to a farm. Some districts operate exclusively on a tax while others use both a tax and water delivery fees. Some districts derive revenue from selling water to other organizations or from other sources such as oil or gas royalties, recreation rental of reservoirs and so on. If a landowner does not want water service, his land can be excluded from the district. He will then not have to pay an annual tax per acre, but he will not be entitled to irrigation water.

Within irrigation districts, the amount of water delivered frequently will not be equal to all acres. Where crop water needs are greatly different, such as small grain compared to orchards or vineyards, then total fees charged for deliveries would be higher for high-water-using crops than for low-water-using crops. Where soil types make a difference in water delivery requirements, then water fees also may vary.

An example of four irrigation districts in California will illustrate how these systems operate. These districts deliver between 2.09 A.F. per irrigated acre to 4.08 AF/acre. Some water is used to recharge the groundwater aquifer on two systems, raising delivery to 2.57 AF/acre and 2.93 AF/acre. One district delivers 33,000 acre-feet to outside users (table 4).

The cost of securing water through direct diversion from the river, purchase from state-owned reservoirs, or pumping groundwater ranges from 34¢/acre-foot

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Table 4--Acreage, water supply, and water delivery in four irrigation districts in California, 1975

Item	South San Joaquin ID	Merced ID	Tulare ID	Lower Tule River ID
Irrigated acreage	65,008	115,336	62,400	87,690
Water obtained - AF	319,600	688,100	232,000	268,000
Water delivered to farmers - AF	265,800	432,000	140,800	183,900
Water sold - AF	--	33,300	--	--
Water used to recharge - AF (assume one-half of loss is recharge)	--	--	42,200	42,100
Adjusted delivery - AF	265,800	432,000	183,000	226,000
Average delivery - AF/acre	4.08	3.74	2.25	2.09
with recharge - AF/acre	--	--	2.93	2.57

to $1.98/acre-foot. On a delivered basis, because of losses, the cost of water rises from 54¢/AF to $2.35/AF (table 5). There is considerable variation in the cost of operating and maintaining these districts, but in the aggregate, costs are reasonably close, ranging from $4.26 to $5.35 per acre-foot of water delivered. Notice that the cost of transmission and distribution of the water supply ranges from 47 cents to $1.29 per acre-foot and that the district with highest distribution costs has the next to lowest O. & M. cost on canals and equipment. The irrigation systems that obtain water at the least cost tend to spend more money on operations such as administration and distributing water, while those that have larger expenses in pumping or purchasing water cut down on administrative and distribution costs. A relatively large water supply allows the district with the highest average delivery per acre to have the lowest cost per acre-foot delivered. However, the district with the lowest delivery per acre has the second lowest cost per acre-foot--only 11 cents per acre-foot more. The district with the next to the lowest delivery per acre has costs of a dollar an acre-foot higher than the lowest cost district. Overhead costs remain even when water deliveries are quite low. The systems with the highest water delivery have the highest cost per acre while the lowest cost per acre is associated with the district that has the lowest water delivery per acre if water used for groundwater recharge is included.

Sources of revenue for the irrigation districts come from taxes, water delivery fees and sales, and other sources (table 6). The districts with the highest water deliveries rely heavily on property taxes. One district charges no delivery fees and the other only 31 cents per acre-foot delivered. The two districts with lower water deliveries levy less property taxes per acre and rely more on water delivery fees. The reason for this is probably because

Table 5--Cost of obtaining and delivering water and operation and maintenance in four irrigation districts, California, 1975

A. Total costs of operation and maintenance

Cost	So. San Joaquin ID	Merced ID	Tulare ID	Lower Tule River ID
	Dollars	Dollars	Dollars	Dollars
Administrative, supervision and engineering costs	360,000	295,000	106,000	149,000
Pumping or purchase of water cost	171,000	235,000	423,000	531,000
Transmission and distribution cost (ditch riders)	344,000	301,000	106,000	107,000
Repair and maintenance of canals and equipment cost	258,000	711,000	217,000	176,000
Other costs	--	504,000	127,000	48,000
TOTAL	1,133,000	2,046,000	979,000	1,011,000
B. Costs per acre-foot and per acre of water delivery			Per Acre-foot	
Cost of securing total supply	.53	.34	1.82	1.98
Cost of water delivered	.64	.54	2.31	2.35
Administrative, supervisory and engineering cost	1.35	.68	.58	.66
Transmission and distribution cost (ditch tenders, etc.)	1.29	.70	.58	.47
O & M of canals and equipment	.97	1.64	1.18	.78
Other costs	--	1.17	.69	.21
TOTAL COST PER ACRE-FOOT DELIVERED	4.26	4.73	6.97	5.51*
*Including recharge			5.35*	4.47*
			Per Acre	
Total cost per acre served	17.43	17.74	15.69	11.53
Average water delivered per acre, acre-feet	4.08	3.74	2.25	2.09
with recharge	--	--	2.93	2.59

Table 6--Sources of revenue for four irrigation districts, California, 1975

Item	South San Joaquin ID	Merced ID	Tulare ID	Lower Tule River ID
	Dollars	Dollars	Dollars	Dollars
Taxes	780,000	2,022,000	474,000	419,000
Water fees (*includes 33,000 AF sales outside)	0	147,000*	536,000 1/	736,000 1/
Other	267,000	44,000	80,000	75,000
TOTAL	1,047,000	2,213,000	1,090,000	1,230,000
Taxes per acre	12.00	17.53	7.60	4.78
Water fees per AF delivered	0	.31	3.80	4.00
Total revenue per AF delivered	3.94	5.12	5.95	5.44

1/Includes recharge.

water deliveries are much more uneven in the districts with less water. Some of the farmers rely heavily on privately owned wells for a portion of their irrigation water. Thus, those receiving larger deliveries through the district are charged according to amount of water delivered to their farms.

Taxes on irrigated lands are $12.00 to $17.53 per acre on the high-delivery companies, while the property tax is only $4.78 and $7.60 per acre on the districts with lower average delivery. Much of the revenue is generated through water delivery fees under these districts.

These few examples illustrate that there is considerable variation in the way irrigation organizations raise revenue to pay for the operation and maintenance of their systems.

The mutual companies simply divide the costs by the shares of stock and assess each share its proportional share. In return for the payment of assessments, each share receives its proportionate share of water.

Under the irrigation districts, some raise revenue by levying a tax on each irrigated acre and delivering water according to tax paid. Others levy a much lower tax per acre to pay part of the cost of operating the system and then charge a water delivery fee in order to offset the costs associated with higher water deliveries to some lands.

Water Control

The most important feature in making an irrigation system work is water control. The irrigation system must be designed so that the operators can deliver water to farms in specified amounts. It is even more desirable that the delivery time be controlled, making it possible to deliver water to each irrigator when he needs it to irrigate crops.

It is also necessary that the system be able to control deliveries so that water supply is not excessive at some farms and deficient at others. The ability to control time and amount of deliveries leads to more efficient use of water in crop production and higher yields. Also, the ability to control water means that water can be withheld, thus insuring that farmers will pay for the water delivered. Most U.S. systems require payment or part payment for water before the season starts. Irrigation officials have discovered it is very difficult to collect once the water is used.

Water control is best achieved by designing the system so that a ditch tender or rider can supervise water delivery (i.e., open and close the headgate) to each individual water user. In many systems only the ditch rider is allowed to open and close headgates which are then locked. Farmers can order the water needed each week or each time water is run in the canal. One of the practical reasons for requiring water orders and allowing only the ditch tender to open and close headgates is to maintain orderly control over distribution of water in the canal. The canal operators need to know how many irrigators wish to be served along each section of canal so they can adjust the flow in the canal or adjust number of users to match the flow. They also can determine when each of the headgates should be opened and closed in order to deliver the required amount of water.

Headgate control is also necessary to achieve or enforce equity. No water user should get more than his entitlement (share) nor should any user get less than his entitlement. If abundant water occurs, all should share; similarly, in times of shortage, all should bear the shortage according to the rules of the system.

In some irrigation organizations, the water user is notified of the amount of water he is entitled to receive before the season starts. This is set up as an account similar to a bank account, subject to delivery of so much water per irrigation period or the water can be drawn as needed when the supply is stored in a reservoir. On pro-rata systems/if the farmer does not want water during any particular run of the canal, he must inform the ditch tender not to deliver water. On storage systems, the farmer must place an order when he wants water delivered at his headgate; usually he will specify amount of flow along with the length of time he wants water, normally one or more days.

All water deliveries are charged to the water user's account so that the amount delivered to a water user will not exceed the water allocated to the user. A system such as this can prevent over-watering, if this is a problem, but it can also encourage trading of water among farmers on a system, if some farmers have more than needed at times and others can use more water. Farmers can pay each other for water traded or can replace the water at another time. Trading is advantageous because it can lend flexibility in water deliveries and it can also encourage water deliveries to farmers who raise higher value crops. If a farmer uses excess water on a crop, he will forgo the return he could receive from selling some of his water to another farmer.

Renting or selling water as described above is quite common in some areas of the western United States. Farmers own shares in the irrigation canal company, they pay the cost of operating the system, the water supply received by each farmer depends upon the number of shares owned. All water deliveries are subtracted from their water accounts, and the farmers trade (buy and sell) water when it is advantageous to do so. One Spanish irrigation canal company holds an auction where the company sells water before each run and farmers buy and sell water they own among themselves each time water is delivered in the canal.

With a controlled water supply such as the High Dam at Aswan creates for the Nile, it should be possible to control water diversions to various irrigation districts. The districts should be able to set up a program of water allocation to farmers based on farm size and crops. Each farmer could be allotted a specific quantity of water for a crop season, deliveries to be made as crops need water. Where two or three crops a year are grown, a water allocation for each season would be most appropriate. Then week by week or rotation by rotation, water could be delivered and charged to each farmer's account. In this manner, water application rates could be controlled. If the farmers are to be charged for water delivery, then no water should be delivered until payment is made.

The biggest problem that I see in bringing more efficient irrigation to Egyptian agriculture is delivery below field level, particularly when several farmers pump or raise water from the same segment of canal. This system is enormously inefficient in terms of energy and manpower. In an energy-short world, where manpower and animal power tend to be scarce or costly, raising water is an outright waste of scarce resources.

It also makes it very difficult for the operators of the system to control water deliveries to individual farmers. For when all are lifting water from below the field, the farmer with the most resources, energy, manpower, mechanical or animal power, can get a larger share of the water.

Envision how much better it would be if the canal were above the fields and a ditch tender came by on the appointed morning and opened, set and locked a headgate for a certain flow for a set period. The farmer would know how much water he was to get and the operators of the irrigation system would also know. Each farmer would get his share and the diversion into the main canals could be set to supply a specific quantity of water to the farms to be served that day on each canal sector. On large systems a standard rotation could be used: 3 days on, 6 days off, similar to the current practice. Control of water deliveries would be possible, and farmers would be relieved of the burden of lifting water to their fields. The amount of water put on the land could be controlled by deliveries, and excessive irrigation could be controlled. Those who insisted on more water would be charged for extra deliveries. Those farmers who did not use their entitlement could sell it to other farmers and collect for the water delivered to another user.

Staff Paper #42

AGROMETEOROLOGICAL STATIONS FOR CROP WATER REQUIREMENTS

Richard Cuenca

January, 1980

INTRODUCTION

The following paper was developed by the author in cooperation with other project personnel while on assignment with the USAID Egypt Water Use Project (EWUP) during December-January 1979-80. The main objective of this paper is to specify recommendations for the location and instrumentation of agrometeorological stations. The objective is further defined by the fact that the data collected will be used to estimate crop water requirements using the most applicable methods for computing reference evapotranspiration. Consideration was made in the development of this paper of local conditions found at the EWUP field sites. This includes the consideration that automatic recording instruments may not always have dependable power sources nor will personnel trained in the maintenance and operation of such instruments always be available. It is believed that the establishment of reliable and accurate instrumentation at agrometeorological stations at the three field sites will allow for the collection of a meaningful data base upon which to evaluate the efficiency of irrigation systems in meeting crop water requirements and to use as the basis for future planning.

SITE SELECTION

The selection of an agrometeorological station site will require a balance between features to be found at the "optimum" site and the land which is available to the project for the construction of a station. As much as possible, the site should represent the topography and climate of the irrigation project area. Ideally the site should be located directly in and surrounded by an irrigated field planted to berseem (alfalfa), grass or other low level crop, which is kept in a well watered condition throughout the year. If the wind has a predominant direction, the irrigated field should have the longest dimension in the upwind direction. The site should not be located near an abrupt change in type of vegetation nor near a change from vegetated to arid soil surfaces. Vegetation surrounding the site should be low, less than 0.5 m if possible, and there should be no interference at the site in terms of shading or wind blockage from buildings or trees. The horizontal distance between the site and any building or trees affecting wind patterns should be five to preferrably ten times the height of the structure or tree. The agrometeorological site should not be located near large bodies of water, including lakes, ponds or swampy areas. It is not believed that locating the site near small canals or mescas (field ditches) is a problem.

The main criteria for site selection are that the site should represent the project topography and climate as much as possible. It should be located well within and surrounded by an irrigated area and well away from areas affected by buildings or trees. It should not be located near large bodies of water. A final point is that the agrometeorological station should be placed in an area which is not subject to future development which will necessitate moving the site. Any future change in station location will disrupt the continuity of data being collected and bring into question the consistency of recorded values at a new location. If a station does have to be moved, it is recommended that the new station be established while the original one is still in operation and that records be kept at both stations for a period of one year if possible. If there is a consistent difference in a measured parameter during this period of overlapping operation, it is suggested that the original data be adjusted to conform to the data at the new site.

The station should be fenced to keep out animals and intruders. A fence which does not restrict air movement should be used and a wire mesh fence with 5 cm (2 in) diagonal openings is recommended. The fence should have a gate which can be kept locked when the instruments are not being read. An example of such a station is indicated in Figure 1.

INSTRUMENTATION

The most useful instruments for the EWUP project are those which do not require a power source for operation. The basic limitations of such instruments is that they generally record data associated with a particular point in time, either a maximum or minimum reading or reading at the time of observation. The next level of instrumentation is that which gives a continuous record of the parameter being measured and is operated by 1.5 volt D cell ("flashlight") batteries. A number of useful instruments can be operated from such a source of power. Finally, recording units which operate with a 12 volt DC power source (car batteries) can be used to continuously collect important data.

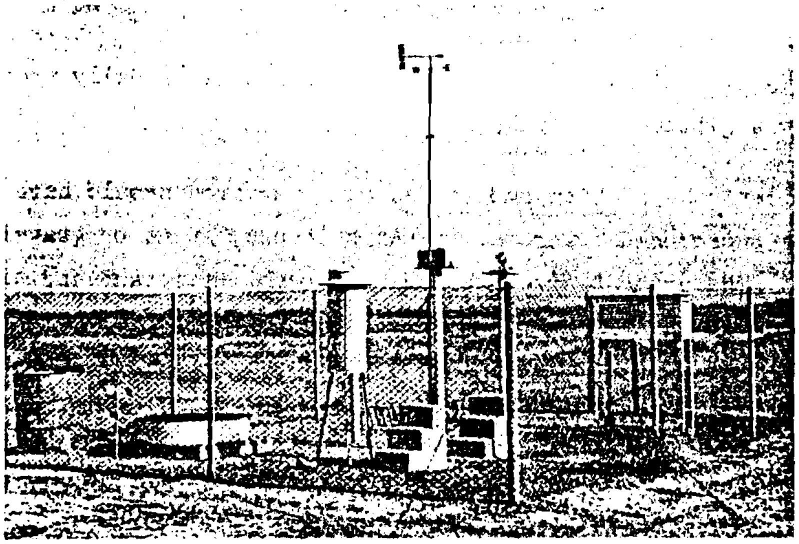

Figure 1. An example of an agrometeorological field station.

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The data collected at the agrometeorological station will be used to compute theoretical crop water requirements. The type of data to be collected, frequency of measurement and required accuracy should therefore be made with reference to the methods applied to compute reference evapotranspiration. As will be indicated in a future paper, the methods to be applied include the Blaney-Criddle, Makkink radiation, pan evaporation, and Penman methods, all with recommended modifications to account for local climatic conditions (Doorenbos and Pruit, 1977). Therefore the data requirements for each of these methods will be analyzed. (The relative merits of each method will not be discussed here but are left for a future paper.)

Blaney-Criddle Method

The FAO modification of the Blaney-Criddle method requires measured mean daily air temperature and estimated values of minimum relative humidity, sunshine hours and daytime wind velocities. Mean daily temperature requires measurement of daily maximum (max) and minimum (min) air temperature. Such measurements are made by a max/min thermometer set with a mercury-in-glass maximum and spirit-in-glass minimum thermometer (see Figure 2) which is read once daily as soon after sunrise or close to 0800 hours as possible. More advanced instruments which require a power source are continuous recording mercury-in-steel or bimetallic thermographs which can be used with daily or weekly recording charts (see Figures 3 and 4). The second required parameter for the FAO modification of the Blaney-Criddle is minimum relative humidity (RH_{min}). This value need only be estimated in ranges of low, medium or high for application with the Blaney-Criddle method. Low indicates a RH_{min} of less than 20 percent, medium from 20 to 50 percent, and high greater than 50 percent. The next parameter is the ratio of daily actual (n) to daily maximum possible (N) sunshine duration in hours. This estimate is also divided into three categories with low having n/N less than 0.6, medium for n/N from 0.6 to 0.8, and high for n/N greater than 0.8. The last parameter is daytime wind which is divided into the categories of zero to 2 m/sec (6.5 ft/sec), 2 to 5 m/sec (6.5 to 16 ft/sec), and 5 to 8 m/sec (16 to 26 ft/sec). General monthly or seasonal conditions for all three of the variables used to adjust the FAO Blaney-Criddle method may be estimated from published weather data, extrapolation from nearby areas, or from local information. Measured values for these parameters are superior to estimates and such measurements will be routinely made for some of the more sophisticated

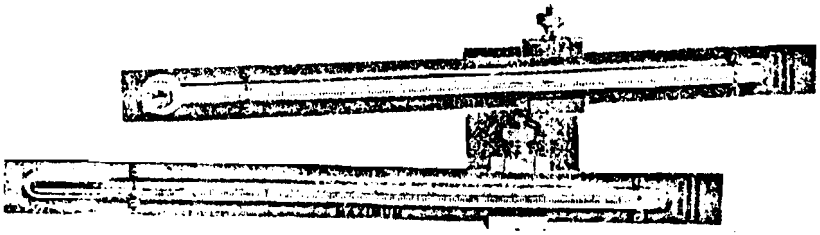

Figure 2. Maximum and minimum thermometer set.

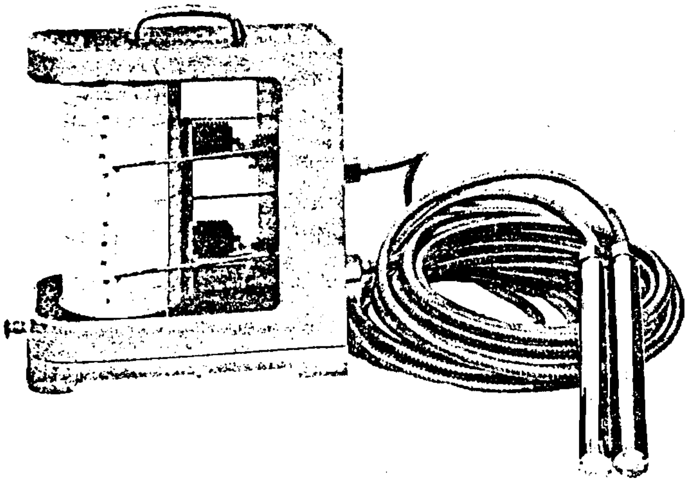

Figure 3. Mercury-in-steel recording thermograph.

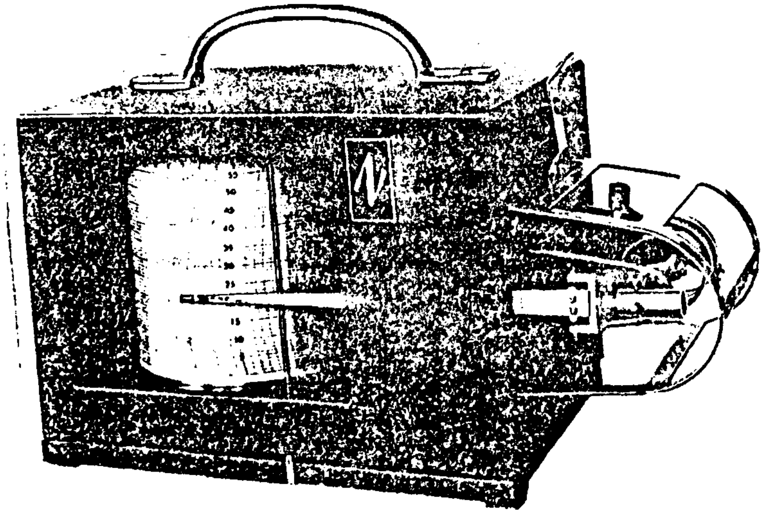

Figure 4. Bi-metallic recording thermograph.

methods of determining reference evapotranspiration.

Makkink Radiation Method

Requirements for the Makkink radiation method include measured air temperature and sunshine, cloudiness or radiation, and estimated wind and humidity. Duration of bright sunshine can be made by observation or may be conveniently measured by use of a sunshine recorder. A typical sunshine recorder is that of the Campbell-Stokes design shown in Figure 5, which uses a solid glass globe to focus the rays of the sun onto a specially treated card which burns in response to bright sunshine. From the mark made on the cards, the hours of bright sunshine during the day can be determined.

The degree of cloud cover observed several times during the day is another method to determine sunshine brightness which can be applied to formulae to calculate solar radiation. The recommended method is to indicate the degree of cloud cover for areas made up of one eighth of the total sky area, called oktas. The procedure is to divide the sky into four quadrants. An estimate of the cloud cover for each quadrant, given in eighths, is made. As an example, if the right front quadrant has one quarter cloud cover, right rear quadrant, three quarter cover, left rear quadrant slightly less than half, and left front quadrant no cloud cover, the cover in oktas is:

$$\frac{1}{4} \cdot \left[\frac{2}{8} + \frac{6}{8} + \frac{3}{8} + \frac{0}{8}\right] = \frac{2.8}{8}$$

or approximately 3 oktas. Traces of clouds are registered as 1/8 or 1 okta. An overcast with some openings is recorded as 7/8 or 7 oktas. Fog which obscures the sky to the point that clouds are not visible is considered as 8 oktas. If the sun, but no clouds, are visible through fog, it is ranked as zero oktas. Observations should be made three or preferably four times per day and the time of observation noted.

Solar radiation can be estimated using measured values of bright sunshine duration or cloudiness. A more accurate determination of solar radiation can be made by special instruments. Such instruments are normally sensitive, require some sort of power source to operate a recorder and require calibration at the time of installation and at least once per year after that. One such instrument available to the Project is a thermo-electric

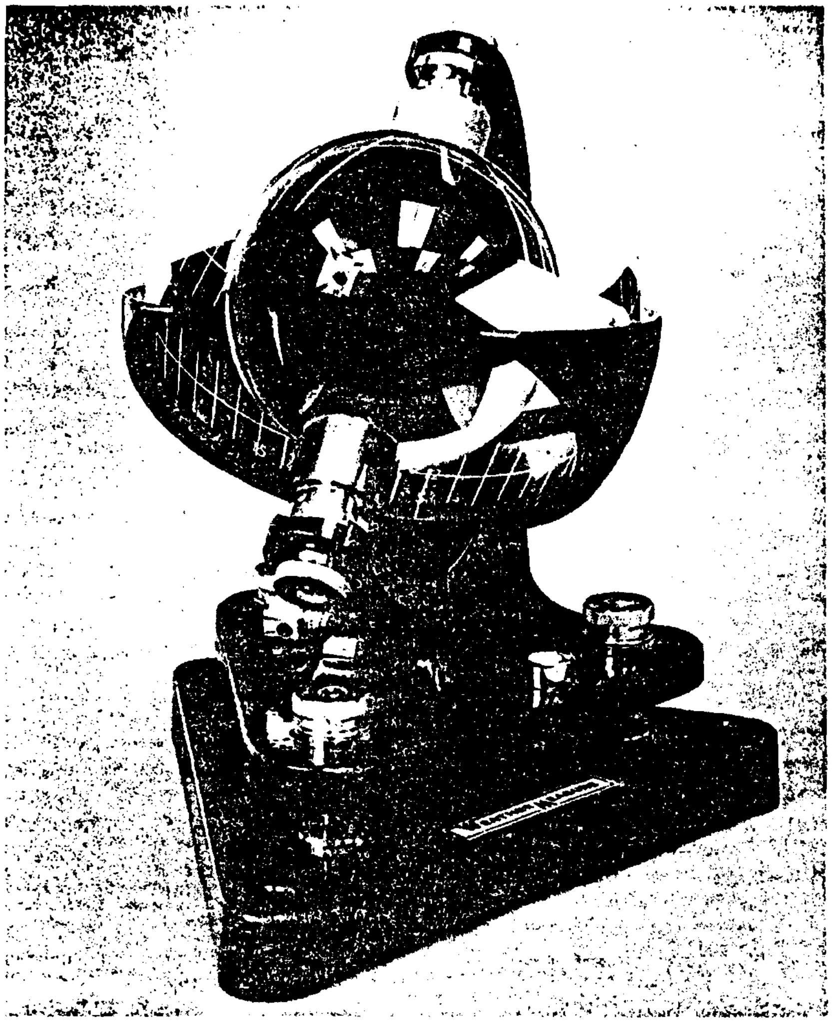

Figure 5. Campbell-Stokes recorder for actual sunshine hours.

pyranometer for measuring solar radiation, shown in Figure 6. Such an instrument converts thermal energy from solar radiation to electric current which is calibrated to indicate the amount of radiation being received. If a recording chart is made during the day, the total amount of daily radiation is obtained by integrating the area under the radiation trace using a planimeter or digitizing unit. If only point measurements are made it is necessary to integrate graphically under lines drawn through the measured points and the additional points of zero radiation at the times of sunrise and sunset. An example is given in Figure 7.

For the FAO modification of the Makkink method, estimates are also needed for mean relative humidity (RH_{mean}) and daytime wind. The mean relative humidity ranges from low, less than 40 percent, to medium-low, 40 to 55 percent, to medium-high, 55-70 percent, and high, greater than 70 percent. Estimates of daytime wind velocity are the same as for the modified Blaney-Criddle except that the category of very strong, greater than 8 m/sec, is included.

Pan Evaporation

To determine reference evapotranspiration using the FAO recommendations with pan evaporation requires estimates of mean relative humidity, 24 hour wind run, and information about the pan environment in addition to measured pan evaporation. The recommended pan is the class A pan which is circular and 120.7 cm (4 ft) in diameter and 25 cm (10 inch) in depth. It is usually made of galvanized iron (22 gauge or 0.8 mm) and mounted on a wooden open frame platform 15 cm (6 inch) above ground level with soil built up to within 5 cm (2 inch) of the pan bottom (see Figure 8). The water level in the pan must be maintained between 5 cm (2 in) and 7.5 cm (3 in) below the pan rim. Readings are made once daily, as near to 0900 hours as possible. Using a stilling well with a fixed point or hook gauge, readings may be made to 0.005 cm using the gauge micrometer (see Figure 9).

The pan site is preferably in grass of about 5 cm (2 in) height and a total area of 20 m by 20 m (60 ft). The pan area should be open and permit free circulation of air. In other respects, the location of the pan should conform to other recommendations for the station site. Screens over the pan should not ordinarily be used unless there is a problem caused by birds or animals drinking from the pan. If such a problem exists, the screen

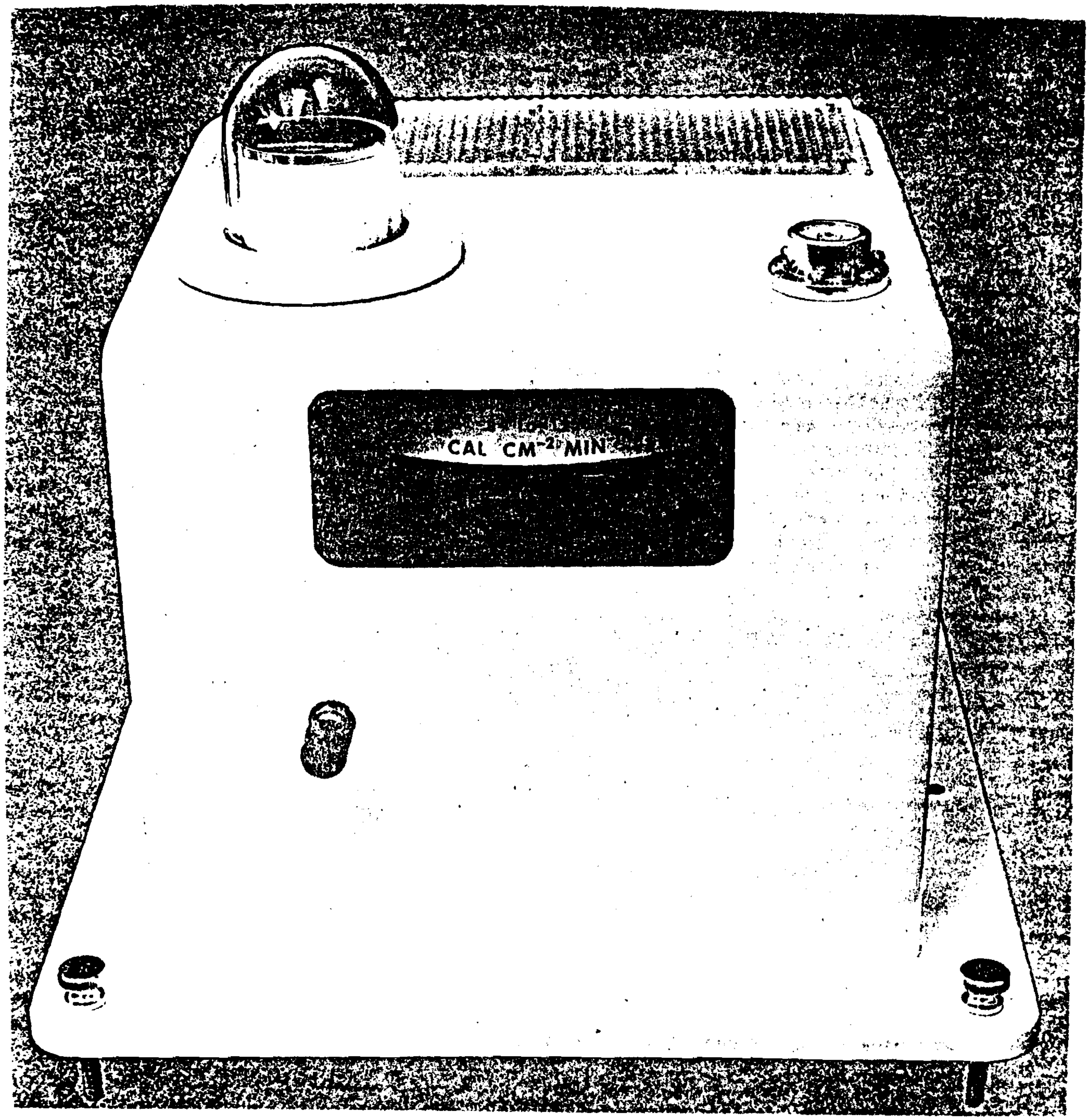

Figure 6. Thermo-electric pyronometer for solar and scattered radiation (global radiation).

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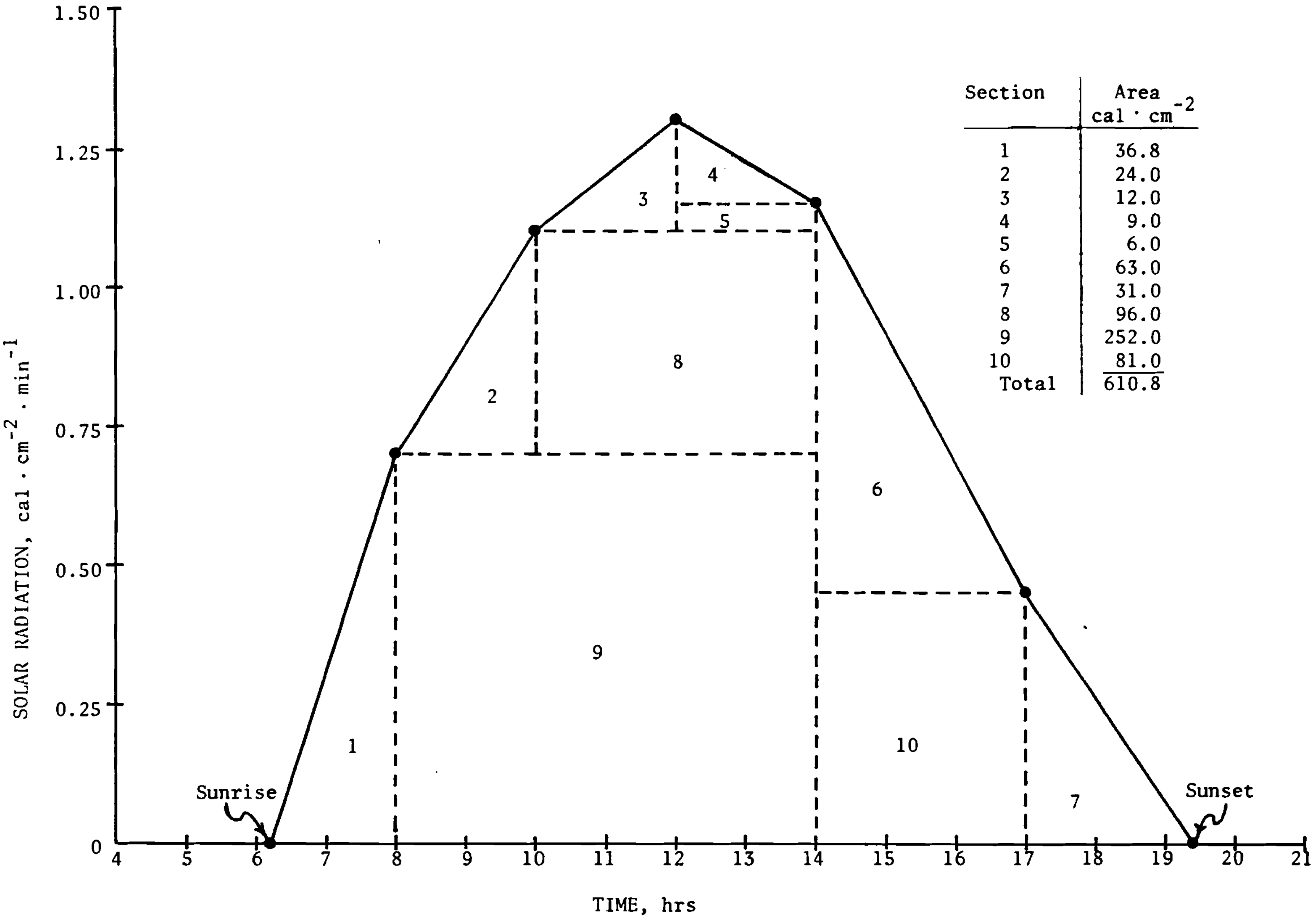

Section	Area cal · cm^{-2}
1	36.8
2	24.0
3	12.0
4	9.0
5	6.0
6	63.0
7	31.0
8	96.0
9	252.0
10	81.0
Total	610.8

Figure 7. Example of graphical integration for daily total solar radiation from point measurements.

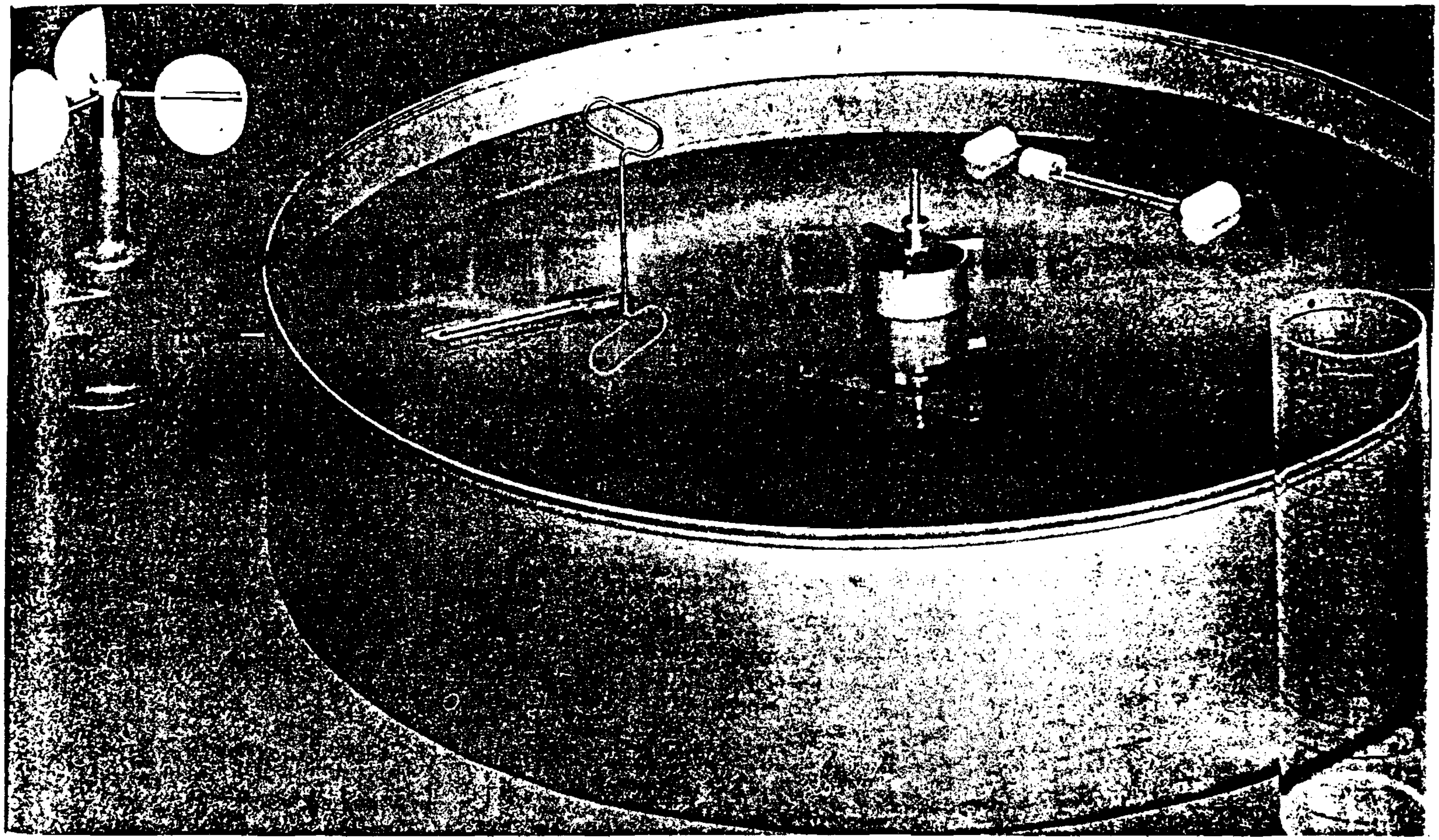

Figure 8. Class A evaporation pan shown with instruments for water temperature and wind speed at pan height.

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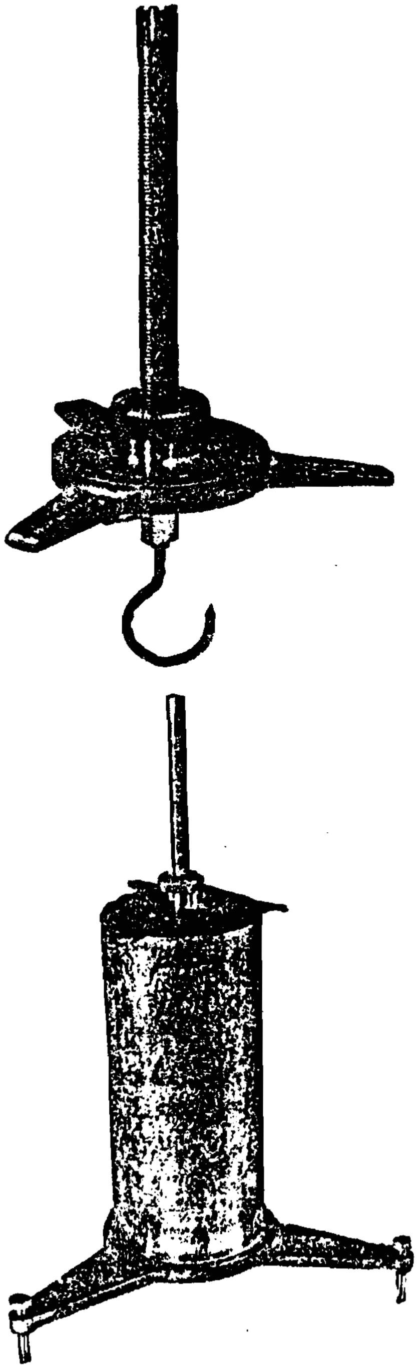

Figure 9. Hook gauge with micrometer and lowered into stilling well.

should be made of the finest size wire and of a design as open as possible so as to cause minimum interference with natural air flows or solar radiation. It is recommended that comparative observations between an unscreened and a screened pan be made for as long a time period as possible, up to one year, to determine the effects of screening.

Penman Method

The FAO modification of the Penman method requires the most intensive data collection of the four methods suggested, and should therefore produce the most accurate monitoring of the microclimate. This method requires daily input of temperature, humidity, wind, and sunshine duration or net radiation. The following section describes instrumentation for humidity, wind, and net radiation measurements.

A number of methods of expressing humidity are used. The most applicable for use with the Penman equation is the relative humidity defined as the actual amount of water vapor of the air relative to the water vapor content when the air is saturated at the same temperature. One means of measuring this relative humidity is by aspirated (i.e. forced circulation) dry and wet bulb thermometers. Such thermometers are combined into what is called the Assmann type aspirated psychometer shown in Figure 10. This consists of two mercury-in-glass thermometers, one of which has the bulb covered by a wet wick. A windup spring-driven fan ventilates air around the thermometer bulbs at a speed of about 5 m/sec (16 ft/sec). The difference in reading between the dry and wet bulb thermometers is termed the wet-bulb depression. Tables for converting wet-bulb depression to values of relative humidity are generally available from the instrument manufacturer. Readings and calibration of both thermometers must be to the nearest 0.1° (0.2°F). Readings are made by wetting the wick with distilled water or rainwater and winding up the fan. After the wet bulb temperature becomes constant, usually in about two or three minutes, both thermometers are read, recorded and checked. The wick has to be replaced every two weeks, or sooner if dust or dirt is visible.

A similar device in principle is the sling psychrometer which uses dry and wet bulb thermometers placed in a frame with a handle around which the thermometers may rotate (shown in Figure 11). The wick is wet and the thermometer holder is whirled about the handle for 60 revolutions at the rate of about two revolutions per second. The same procedure for reading, calibration, and

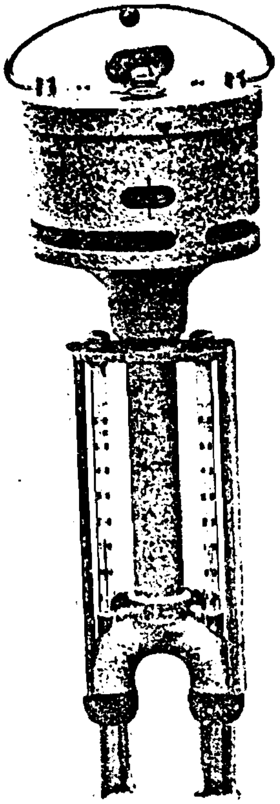

Figure 10. Assmann type aspirated psychrometer.

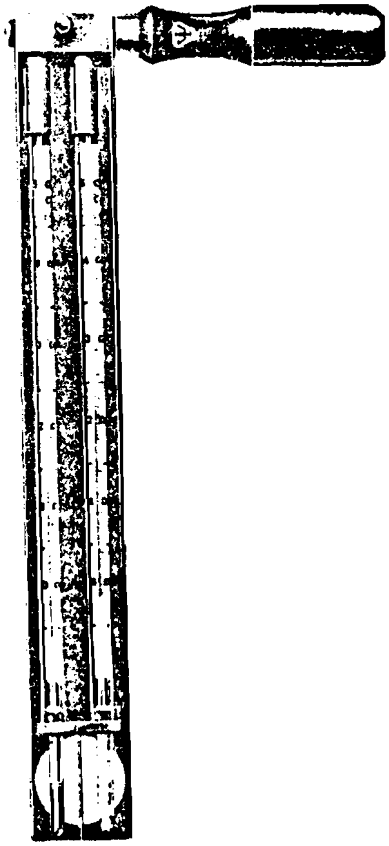

Figure 11. Sling psychrometer with wet and dry bulb thermometers.

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maintenance is followed as for the fan aspirated psychrometer. The speed of whirling increases the wet bulb depression so care must be taken to consistently use the prescribed method.

Automated, continuous recording of humidity is normally accomplished by use of an instrument which combines a hair hygrograph for relative humidity and a thermograph for temperature measurements. Such an instrument is shown in Figure 12. Human hair, which changes length in response to the moisture content of the air, is connected to the pen arm by a system of levers. The hair bundles should receive daily attention and be washed using distilled or rain water and an artist's soft paint brush at least once each week or sooner if dusty. The accuracy of this instrument for humidity is ±5 percent or better. Accurate control of the recording chart can be made by using wet and dry bulb thermometers. There is a loss of sensitivity in the instrument at both very high and very low humidity ranges. The recording charts may operate for a period of up to three months.

Wind is generally measured by freely rotating cup anemometers supported on a vertical axis as shown in Figure 13. Readings of wind velocity may be made on an instantaneous basis using a meter or by measuring the total distance of air which passes the anemometer on a 12 or 24 hour basis using a counter calibrated to give the distance of anemometer travel. The second type of record is more common and more useful. Continuous measurement of wind movement may also be made on charts by recorders which require a power source. The total wind run for a 12 or 24 hour period is determined by integrating the area below the recorded wind velocity. If instantaneous velocity measurements are made, they must be plotted and integrated in a similar fashion as previously described for measurements of solar radiation.

Wind velocity may be estimated by use of the approximate Beaufort Scale applicable when the surroundings are flat, open terrain. The scale is as follows:

Velocity m/sec	Condition
0-0.2	Smoke rises vertically
0.3-1.5	Some smoke drifts, no movement on wind vane
1.6-3.3	Wind felt on face, leaves rustle, wind vane moves
3.4-5.4	Leaves and small twigs move, wind extends light flag

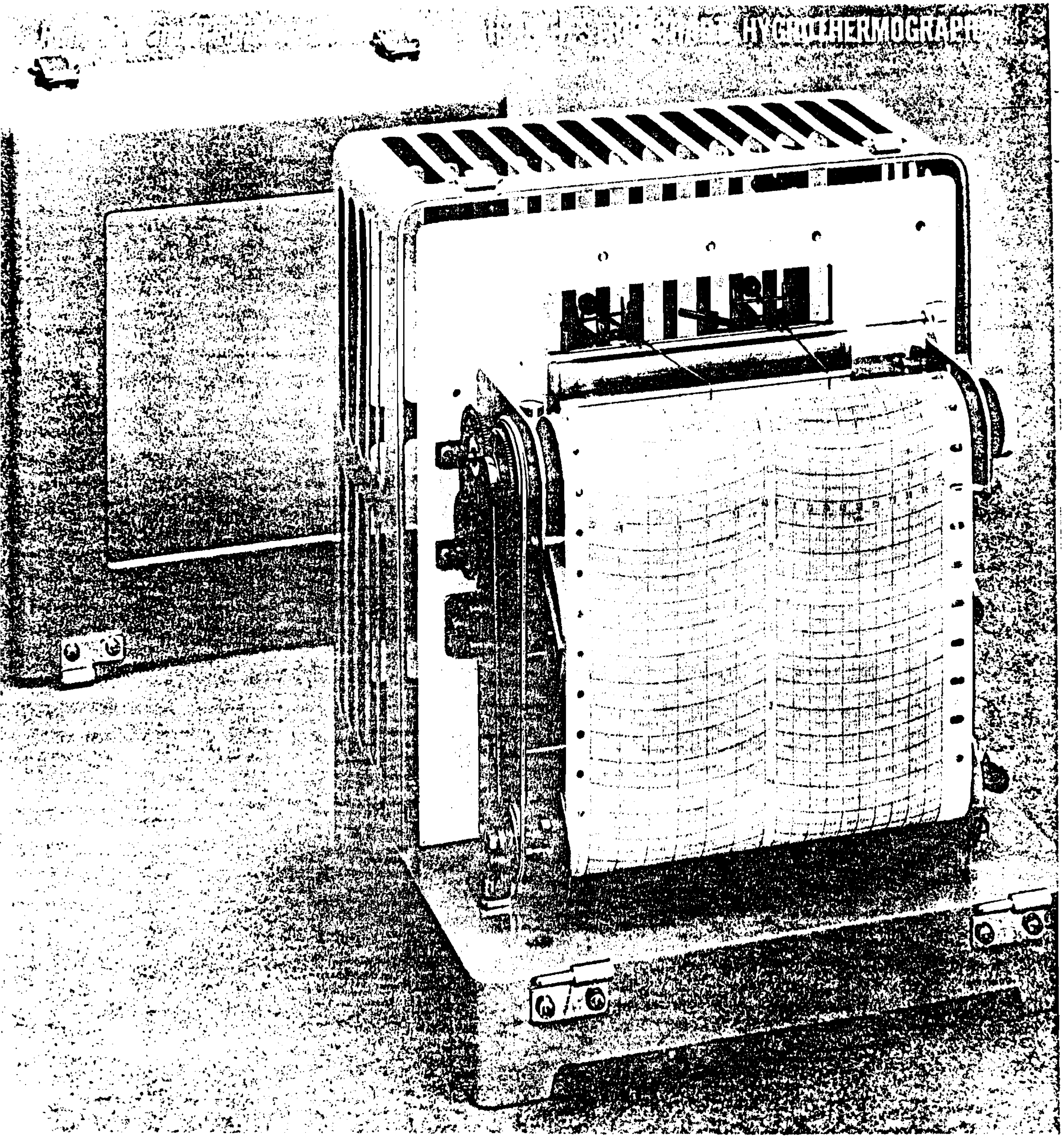

Figure 12. Recording hygrothermograph for temperature and relative humidity.

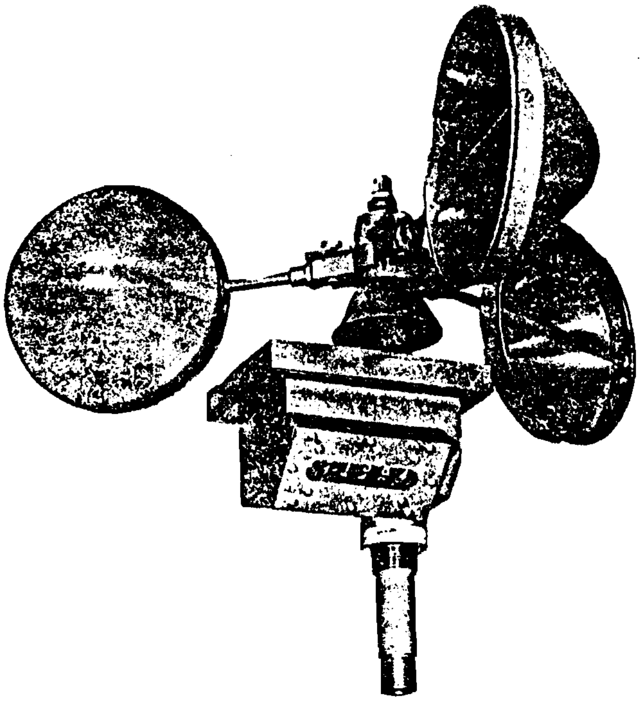

Figure 13. Cup anemometer for wind velocity or wind run over a given time period.

Velocity m/sec	Condition
5.5-7.9	Dust raised, small branches move, paper blows away
8.0-10.7	Small trees sway, crested waves on inland water
10.8-13.8	Large branches move, whistling in power lines, umbrella difficult to use
13.9-17.1	Whole trees in motion, difficulty when walking
17.2-20.7	Twigs break off
20.8-24.4	Chimneys and slates fall
24.5-28.4	Trees uproot, considerable damage
>28.5	Widespread damage

Wind is generally measured at 2 m (6.6 ft) height and this is the recommended height if only one measurement is made. Wind is also sometimes measured at a distance of 5 to 10 cm (13 to 25 in) above the rim of a class A evaporation pan and at a height of 5 m (16 ft). The latter height is probably more useful for long term climatological data analysis.

Wind direction is designated as the direction from which the wind is blowing. It may be conveniently measured on an instantaneous basis by using a wind vane on which the main directions of north, south, east, and west are permanently fixed (see Figure 14). Wind direction is generally given in terms of the sixteen point compass indicated in Figure 15. Recorders for both wind velocity and direction which require a power source are available.

The Penman equation also requires measurements of net radiation. Net radiation is defined as the difference between all incoming radiation, generally shortwave solar, and all outgoing radiation, generally longwave terrestrial. Net radiation can be measured directly over a cropped surface by using two radiation sensors, one directed upward to measure incoming solar radiation and another downward over the crop to measure outgoing terrestrial radiation. Instruments to measure net radiation are generally expensive and require a power source for recording and ventilation of the measuring equipment. Some sets of relatively small thermo-electric pyranometers can be used in both an upward facing and downward facing position over a cropped surface to measure net radiation.

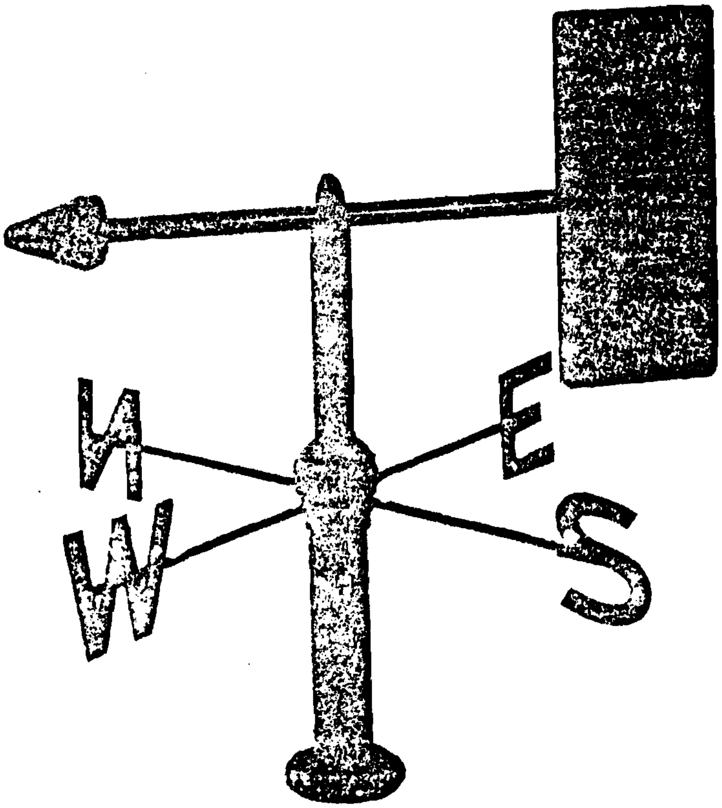

Figure 14. Wind vane for direction of wind.

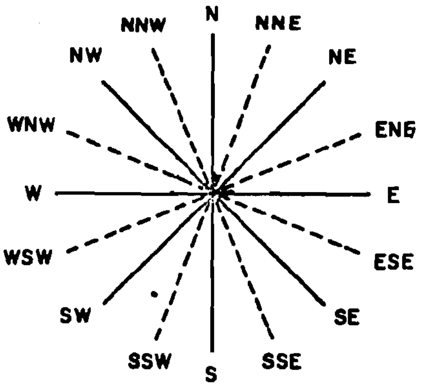

Figure 15. Sixteen point compass to describe direction of wind.

Net radiation can also be approximated using measured solar radiation or estimated solar radiation and reflectance (albedo) and measured cloud cover. The terrestrial longwave radiation must be estimated as a function of measured temperature, vapor pressure, and cloud cover. No instruments other than those already mentioned are required.

Additional Information

An additional climatological parameter which must be considered is precipitation. Considering the EWUP project locations, only rainfall will be considered. Rainfall is measured by totaling or recording instruments. Recording instruments can be used to determine rainfall intensity which is useful in soil erosion studies, and have been adapted for use with spring driven clocks or low voltage battery operated recorders. A number of nonrecording raingauges have been developed and all have similar physical characteristics. They are cylindrical in shape and have a funnel shaped collector which leads into a smaller diameter measurement cylinder (see Figure 16). Such gauges generally have a receiving area of 200 to 500 cm^2 (31 to 77.5 in^2) and have a height of exposure of about 30 cm (76 in). Exposure heights above about 30 cm (76 in) are not recommended due to wind effects on gauge catch. Raingauge siting recommendations are the same as those for general station siting. Measurements of total rainfall catch should be made at the same time each day, preferrably 0800 hours in the morning, using specially calibrated measuring devices supplied with the instrument. Calibrated graduated cylinders are recommended over graduated dip-sticks, but in any case equipment conforming to that already in use within the country should be utilized since catch will vary with instrument type. Rainfall should be observed in units of 0.1 mm (0.01 in). Amounts less than 0.05 mm (0.005 in) should be recorded as "trace".

Recording raingauges come in various designs (see Figure 17). Their chief advantage is that they may be used to determine rainfall intensity which is a necessary factor in determinations of runoff and potential for soil erosion. Total rainfall can be determined directly from the rainfall trace on the chart but this total should always be checked against the readings of a nearby standard raingauge. The slope of the trace of recorded rainfall, indicating the change in depth of rainfall over an increment of time, represents the rainfall intensity. The intensity should be computed over periods with constant slope, i.e. constant intensity. The period of maximum slope represents the maximum intensity.

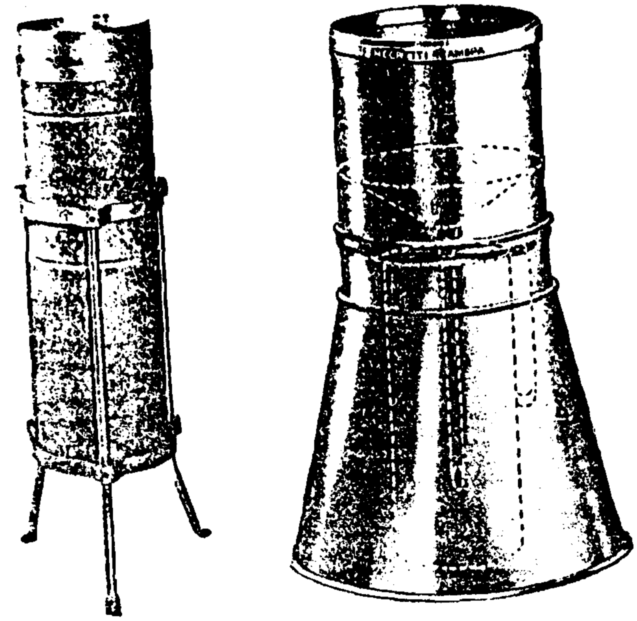

Figure 16. Standard nonrecording raingauges.

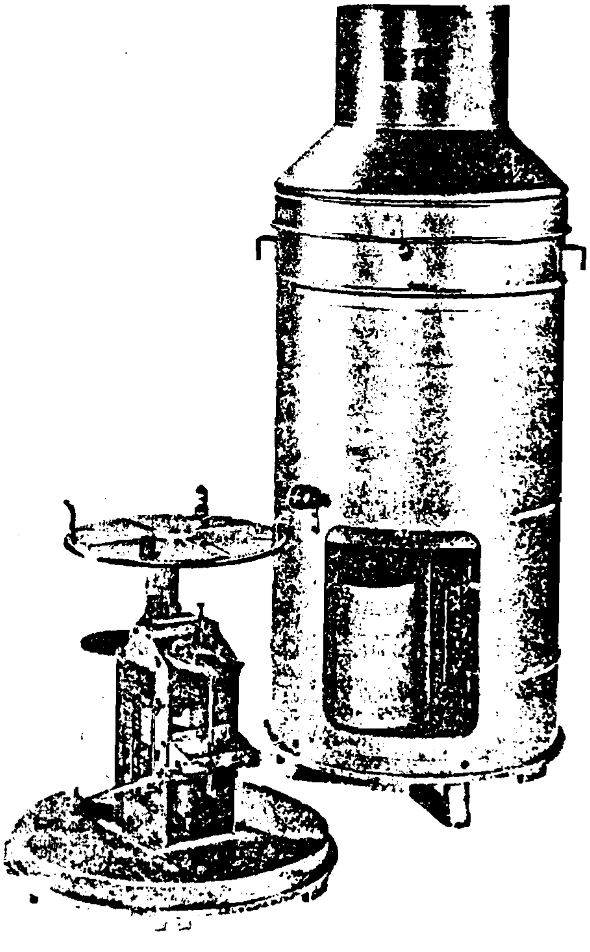

Figure 17. Example of weighing bucket raingauge and recording device.

The most common recorders are the siphon, tilting siphon, tipping bucket and the weighing bucket type. Except for the tipping bucket type, rainfall amounts are recorded on a moving chart by a pen mechanically connected to a float in the collection reservoir or the movement of the weighing device. In the tipping bucket type, each movement of a set of symmetrical buckets about the fulcrum operates the recording pen. Instruments which totalize the rainfall amount, and do not return to zero at some specified level, as some siphon types do, are recommended. Recording devices which are operated by a spring driven clock type mechanism are preferred over those requiring a power source for this project. The tipping bucket type gauge has advantages of accuracy over the weighing bucket type and advantages in operation and maintenance over siphon type rainfall recorders.

Soil temperature at various depths, although not used directly in the computation of reference evapotranspiration, may be an important factor in determining nitrification of organic material and therefore fertilizer requirements. Such measurements are normally made at depths of 5, 10, 20, 50, and 100 cm (2,4,8,20 and 40 inches) under an unshaded grass or bare soil cover. Up to 30 cm (12 in) depth, mercury-in-glass thermometers may be used with the bulb placed at the required depth. For depths below 30 cm (12 in), the typical mercury-in-glass thermometer must be suspended into a thin-walled plastic or metal tube with a sealed bottom placed at the required depth. The bulb of the thermometer itself is embedded in wax or other insulating material to delay temperature change as it is brought to the surface to be read. The tube is capped to keep water from entering.

One additional requirement is that the thermometers used to record maximum and minimum temperature, and actual temperature if recorded, be housed in an appropriate shelter to keep them safe and out of the elements. Various types of thermometer shelters, shown in Figure 18, have been used. Basically it is a wooden, naturally ventilated structure, painted white and supported with base at about 1.5 m above the ground level. Any structure of this type which is naturally ventilated and protects the thermometers from wind or rain is adequate. It is recommended that the shelter be locally made. An additional enclosed and lockable shelter for keeping spare parts and extra recording materials is also recommended.

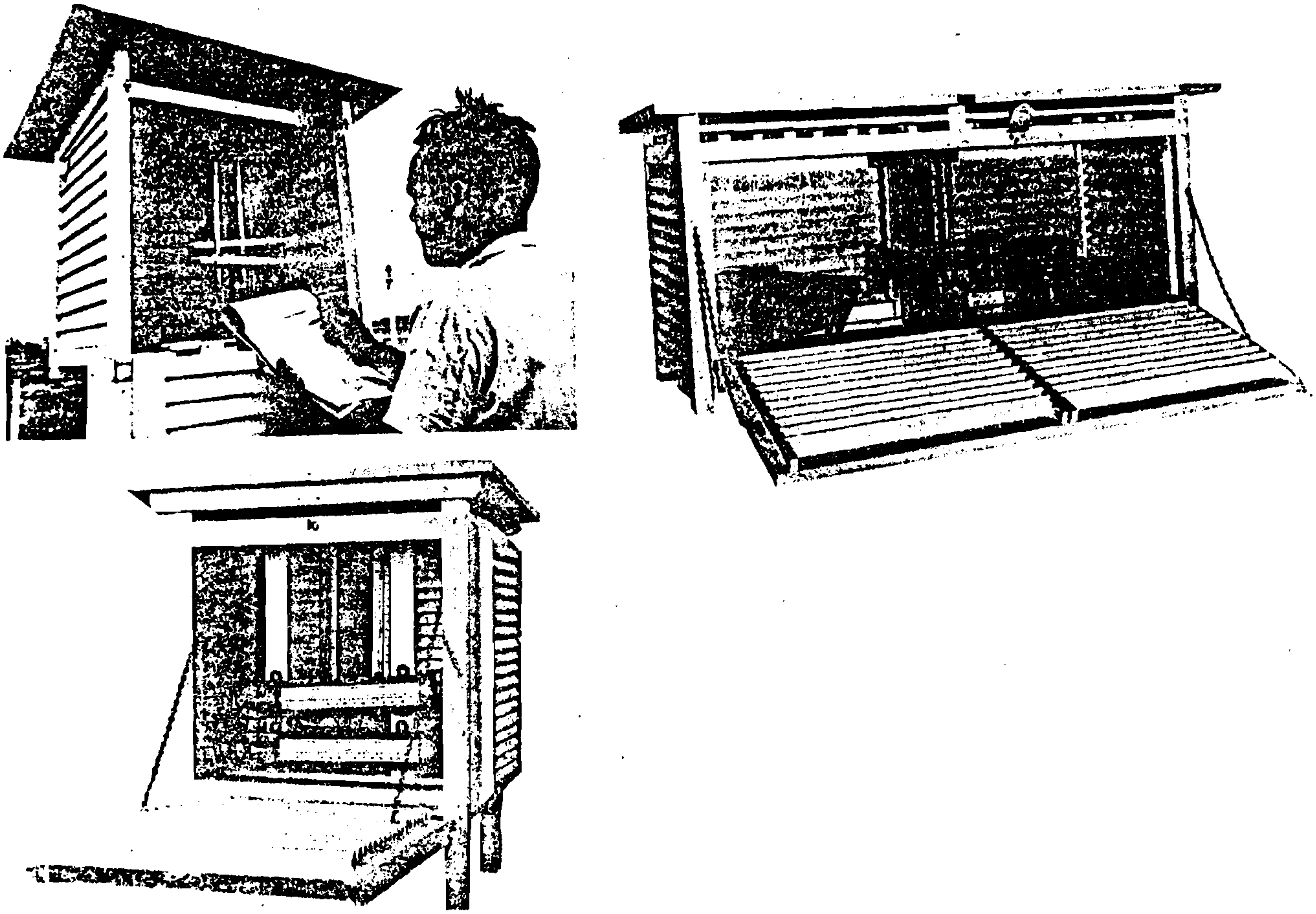

Figure 18. Examples of types of thermometer shelters which may also house hygrothermographs.

STATION LAYOUT

There is no standard layout recommended for field stations. The major requirement is that no instruments, instrument shelters, fence or fenceposts interfere with the measurements to be made. Instruments should be adequately spaced to avoid difficulty in making measurements and a recommended station area is 10 m by 10 m (33 ft). If it is felt that the station may eventually evolve into a major regional meteorological station with additional parameters being measured, then adequate space should be allocated at the initiation of the project. In this case an area of 20 m by 20 m (66 ft) would not be unreasonable.

OBSERVATION PROCEDURES

The observation procedures detailed in this section indicate the measurements to be made to use the FAO modified Penman method and pan evaporation methods to determine reference ET. The measurements made for these methods will also allow for use of the Blaney-Criddle and Makkink radiation methods.

Observations should be made at the same times each day. Most measurements are made in the morning and this should be done as near to 0800 hours as possible. Other measurements made instantaneously throughout the day in lieu of automatic recording instruments should be made at about two hour intervals from the first morning measurement. If only two measurements are to be made daily, the second should take place at 1400 hours in the afternoon. The last measurement for instantaneous values should be made at about 1700 hours in the evening. In any case, local customs must be accounted for and a reasonable pattern which can be followed everyday should be developed. Once this schedule is established, it should be maintained consistently. The exact time of actual observation should be noted on daily record sheets based on a 24 hour clock.

An observation sheet, an example of which follows, should be filled out on a daily basis. In addition to the specific information required on the sheets, it is extremely important that remarks be made regarding unusual or noteworthy climatic conditions, condition of the cropped area extending from the station, and the condition of the station and instruments. Examples might be whether there was dew or fog, if the surrounding crop land had been irrigated or harvested, and if the evaporation pan needed cleaning or the raingauge appeared to be leaking. This type of information is extremely valuable and should be noted daily. An indication should be made even if nothing remarkable is noticed to insure that the record is completely filled out.

The procedure for reading the instruments is indicated with regards to instruments which are available at EWUP project sites or those which are recommended for those sites. Reference should be made to the sample observation sheet. The date, time of measurement and name of observer should be recorded. During the first measurement in the morning of each day, the temperatures in the instrument shelter should be recorded. This includes actual, maximum and minimum temperature, even though the maximum temperature pertains to the previous day. Next the wet and dry bulb thermometers for calculation of relative humidity should be read. The Assmann type aspirated psychrometer is recommended. The sling psychrometer should be used if no Assmann type is available or until one is available. In either case, the wick is wet and the instrument aspirated according to instructions given under the instrument description. At the end of the aspiration time, the dry and wet bulb temperatures are recorded. Wet bulb depressions should be computed at this time and also recorded. The reasonableness of the wet bulb depression should be checked by comparison with the previous day's reading. The wick should also be checked at this time for dust or dirt. This concludes the temperature measurements.

If a recording hygrothermograph is used, the date should be marked on the recording chart and the temperature should be checked daily for comparison with the standard thermometers. The hygrothermograph should also be checked weekly for relative humidity against the psychrometer measurement. The hair bundle must be cleaned weekly according to the instructions given in the Instrumentation section. It is important that the hair bundle is not touched by the fingers during the cleaning process. The hygrothermograph must be kept in the instrument shelter along with the thermometers. The chart paper and battery must be replaced according to the manufacturers instructions (at about 90 days for the project instruments). As soon as the chart is removed, it should be analyzed for daily maximum and minimum relative humidity and the results tabulated. Mean daily humidity should also be computed at this time. This may be done by using the digitizing capabilities of the HP 9825 computer along with an averaging program. If the digitizing unit is used for mean relative humidity, it can also be programmed to output daily maximum and minimum relative humidity.

SAMPLE FIELD BOOK SHEET

Station ______________________________ Date ______________________________

Observer ______________________________

Measurement	Time				
Temperature, °C					
Temp, drybulb, °C					
Temp, wetbulb, °C					
Temp, max, °C					
Temp, min, °C					
Rainfall, mm					
Wind: Reading					
Run, km					
Evaporation: Reading					
Evap, mm					
Reading after filling					
Cloud Cover, oktas					
Solar radiation, cal·cm^{-2} sec^{-1}					
Bright sunshine, hrs					

Remarks: (Note time preceeding each remark.)

Instruments:

Fields:

Weather:

Following humidity, the solar radiation should be measured using the thermo-electric pyranometer found at the field sites. The instruments available to the project have a built-in integrating circuit. This circuitry is used to automatically integrate the total amount of solar radiation measured by the instrument between any two time periods of measurement. When the button on the front of the instrument is pushed, the light emitting dial indicates the current reading of the integrator. When the button is pushed a second time, say 24 hours later, the second reading should be recorded and subtracted from the first. The difference between these two readings is the integrated amount of solar radiation measured by the instrument in calories per square centimeter during the time between two successive readings.

The instruments being used have a dessicant cartridge within them. This cartridge must be kept operational to insure satisfactory and accurate readings of the instrument. The humidity reading for the dessicant cartridge is located on the end of the cartridge in the back of the instrument on the lower left hand corner. The humidity reading is indicated by the dot in the center of the cartridge mounting. If the cartridge is in good condition the center dot is blue. When the cartridge needs to be reclaimed, the dot turns from blue to pink. Dessicant is reclaimed by removing it from the cartridge and baking it in a shallow pan at 175°C (350°F) for about 10 minutes. The dessicant must be immediately placed within an airtight container upon removal from the oven. It should be transported to the field in the airtight container and replaced in the cartridge which is placed back into the instrument. Moisture must not be allowed to condense inside the dome on top of the instrument. Such conditions may damage the electronic components of the instrument. For this reason, the dessicant must always be kept in good condition.

Next the rainfall reading should be made. If it is raining while this measurement is being made, it should be noted and the reading made as quickly as possible. The windrun reading should be made and if a totalizing counter is used, the actual reading should be recorded and the run since the last reading should be calculated and recorded. Continually recorded wind speed must be analyzed by integrating the area under the curve to determine the total windrun as a function of time. For this project it is recommended that this analysis be made on a regular three month basis or sooner if the chart must be replaced more frequently. This should be done by using the digitizing capabilities of the HP 9825 and developing a computer program to output total windrun on each day from 0600 to 1800 hours, from 1800 to 0600 hours of the next day, and the total 24 hour run from 0600 hours to 0600 hours of the next day. The total windrun for 24 hours should then be checked with that recorded on the anemometer counter. Both instruments should have the same reading if at the same height. If set at different heights, the higher anemometer should always record a greater daily windrun.

The next reading to be made is from the evaporation pan. This will normally be made using a hook gauge in a stilling well. The current reading should be made, subtracted from the previous reading and the difference recorded. This difference should be checked with the previous day's reading for reasonableness. The water level in the pans should next be checked. If it is estimated that the evaporation from an additional day will reduce the water level below 7.5 cm (3 in), the pan must be filled from a storage container, such as a large barrel, kept nearby. The water level must be measured with the hook gauge immediately following the pan filling and this reading recorded. The pan should also be checked for leaks and should be cleaned on a regular basis. The pan must be cleaned whenever the pan or water surface becomes so discolored as to change the reflective properties of the pan.

The final reading to be made in the morning is for cloud cover. This will be done by observation using the method described under the radiation section to determine the number of oktas. If a Campbell-Stokes sunshine recorder is used, the card should be changed at this time and the instrument checked for adjustment. The card should be analyzed each day for actual bright sunshine hours and the value recorded. Visual observation of cloud cover should be continued even if a sunshine recorder or pyranometer is used.

Readings made at other times during the day follow the same format as the morning reading except that fewer instruments are read. At any other time during the day, the time of observation should be noted and the following observations should be made: actual temperature, relative humidity, solar radiation, windrun, and cloud cover. Arrangements should be made to read the stations seven days per week.

It is strongly recommended that at each of the three project sites, an engineer or agronomist be put in charge of the meteorological station and given full responsibility for its operation. This individual must carefully read the operation manual for every instrument and be familiar with its operation and maintenance. This individual should also go to the field the first day of each week along with the technician making the readings. At this time each instrument should be checked to see that it is operating properly and any necessary maintenance carried out in the field or the instrument should be brought into the office for major maintenance or calibration. The technician's procedures should also be checked during this visit. Any required calculations using the data should be done on a regular basis upon return from the field the first day of the week. All operations with the previous week's data should be done on this day and any questionable trends in the data should be looked for. Such trends may indicate a malfunctioning instrument or poor recording procedures.

Extra recording charts, recording ink, batteries, adjustment tools and spare parts should be kept on hand at each of the three field stations in a locked cabinet. When the extra material is put into operation in the field, replacement can be ordered from Cairo. The order should be processed upon arrival so that each field station has a complete set of equipment and parts to maintain daily operation of the field sites.

REFERENCES

Doorenbos, J. 1976. FAO Irrigation and Drainage Paper 27, Agrometeorological Field Stations. United Nations, Rome, 94 pp.

Doorenbos, J. and W.O. Pruitt. 1977. FAO Irrigation and Drainage Paper 24 revised, Crop Water Requirements. United Nations, Rome, 144 pp.

Rosenberg, N.J. 1974. Microclimate: The Biological Environment. John Wiley and Sons, New York, 315 pp.

Staff Paper #43

SOIL FERTILITY SURVEY OF KAFR EL SHEIKH
I. Phosphrus

Parviz Soltanpour

January, 1980

1. Introduction

The Egypt Water Use and Management Project (EWUP) is a cooperative project between the governments of Egypt (GOE) and U.S.A. to improve the on-farm irrigation and agronomic management practices of the Egyptian small farmers. The project has three components: A) survey of the on-farm water and agronomic management practices and identification of the primary constraints to increased production and efficient water use, B) search for solution of the problems, and C) dissemination of the findings to the farmers through demonstration and extension methods.

One of the subcomponents of A is the soil fertility survey.

The objectives of the soil fertility survey were:

i) To obtain information on the present levels of plant nutrients in farm fields located in Abu Raya cooperative hods (large basins).

ii) To obtain information on the variability in soil fertility among farms in the same hod.

iii) To obtain information on the variability in soil fertility between hods.

iv) To study the feasibility of soil testing for fertilizer recommendations in Kafr el Sheikh.

v) To utilize the data obtained for designing soil sampling procedures.

2. Background

The Abu Raya cooperative in Kafr el Sheikh governorate has been selected as one of the three EWUP study sites. This selection was based on the agronomical, socioeconomical, and engineering considerations by the EWUP scientists.

The GOE by law requires that each farmer in Abu Raya cooperative (and many other cooperatives) to plant his farm to cotton and rice in a 2 year rotation. The Abu Raya cooperative has 5 hods (large basins) each following the government sepcified rotation. In the two year rotation, the summer crops are cotton and rice . Cotton is usually planted in March, picked in mid or late August, and the harvest is usually complete by the end of September. Rice is transplanted during June from nurseries which were planted in late April and May. Rice harvest starts in October and continues into November. Winter crops such as wheat, berseem, and flax are usually used in the rotation. The frequency and relative frequency of different rotations practiced in the farms sampled are given in the following table.

Table 1. Frequency and Relative Frequency of rotations Used in the Farms Sampled

Cotton farms

Rotation	Frequency	Relative frequency %
Rice - berseem - cotton	39	78
Rice - fallow - cotton	9	18
Rice - chickpeas - cotton	1	2
Rice - onions - cotton	1	2
Total	50	100

.../...

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Rice farms

Rotation	Frequency	Relative frequency %
Cotton - berseem - rice	21	26
Cotton - flax - rice	30	38
Cotton - wheat - rice	28	35
Cotton - bean - rice	1	1
Total	80	100

It seems that following a crop of rice and before planting cotton, a relatively large number of farms are fallowed (18%). This information should be verified. Egypt can not afford to fallow valuable agricultural land. The reasons for fallowing (labor availability, lack of mechanization etc.) is a vital area of research for Egypt.

The farm size distribution histogram for each hod is given in the appendix.

3. Survey Method

The soil samples were obtained from the basins to be planted to cotton or rice within the hods. Four hods were surveyed in the Abu Raya cooperative: Matarine 1, Matarine 2, Bakir 1, and Bakir 2 with cultivated areas of 560, 335, 438, and 381 feddans respectively. The 1978 cotton and rice farms to be sampled were drawn at random from the list of farms in each hod. The farms sampled represented about 10% of the total cotton area and 10% of the total rice area in each hod. Clean shovels were used to take samples. Samples were obtained from 0 - 20 cm depth. Two sampling units (sampling unit = one shovel full of soil) were obtained from each farm measuring one feddan or less. If farms were greater than one feddan in area then four sampling units obtained per farm. Subsoil samples (20 - 40 and 40 - 60 cm) were obtained from a few farms (see table A1 and A2 in the appendix for infromation on the size and crop rotation of the farms sampled).

4. Analytical Method

The samples were air dried. Availability index for phosphorus was determined by extracting two subsamples from each sampling unit with 0.5N $NaHCO_3$ ( ), and determining phosphorus by the blue (phosphomolybdo complex)method using ascorbic acid as the reductant ( ).

5. Statistical Analysis

Histograms of the phosphorus values for each basin were prepared by usign the HP 9825 A computer to visually examine the normality of the distributions*. If visual examination showed nonnormal distribution, then a log transfromation was used. The normality of nontransformed data was compared to that of the transformed data by using a quick test. The standard deviation of each observation was divided by the mean of deviations (sign ignored). This ratio is close to 1.25 for a near normal distribution ( ). Other transformations, may have been used, but in this study a logarithmic transformation was found adequate

5.1. Within farm variability

The paired plot technique ( ) was used to test the mean difference between the two sampling units (cores) taken per farm. The differences between pairs of cores were calculated (d values). Then the mean and the standard deviations of the d values were determined using the following formulae:

$$\bar{X}_d = \frac{\Sigma d}{n} \qquad (1)$$

$$S_d^2 = \frac{\sum_{i=1}^{n} (xi - \bar{X}_d)^2}{n - 1} \qquad (2)$$

$\bar{X}_d$ = Mean of d values

Σd = Sum of d values

n = Number of cotton or rice farms sampled per hod.

s_d = Standard error of d values

$\Sigma(xi - \bar{x}_d)^2$ = the sum of the squares of the deviations from the mean

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* The help of Mr. Helal for preparation of the histograms is acknowleged

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Then the student's t test was used to see if the mean of the differences in pairs are significantly different from zero using the following formula:

$$t = \frac{\bar{x}_d - 0}{s / \sqrt{n}} \qquad (3)$$

Where all the symbols have already been explained.

The two-tailed table was entered at the 5% probability level and n-1 degrees of freedom to determine the significance of the t value.

5.2. Analysis of Variance

In order to determine if the differences between soil phosphorus levels in different farms in the same summer crop and within the same hod were significant the analysis of variance techniques was used (   ). The 2 sampling units taken from each farm were used as replicates. The total, farm and error sums of squares, and mean squares and F values for farms were calculated.

Samples from all basins (hods) with the same summer crop were analyzed to determine if the soil fertility of different hods were significantly different.

5.3. Sampling Plan and Intensity

Sampling plan indicates how a sample should be taken (random, stratified, or systematic). The analysis of variance results were used to determine sampling plan.

Sampling intensity determines how many sampling units should be taken from an area.

The number of sampling units that will give a 95% confidence interval of different lengths were determined by using the following formula:

$$D = t \frac{s}{\sqrt{n}} \quad (4) \qquad \text{or} \qquad n = \frac{t^2 \, s^2}{D^2} \quad (5)$$

Where t is the t value at the 5% level of porbability and the degrees of freedom used to calculate s , s is the standard deviation and D is confidence interval desired. A t value of 2.1 was used in this study.

6. Results and Discussion

The phosphorus distirubtion f or all cores taken from cotton farms (table 2) show that 18% of the soil surface samples tested low (0 - 4 PPM) in phosphorus, and 62% tested medium (4 - 8 PPM). In rice farms 6% of the cores tested between 0 and 4 PPM and 58% tested between 4 and 8 PPM.

In the rice and cotton field soil samples (table 3), 11% of all cores taken tested low (0 - 4 PPM), 60% medium (4 - 8 PPM), 24% high (8 - 12) and 5% very high in phosphorus.

The deep samples showed that (table 4) mean phosphorus values for cotton fields were 5.3, 5.1 and 8.5 PPM and for rice fields were 7.9, 6.4 and 7.0 PPM in 0 - 20, 20 - 40, and 40 - 60 cm depth respectively (tables 4 & 5)

The Abu Raya cooperative soils seem to be moderately well-supplied with phosphorus. Responses of crops to phosphorus have been in the order of 10 to 15%.[1/]

Histograms of soil cores (figs A1 & A2 , appendix) showed that the phosphorus distributions were not normal except for one case (bakir 2 cotton farms). A logarithmic transformation made the distributions look more normal (figs A1 & A2 appendix). The quick test for normality confirmed the observations (talbe 6). The logarithmic transformation reduced the coefficient of variability.

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[1] Personal communications with Dr. Serry, Director of Soil and Water Research Institute

All the statistical analyses were performed on the transformed data.

The results showed that the mean differences between the two cores taken per farm on the same hod were small and nonsignificant in 7 out of 8 basins. The mean core difference of one PPM was statistically significant for Bakir 2 cotton fields. However, for practical purposes the differences are small.

The between farm differences in the mean phosphorus level were not significant in 5 out of 8 basins

The differences in phosphrus levels of different crop basins in the same hod were significant.

6.1. Sampling Plan

The question of sampling plan and strategy (how to take samples) needs a thorough discussion. The ideal sampling strategy would be to have each farmer take a soil sample from his farm and have it analyzed. This plan can not be used in Egypt at this time due to the lack of funds, the necessary infrastructure and laboratory facilities. The economical feasibility of this ideal sampling plan should be studied. Since the average farm size in Egypt is small (about 2 F), the cost of soil sampling is relatively large. Considering that there are about 6,000,000 feddans of cultivated land in Egypt, 3,000,000 samples would be tested under the ideal soil sampling strategy discussed above, assuming annual sampling and testing.

The second strategy is sampling each crop basin (cotton v.s. rice) in a hod and making fertilizer recommendations accordingly. The results of this study show that this strategy will help many farmers in the crop basin, but theoretically may penalize the farmers with very low and very high soil fertility compared to the ideal strategy. To examine this possibility let us compare fertilizer recommendations for one crop such as cotton based on the average soil fertility level of the crop basin versus the recommendations based on soil fertility level of each farm. A general recommendation currently used in Egypt for phosphorus fertilizer recommendation for cotton is that soils testing 8 PPM of phosphorus (P) or lower, require phosphorus fertilizer.[1] Let us use Bakir 2 cotton basin as an example. This basin showed that farm fertility levels were significantly different. The average farm phosphorus levels ranged from about 4 PPM to 7 PPM. Based on these data the phosphorus fertilizer recommendation will be the same for all the farms. Therefore, in this case sampling each farm separately or sampling the cotton basin as a whole would have resulted in the same fertilizer recommendation.

Based on the data obtained from 130 farms in Abu Raya cooperative, it is recommended that each crop basin be soil sampled at random for the purpose of phosphorus fertilizer recommendation. A recommendation for other elements will be made after data for other elements have been analyzed.

6.2. Sampling intensity

As was mentioned before the phosphorus distirbutions were not normal and were transformed to their logarithmic analogues. The analysis of the transformed data (table 8) show that the number of cores required to composite in order to get a 95% confidence interval (CI) of about ± 20% of the geometric mean ranged from 9 to 31. The numbers required for a CI of ± 10% was excessive (31 to 111). For a field testing low in phophorus (less than 8 PPM) the difference between 10 and 20% confidence intervals is small. Therefore one may choose the ± 20% CI for practical purposes.

Using a CI of ± 20%, it is recommended that 30 cores per any crop basin within a hod be obtained. These cores then should be thoroughly mixed in a plastic bucket or pan to prevent contamination of soil with micronutrients such as zinc and iron. Then a subsample will be obtained and called the "composite sample". This sample should be air

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[1] Personal communication with Dr. Ali Serry, Direcotr of Soil and Water Research Institute.

dried as soon as possible, placed in sampling bags, marked porperly and sent to the laboratory for analysis and fertilizer recommendations. The loboratory making the fertilizer recommendations should receive with each sample information about crop rotation used, yield levels, and soil types.

Another question to be answered is how often one should sample the field. For elements such as nitrogen, soil sampling and testing before each crop may be required. But, for P, one sample may be obtained per year. The sample may be obtained before the winter crop and a phosphorus fertilizer recommendation for all crops in the rotation made accordingly. Before winter crops are planted, soils are relatively dry, thus making the sampling task easier. Use of stainless steel soil sampling tubes is more convenient. If the soil is wet during sampling, then a stainless steel auger may be used.

6.3. Sampling depth

A limited number of farms were sampled to a depth of 60 cms. The results indicated that mean soil phosphorus levels were 5.3 to 8.5 in surface soil and subsoil in cotton farms. These values were 7.9 and 6.4 for rice farms. Therefore, it is recommended that more soil sampling accompanied by soil test calibration experiments be carried out to determine the importance of deep sampling. The coefficient of variabilities in cotton and rice fields were higher for deep samples compared to the surface samples. This observation is contrary to the common belief that surface soil fertility is more heterogeneous than subsoil fertility ( ). The high clay content of Abu Raya soils and cracking of these soils and subsequent falling of surface soil to the subsoil layers through these cracks may be responsible for the heterogeneity of subsoil.

Therefore, it is recommended that at this time deep soil samples,(to a depth of 60 cm) be obtained for soil fertility determinations. The intensity of soil sampling was determined by using the data of surface soils. The intensity of sampling may be calculated from the subsoil fertility data when more data are available

7. Conclusions

The soil fertility sruvey indicated that farm in Abu Raya basin are moderately supplied with available soil phosphorus. The increase in yields due to phosphorus fertilization is estimated at about 10 to 15% in general. The soil fertility survey indicated that within farm variability was samll, on the average. The phosphorus level in farms within the same crop basin were not significantly different in 5 out of 8 basins.

The results indicated that each crop basin should be sampled separately for a phosphorus fertilizer recommendation. Each sample should be taken from 0 - 60 cm depth and be a composite of at least 30 cores taken per each cotton or rice basin. This sampling intensity resutls in a sampling error of about ± 20 %.

The detailed procedure for sampling has been discussed in the text

PS/1s

References:

El-Togby, 1976. Contemporary Egyptian Agriculture. Ford Foundation

Ezekiel, Mordecai and K. A. Fox, 1959. Methods of correlation and regression analysis. P9, John Wiley and Sons, Inc. N.Y. London, Sydney.

Reuss, J . O., P. N. Soltanpour, and A. E. Ludwick, 1977. Sampling distribution of nitrates in irrigated fields. Agron. J. 69:588-592.

Snedecor and Cochran, 1974. Statistical Methods. Iowa State Univ. Press, Ames, Iowa, U.S.A.

TABLE 2. FREQUENCY AND RELATIVE FREQUENCY OF DIFFERENT SOIL PHOSPHRUS LEVELS IN ABU RAIA COOPERATIVE FOR COTTON AND RICE FIELDS.

CROP	PHOSPORUS CLASS	FREQUENCY				RELATIVE FREQUENCY				
	P, PPM	M1*	M2	B1	B2	M1	M2	B1	B2	COMBINED
						%				
COTTON	0 - 4	1	8	3	9	5	17	17	29	18
	4 - 8	16	24	10	22	80	51	55	71	62
	8 - 12	3	12	2	0	15	26	11	0	15
	> 12	0	3	3	0	0	6	17	0	5
RICE										
	0 - 4	2	1	2	4	5	2	5	12	6
	4 - 8	21	20	29	23	51	43	76	67	58
	8 - 12	15	21	6	6	37	46	16	18	30
	> 12	3	4	1	1	7	9	3	3	6

* M1 = MATARINE 1
M2 = MATARINE 2
B1 = BAKIR 1
B2 = BAKIR 2

TABLE 3. DISTRIBUTION OF PHOSPHORUS IN COTTON AND RICE FIELDS

PHOSPHORUS PPM	FREG.	REL. FREG. %
0-4	3 0	11
4-8	16 5	60
8-12	6 5	24
> 12	1 5	5
	27 5	100%

TABLE 4. PHOSPHORUS VALUES IN DEEP SAMPLES - COTTON FARMS

	P, PPM		
	0-20 CM	20-40 CM	40-60 CM
	5.0	5.5	5.5
	5.5	4.5	5.5
	5.5	5.5	10.0
	5.5	8.0	9.0
	4.5	8.0	15.0
	7.0	–	15.5
	8.5	5.6	11.0
	3.5	4.0	8.5
	4.0	4.0	9.0
	5.5	6.0	9.0
	4.0	5.0	5.5
	7.0	4.0	9.0
	5.0	5.5	7.0
	–	2.0	2.5
	4.5	5.0	8.0
	5.0	4.5	6.0
MEAN	5.3	5.1	8.5

TABLE 5. PHOSPHORUS VALUES IN DEEP SAMPLES - RICE FARMS

	P, PPM	
0-20 CM	20-40 CM	40-60 CM
5.5	6.0	11.0
11.5	5.5	5.5
9.5	8.0	20.0
8.5	5.5	10.0
11.0	8.5	5.0
8.5	5.0	3.0
12.5	5.0	7.0
6.0	4.0	12.0
11.5	7.0	11.5
8.5	8.0	11.0
8.5	4.0	7.0
9.0	8.0	9.0
5.0	4.0	2.5
5.5	5.5	4.0
8.5	5.5	8.0
5.5	4.0	–
5.5	5.5	4.0
6.0	4.0	5.0
5.5	9.0	5.5
18.0	11.0	13.0
5.5	8.0	4.5
6.0	2.5	4.5
8.5	13.0	9.0
9.0	9.0	9.5
5.5	4.0	4.0
4.0	6.0	8.0
7.0	5.0	5.0
9.0	5.5	5.0
6.0	5.0	5.0
9.5	8.5	4.5
5.5	6.0	5.0
8.0	8.5	5.5
MEAN 7.9	6.4	7.0

TABLE 6. — The coefficient of variabilities and $\frac{s}{\bar{d}}$ values for the nontransformed and the transformed data.

RICE	NONTRANSFORMED		LOG TRANSFORMED	
	C.V. %	$\frac{s}{\bar{d}}$	C.V. %	$\frac{s}{\bar{d}}$
M 1	41	1.33	18%	1.20
M 2	41	1.46	18%	1.29
B 1	37	1.46	16%	1.31
B 2	37	1.35	17%	1.22

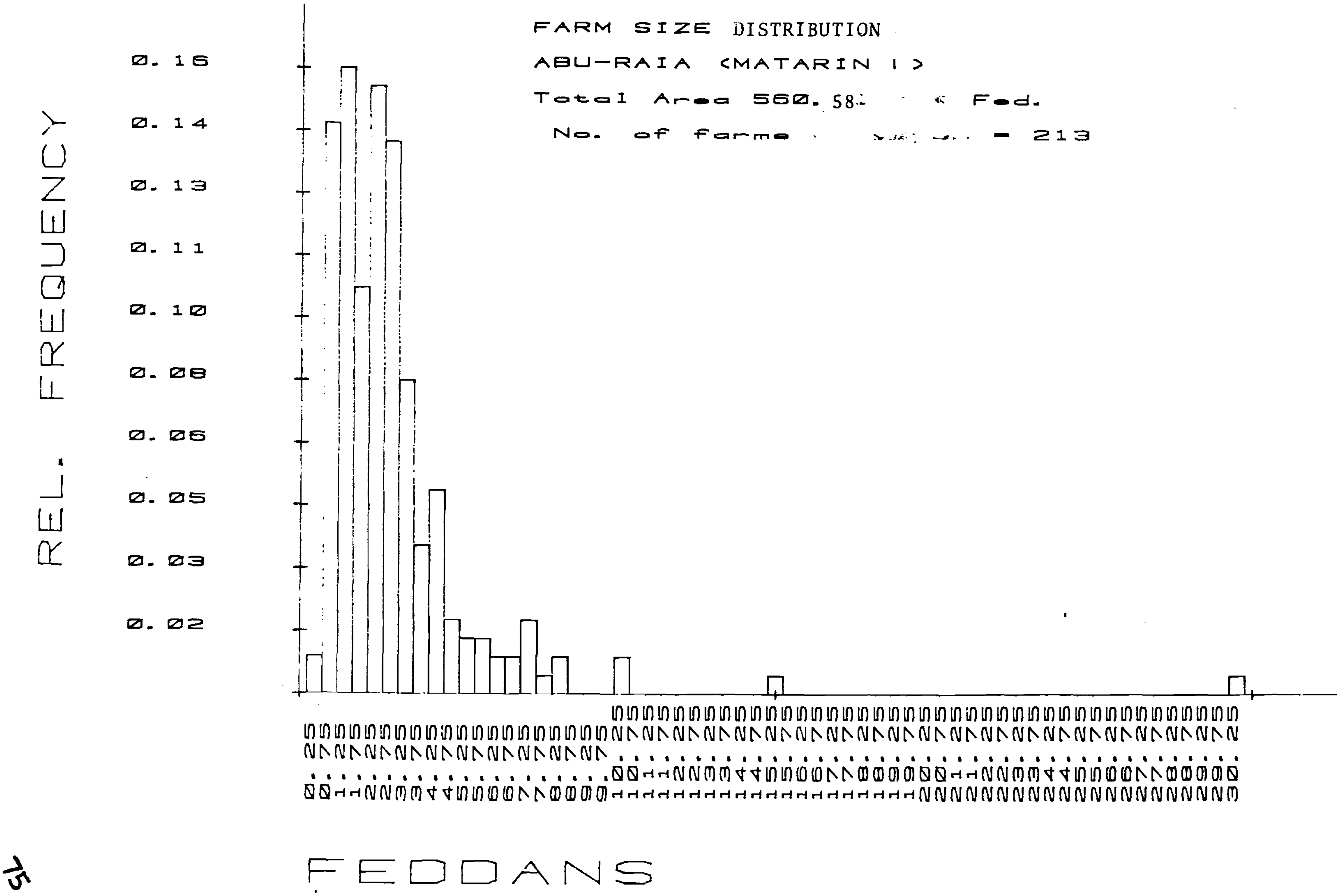
COTTON				
	C.V. %	$\frac{s}{\bar{d}}$	C.V. %	$\frac{s}{\bar{d}}$
M 1	27	1.36	15	1.38
M 2	50	1.41	21	1.23
B 1	58	1.39	25	1.29
B 2	23	1.25	15	1.30

TABLE 7. MEAN PHOSPHORUS VALUES FOR DIFFERENT HODS

	COTTON PPM	RICE PPM
MATARINE 1	$\bar{X}$ = 6.0	$\bar{X}$ = 8.4
MATARINE 2	7.2	8.3
BAKIR 1	7.7	6.6
BAKIR 2	4.7	6.9
	$\bar{X}$ = 6.4	$\bar{X}$ = 7.6

TABLE 8. - NUMBER OF CORES TO COMPOSITE TO GET 95% CONFIDENCE INTERVAL INDICATED BELOW AS % GEOMETRIC MEAN.

COTTON	91-110%	83-120%	77-130%	71-140%	67-150%
M1	31	9	4	3	2
M2	75	21	10	6	4
B1	111	31	15	9	6
B2	26	7	4	2	2
RICE					
M1	66	19	9	6	4
M2	66	19	9	6	4
B1	44	12	6	4	3
B2	51	14	7	4	3


FARM SIZE DISTRIBUTION
ABU-RAIA <MATARIN I>
Total Area 560.58 Fed.
No. of farms = 213
REL. FREQUENCY
0.16
0.14
0.13
0.11
0.10
0.08
0.06
0.05
0.03
0.02
FEDDANS
0.25
0.75
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1.75
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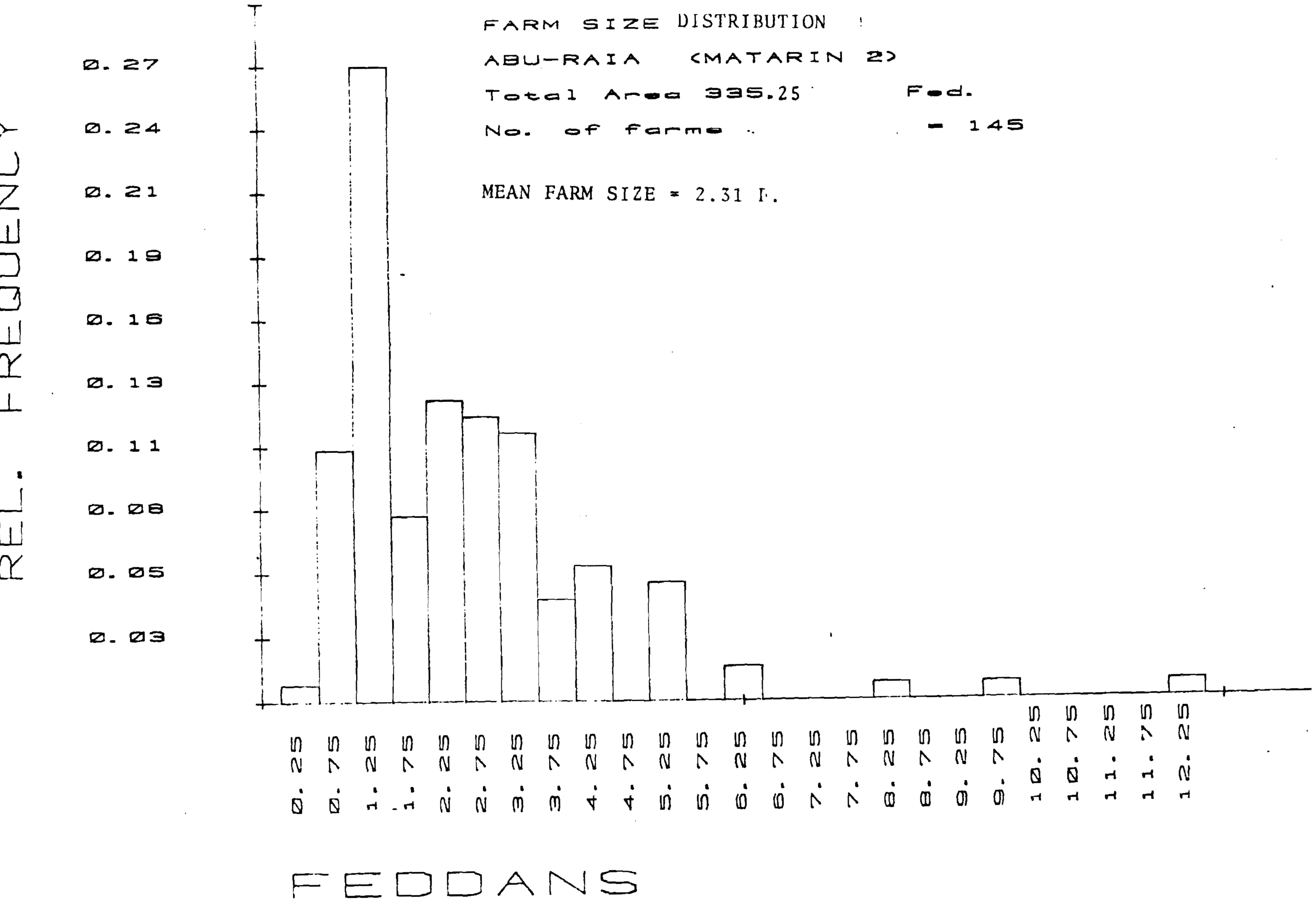
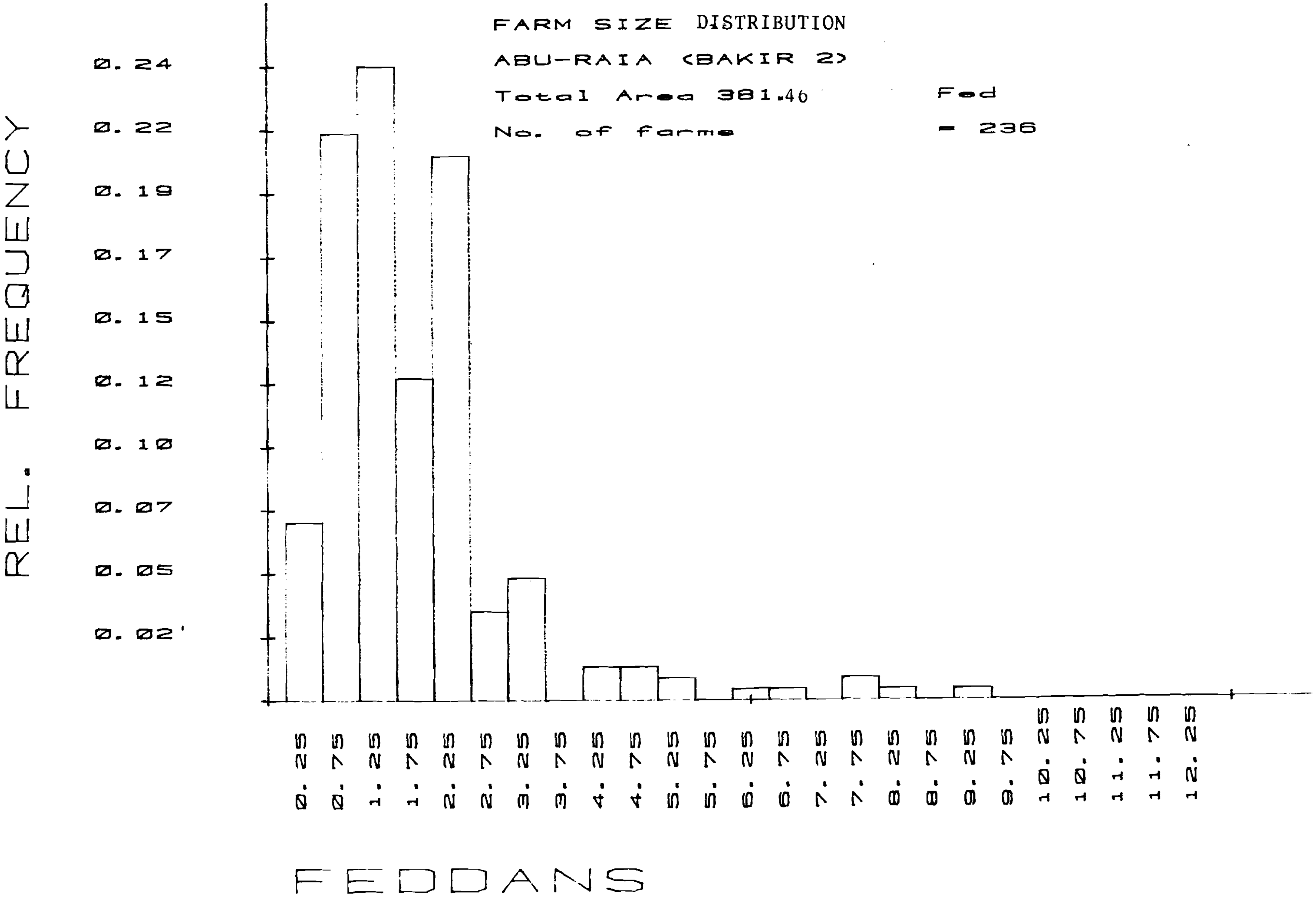
30.25


FARM SIZE DISTRIBUTION
ABU-RAIA (MATARIN 2)
Total Area 335.25 Fed.
No. of farms = 145
MEAN FARM SIZE = 2.31 F.
REL. FREQUENCY
0.27
0.24
0.21
0.19
0.16
0.13
0.11
0.08
0.05
0.03
0.25
0.75
1.25
1.75
2.25
2.75
3.25
3.75
4.25
4.75
5.25
5.75
6.25
6.75
7.25
7.75
8.25
8.75
9.25
9.75
10.25
10.75
11.25
11.75
12.25
FEDDANS


FARM SIZE DISTRIBUTION
ABU-RAIA (BAKIR 2)
Total Area 381.46 Fed
No. of farms = 236
REL. FREQUENCY
0.24
0.22
0.19
0.17
0.15
0.12
0.10
0.07
0.05
0.02
0.25
0.75
1.25
1.75
2.25
2.75
3.25
3.75
4.25
4.75
5.25
5.75
6.25
6.75
7.25
7.75
8.25
8.75
9.25
9.75
10.25
10.75
11.25
11.75
12.25
FEDDANS

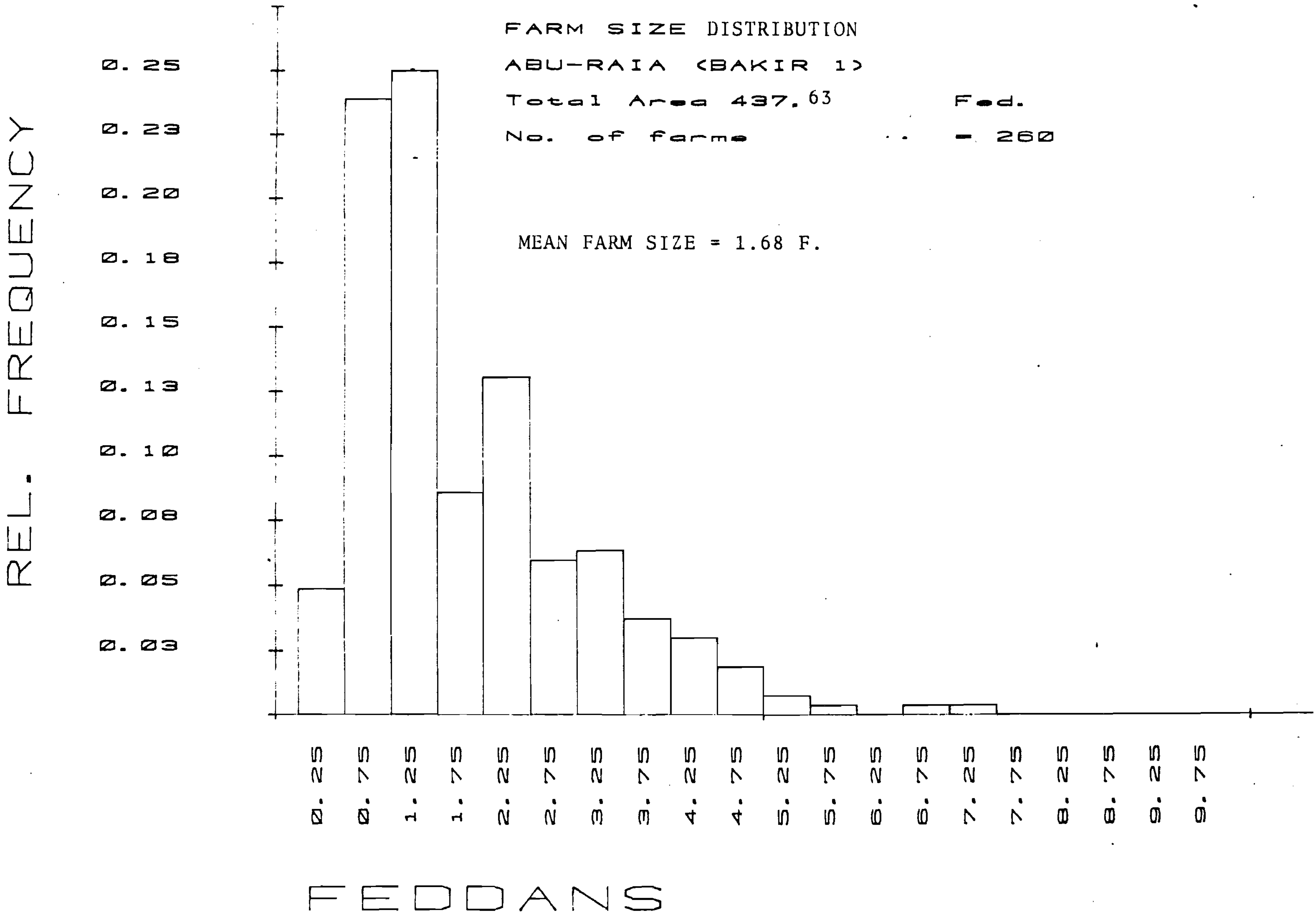

FARM SIZE DISTRIBUTION
ABU-RAIA (BAKIR 1)
Total Area 437.63 Fed.
No. of farms = 260
MEAN FARM SIZE = 1.68 F.
REL. FREQUENCY
0.25
0.23
0.20
0.18
0.15
0.13
0.10
0.08
0.05
0.03
0.25
0.75
1.25
1.75
2.25
2.75
3.25
3.75
4.25
4.75
5.25
5.75
6.25
6.75
7.25
7.75
8.25
8.75
9.25
9.75
FEDDANS

Table A1: Data collected in the cotton farms sampled in 1978.

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.	Summer	Winter		0-20 cm.	20-40 cm.	40-60 cm.		
							m^3/F	ppm	ppm	ppm	F	
Matarine 1 with a total area of 100 F. Planted to Cotton	1	1 2			Rice	Berseem	15	8.5 9.0				Mohamed Agibah
	2	3 4			Rice	Berseem	0	5.5 5.5				Ibrahim Abdullah
	3	5 6			Rice	Berseem	0	4.5 5.0				Hanem Mossa
	4	7 10	8 11	9 12	Rice	Fallow	0	5.0 5.5	5.5 4.5	5.5 5.5		Fahmi Abo-El Ezz
	5	13 14 13A 14A			Rice	Berseem	20	— 9.5 5.5 5.5				Fathi Gadallah
	6	15 16			Rice	Chick Peas	0	5.5 —				Khalid El-Shoubry
	7	17 18 17A 18A			Rice	Fallow	0	4.5 5.5 4.5 7.0				Moustafa El Mallah
	8	19 20 19A 20A			Rice	Fallow	0	5.5 5.5 8.0 4.5				Abdel Hamid El Shoubri

Table A1 - Continued

Hod ID	Farm ID	Soil Sample ID 0-20 cm.	20-40 cm.	40-60 cm.	Previous Crops		Manure	Phosphorus (P) Values 0-20 cm.	20-40 cm.	40-60 cm.	Farm Size	Farmer Name
					Summer	Winter	m3/F	ppm	ppm	ppm	F	
Matarine 2 with a total area of 240 F. Planted to Cotton	1	21 22			Rice	Berseem	20	5.5 5.5				Ahmed Gadallah
	2	23 26	24 27	25 28	Rice	Fallow	20	5.5 5.5	5.5 8.0	10.0 9.0		Abdel-Alim Gadallah
	3	29 30			Rice	Berseem	20	5.5 —				Mohame Gadallah
	4	31 32			Rice	Berseem	15	7.0 8.0				Mansour Mansour
	5	33 34			Rice	Berseem	15	4.0 9.5				Ramzy Eliwa
	6	35 36 35A 36A			Rice	Berseem	—	9.5 9.0 6.0 5.5				Hamed El-Sawi
	7	37 38			Rice	Berseem	15	24.0 11.0				Ahmed Shoeb
	8	39 40			Rice	Berseem	15	13.0 8.0				El Shamekh El Senosi
	9	41 44	42 45	43 46	Rice	Berseem	—	4.5 7.0	8.0 —	15.0 15.5		Mohamed Abdou
	10	47 48			Rice	Berseem	15	8.0 10.0				Abdel-Gawad Zayaan

Table A1 - Continued

Hod ID	Farm ID	Soil Sample ID 0-20 cm.	Soil Sample ID 20-40 cm.	Soil Sample ID 40-60 cm.	Previous Crops Summer	Previous Crops Winter	Manure	Phosphorus (P) Values 0-20 cm.	Phosphorus (P) Values 20-40 cm.	Phosphorus (P) Values 40-60 cm.	Farm Size	Farmer Name
							m3/F	ppm	ppm	ppm	F	
Matarine 2 with a total area of 240 F. Planted to Cotton	11	49 50 49A 50A			Rice	Berseem	15	10.0 10.0 4.0 5.0				Ahmed Shehata
	12	51 52			Rice	Berseem	—	5.5 5.0				Om-Mohamed Helal
	13	53 54			Rice	Fallow	—	7.0 3.5				Mohamed Hamad
	14	55 56 55A 56A			Rice	Berseem	20	4.0 9.0 7.0 5.5				Fadl Zidan
	15	57 58			Rice	Fallow	—	5.0 6.0				Shafika Essa
	16	59 60			Rice	Berseem	20	2.5 5.5				Shafika Essa
	17	61 64	62 65	63 66	Rice	Berseem	20	8.5 3.5	5.6 4.0	11.0 8.5		Abdel Wahab Zahra
	18	67 68 67A 68A			Rice	Berseem	15	4.0 15.5 9.0 6.0				Basioni El Zohery
	19	69 70			Rice	Berseem	15	9.5 4.0				Hanem Metwally

Table A1 - Continued

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Matarine 2	20	127 128			Rice	Berseem	20	9.0 5.5				Fathia El-Sebaey
Bakir 1 with a total area of 90 Fed. Planted to Cotton	1	71 72 71A 72A			Rice	Berseem	10	3.5 6.0 6.0 5.5				Abo-El Yazed Taha
	2	73 74			Rice	Berseem	20	5.5 5.0				Abdel-Salam El Nezami
	3	75 78	76 79	77 80	Rice	Fallow	—	4.0 5.5	4.0 6.0	9.0 9.0		Fathi Khalifa
	4	81 82			Rice	Berseem	20	6.0 9.5				Ali Khalifa
	5	83 84			Rice	Berseem	—	20.5 8.0				El Sayed Baraka
	6	85 86 85A 86A			Rice Rice	Onion Berseem	25	5.0 13.0 8.5 15.5				Abdel-Alim El Zayaat

Table A1 - Continued

Mod ID	Farm ID	Soil Sample ID 0-20 cm.	Soil Sample ID 20-40 cm.	Soil Sample ID 40-60 cm.	Previous Crops Summer	Previous Crops Winter	Manure m^3/F	Phosphorus (P) Values 0-20 cm. ppm	Phosphorus (P) Values 20-40 cm. ppm	Phosphorus (P) Values 40-60 cm. ppm	Farm Size F	Farmer Name
Bakir 1	7	87 90	88 91	89 92	Rice	Berseem	15	4.0 7.0	5.0 4.0	5.5 9.0		Abdel-Aziz Abdel-Hadi
Bakir 2 with a total of 160 Fed. Planted to Cotton	1	93 94 93A 94A			Rice	Berseem	15	5.0 5.0 3.5 6.0				Shahin Shahin
	2	95 96			Rice	Berseem	10	5.0 7.0				Refaat Ghanem
	3	97 100	98 101	99 102	Rice	Berseem	15	5.0 —	5.5 2.0	7.0 2.5		Bahnas Ghanem
	4	103 104 103A 104A			Rice	Berseem	—	4.0 4.5 5.0 4.5				Mansour Khidr
	5	105 106 105A 106A			Rice	Berseem	20	4.5 4.0 4.0 4.0				Nehnaah El Beheri
	6	107 108			Rice	Berseem	10	4.5 3.0				Abdel Aziz Hamada
	7	109 110			Rice	Berseem	—	4.5 4.5				Ramadan Shalaby

Table A1 - Continued

Mod ID	Farm ID	Soil Sampl ID 0-20 cm.	20-40 cm.	40-60 cm.	Previous Crops Summer	Winter	Manure m^3/F	Phosphorus (P) Values 0-20 cm. ppm	20-40 cm. ppm	40-60 cm. ppm	Farm Size F	Farmer Name
Bakir 2	8	111 112			Rice	Berseem	—	4.0 5.5				Naema Baraka
Planted to	9	113 114			Rice	Fallow	20	7.0 7.0				Mohamed Hamad
Cotton	10	115 118	116 119	117 120	Rice	Berseem	20	4.5 5.0	5.0 4.5	8.0 6.0		Ali El-Kadom
	11	121 122			Rice	Berseem	—	4.5 4.5				Ali El-Kadom
	12	123 124			Rice	Berseem	25	6.0 6.0				Abdel-Sami El Zayaat
	13	125 126			Rice	Berseem	20	3.0 2.5				Amnah Abdel-Hadi

Table A2. Data collected in the rice farms sampled in 1978.

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (Γ) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Matarine 1 with a total area of Fed. Planted to Rice	1	287 288			Cotton	Berseem		9.0 9.0				Ibrahim Shaanon
	2	285 286			Cotton	Flax		11.0 11.0				Ansaf El-Badri
	3	283 284			Cotton	Flaz		5.0 7.0				Ibrahim El-Badri
	4	281 282			Cotton	Wheat		6.0 6.0				Hanem El-Baragi
	5	279 280			Cotton	Wheat		7.0 5.5				Aziza Ismail
	6	277 278			Cotton	Wheat		5.5 8.5				Abdel Hai Sultan
	7	275 276			Cotton	Berseem		14.0 9.0				Moustafa Gadallah
	8	269 272	270 273	271 274	Cotton	Berseem		5.5 11.5	6.0 5.5	11.0 5.5		Ahmed Abdel-Rahman
	9	263 266	264 267	265 268	Cotton	Flax		9.5 8.5	8.0 5.5	20.0 10.0		Azzah El-Garoon
	10	261 262			Cotton	Berseem		21.5 —				Sobhi Gadallah
	11	259 260			Cotton	Wheat		11.0 9.5				Mohamed Gadallah

Table A2 - Continued

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Matarine 1	12	353 354			Cotton	Berseem		7.0 5.5				
	13	351 352			Cotton	Wheat		5.5 5.5				Hanem Mossa
	14	349 350			Cotton	Flaz		5.5 5.5				Ibrahim Gadallah
	15	347 348			Cotton	Wheat		8.0 4.0				Hassain Thabet
	16	303 304			Cotton	Wheat		5.0 5.5				Mohamed Henish
	17	301 302			Cotton	Wheat		5.0 7.0				Om Ibrahim Ahmed
	18	299 300			Cotton	Wheat		10.0 16.0				Saad Asaad
	19	297 298			Cotton	Flax		6.0 4.0				Mohieldine El Shabry
	20	291 294	292 295	293 296	Cotton	Wheat		11.0 8.5	8.5 5.0	5.0 3.0		Abdel Atif Farag
	21	289 290			Cotton	Flax		6.0 8.5				Ibrahim Shaanon

Table A2 - Continued

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus(P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m3/F	ppm	ppm	ppm	F	
Matarine 2 with a total area of [illegible] Fed. Planted to Rice	1	233 234			Cotton	Wheat		9.5 18.0				Mohamed Hamad
	2	235 236			Cotton	Wheat		9.0 8.5				Mohamed Issa
	3	237 240	238 241	239 242	Cotton	Flax		12.5 6.0	5.0 4.0	7.0 12.0		Abdel Hamid Ahmed
	4	243 244			Cotton	Wheat		9.0 8.5				Karima Zaahra
	5	245 246			Cotton	Flax		8.5 5.0				Bedir Shalaby
	6	247 250	248 251	249 252	Cotton	Wheat		11.5 8.5	7.0 8.0	11.5 11.0		Hanem Saleh
	7	253 254			Cotton	Bean		9.0 7.0				Mohamed El-Asnag
	8	255 256			Cotton	Flax		8.5 11.5				Amina Hussain
	9	257 258			Cotton	Flax		21.5 10.5				Ahmed Abdel-Baki
	10	305 308	306 309	307 310	Cotton	Wheat		8.5 9.0	4.0 8.0	7.0 9.0		Mabrouka Gadallah
	11	311 314	312 315	313 316	Cotton	Flax		5.0 5.5	4.0 5.0	2.5 4.0		Abdel Alim Gadallah

Table A2 - Continued

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Matarine 2	12	317 318			Cotton	Wheat		5.0 7.0				Salem Maari
	13	319 322	320 323	321 324	Cotton	Berseem		8.5 5.5	5.5 4.0	8.0 —		Abdel Alim Gadallah
	14	327 328			Cotton	Berseem		7.0 5.5				Mansour Abdel Rahman
	15	329 330			Cotton	Wheat		11.0 6.0				El Zarif Ibrahim
	16	331 332			Cotton	Flax		5.5 4.0				Moustafa El Mallah
	17	333 334			Cotton	Flax		5.0 8.0				Taha Mansour
	18	335 336			Cotton	Flax		5.5 5.0				Mohamed El Sokkary
	19	337 338			Cotton	Flax		14.0 8.5				Gamil Eliwa
	20	339 340			Cotton	Berseem		4.5 9.0				Hamada Eliwa
	21	341 342			Cotton	Wheat		9.5 9.0				Ibrahim Eliwa
	22	343 344			Cotton	Berseem		6.0 9.5				Hamad Elsawi
	23	345 346			Cotton	Berseem		5.5 8.0				Khadr Khadr

Table A2 - Continued

Hod ID	Farm ID	Soil Sample ID 0-20 cm.	Soil Sample ID 20-40 cm.	Soil Sample ID 40-60 cm.	Previous Crops		Manure	Phosphorus (P) Values 0-20 cm.	Phosphorus (P) Values 20-40 cm.	Phosphorus (P) Values 40-60 cm.	Farm Size	Farmer Name
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Bakir 1 with a total area of Fed. Planted to Rice	1	143 144			Cotton	Berseem		7.0 7.0				El Shawadfi Attia
	2	145 148	146 149	147 150	Cotton	Berseem		5.5 6.0	8.0 2.5	4.5 4.5		Abdel Aziz Abdel Hadi
	3	151 152			Cotton	Flax		4.5 4.5				Helal Zayed
	4	153 154			Cotton	Flax		5.5 9.5				Mahmoud Attia
	5	155 156			Cotton	Flax		9.5 6.0				Mohamed El-Zayaat
	6	157 158			Cotton	Flax		7.0 5.0				Sayed Barakah
	7	159 160			Cotton	Wheat		6.0 9.5				Yosef Barakah
	8	161 164	162 165	163 166	Cotton	Berseem		8.5 9.0	13.0 9.0	9.0 9.5		Seham Zayed
	9	167 168			Cotton	Flax		4.0 8.0				Khadra Zayed
	10	169 170			Cotton	Wheat		9.0 5.0				Lotfia Ismail
	11	171 172			Cotton	Flax		5.5 7.0				Ibrahim Ismail

Table A2 - Continued

Hod ID	Farm ID	Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
		0-20 cm.	20-40 cm.	40-60 cm.	Summer	Winter		0-20 cm.	20-40 cm.	40-60 cm.		
							m^3/F	ppm	ppm	ppm	F	
Bakir 1	12	173 174			Cotton	Berseem		7.0 5.5				Saber Ismail
	13	175 176			Cotton	Berseem		5.5 5.5				Basioumi Salem
	14	177 180	178 181	179 182	Cotton	Wheat		5.5 6.0	5.5 4.0	4.0 5.0		Ibrahim El Sherbini
	15	183 184			Cotton	Wheat		7.0 5.0				Fawzy Kenebar
	16	185 188	186 189	187 190	Cotton	Flax		5.5 18.0	9.0 11.0	5.5 13.0		Fawzy Kenebar
	17	191 192			Cotton	Flax		4.0 5.5				Abdel Rahman Shalaby
	18	193 194			Cotton	Flax		6.0 5.0				Abdel-Monem El-Shinnawy
	19	195 196			Cotton	Berseem		5.5 5.5				Abdel-Monem El-Shinnawy

Table A2 - Continued

		Soil Sample ID			Previous Crops		Manure	Phosphorus (P) Values			Farm Size	Farmer Name
od ID	Farm ID	0-20 cm.	20-40 cm.	40-60 cm.				0-20 cm.	20-40 cm.	40-60 cm.		
					Summer	Winter	m3/F	ppm	ppm	ppm	F	
Bakir 2 with a total area of [illegible] Fed. Planted to Rice	1	231 232			Cotton	Berseem		6.0 7.0				Shaheen Shaheen
	2	129 130			Cotton	Wheat		4.5 4.0				Mohamed Hamad
	3	131 132			Cotton	Flax		6.0 5.5				El Said Mossa
	4	133 136	134 137	135 138	Cotton	Flax		5.5 4.0	4.4 6.0	4.0 8.0		Fatahalla El Naggar
	5	139 140			Cotton	Flax		5.5 5.0				Mohamed El Naggar
	6	141 142			Cotton	Berseem		5.5 4.0				Ali El- Naggar
	7	197 198			Cotton	Berseem		5.0 6.0				Abdel-Maabad Salem
	8	199 202	200 203	201 204	Cotton	Flax		7.0 9.0	5.0 5.5	5.0 5.0		El Sayed Salem
	9	205 208	206 209	207 210	Cotton	Wheat		6.0 9.5	5.0 8.5	5.0 4.5		El Sayed Salama
	10	211 214	212 215	213 216	Cotton	Berseem		5.5 8.0	6.0 8.5	5.0 5.5		Fahmi Beltagi
	11	217 218			Cotton	Wheat		9.5 16.0				Yonis Helal

Table A2 - Continued

Mod ID	Farm ID	Soil Sample ID 0-20 cm.	20-40 cm.	40-60 cm.	Previous Crops		Manure	Phosphorus (P) Values 0-20 cm.	20-40 cm.	40-60 cm.	Farm Size	Farmer Name
					Summer	Winter	m^3/F	ppm	ppm	ppm	F	
Bakir 2	12	219 220			Cotton	Berseem		9.5 16.0				Abdel Fattah Attia
	13	221 222			Cotton	Flax		6.0 8.0				El Said Hashem
	14	223 224			Cotton	Flax		6.0 6.0				Wafik Shahin
	15	225 226			Cotton	Wheat		7.0 8.0				Fathi Shahin
	16	227 228			Cotton	Berseem		12.0 8.5				Farida El Shobki
	17	229 230			Cotton	Wheat		4.0 5.5				Moustafa Shahren

Fig. A1 - Soil Phosphorus, PPM

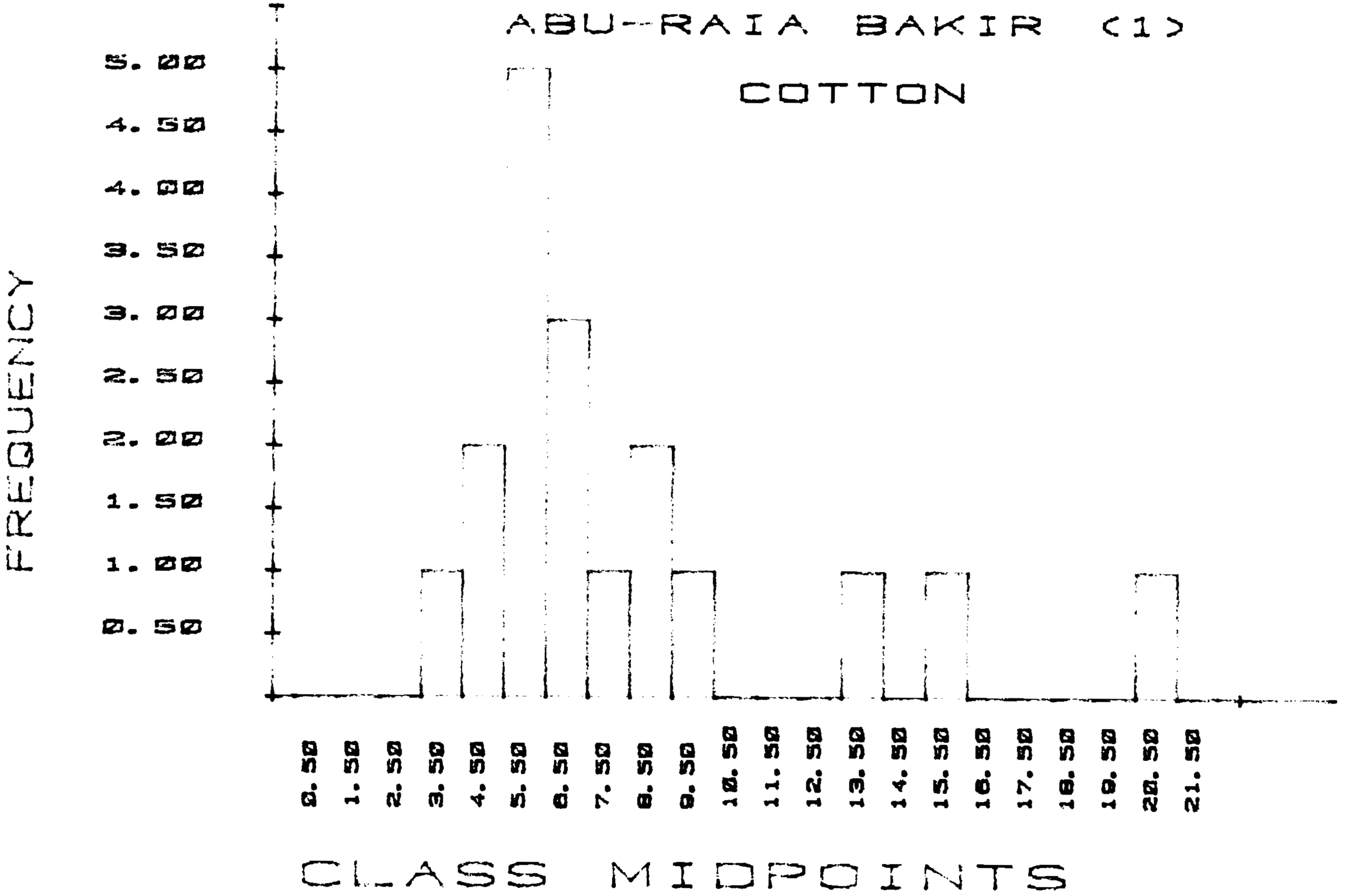


Fig. A1 - Log of Soil Phosphorus Values in PPM

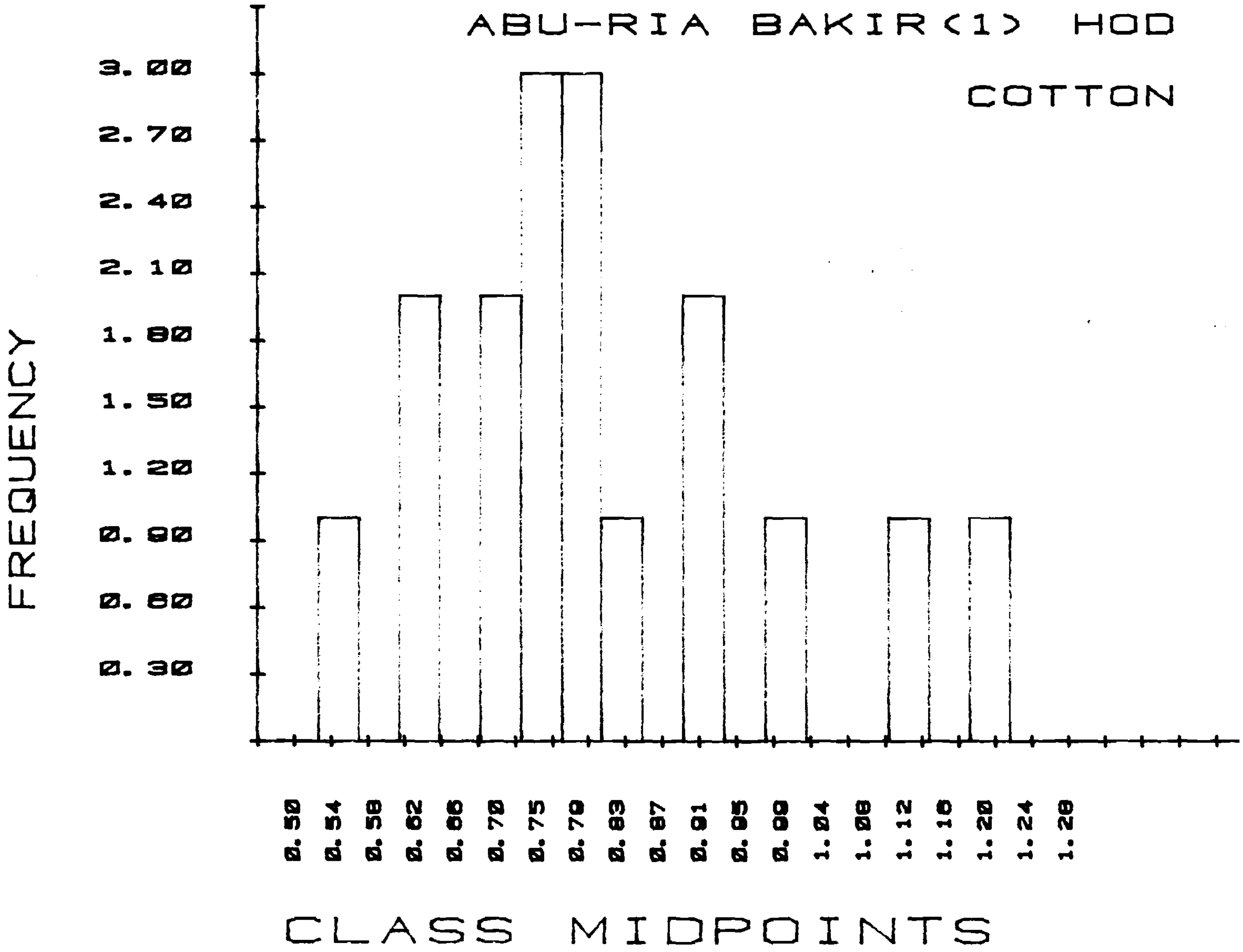


Fig. A1 - Soil Phosphorus, PPM

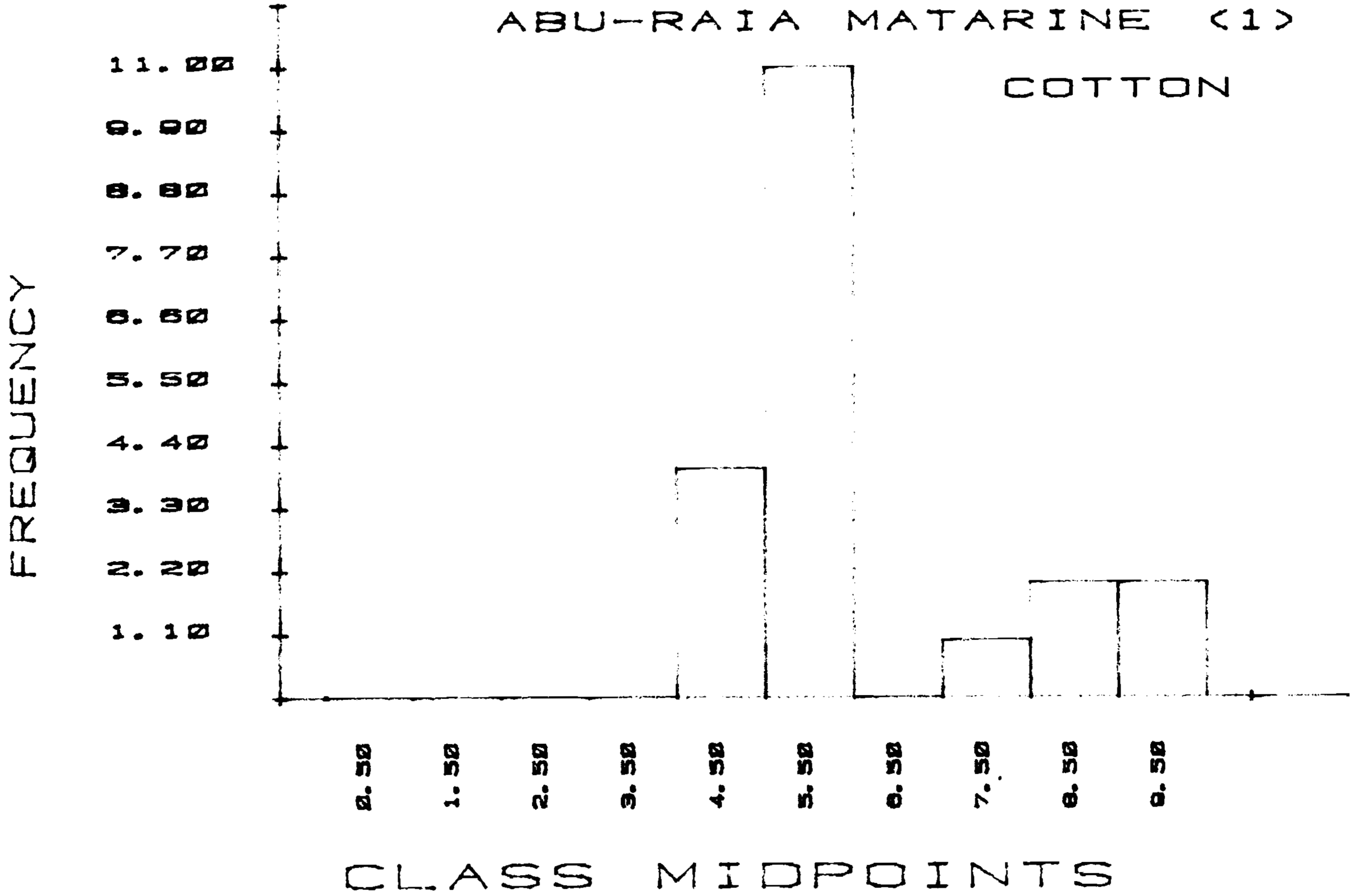


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Fig. A1 - Log of Soil Phosphorus Values in PPM

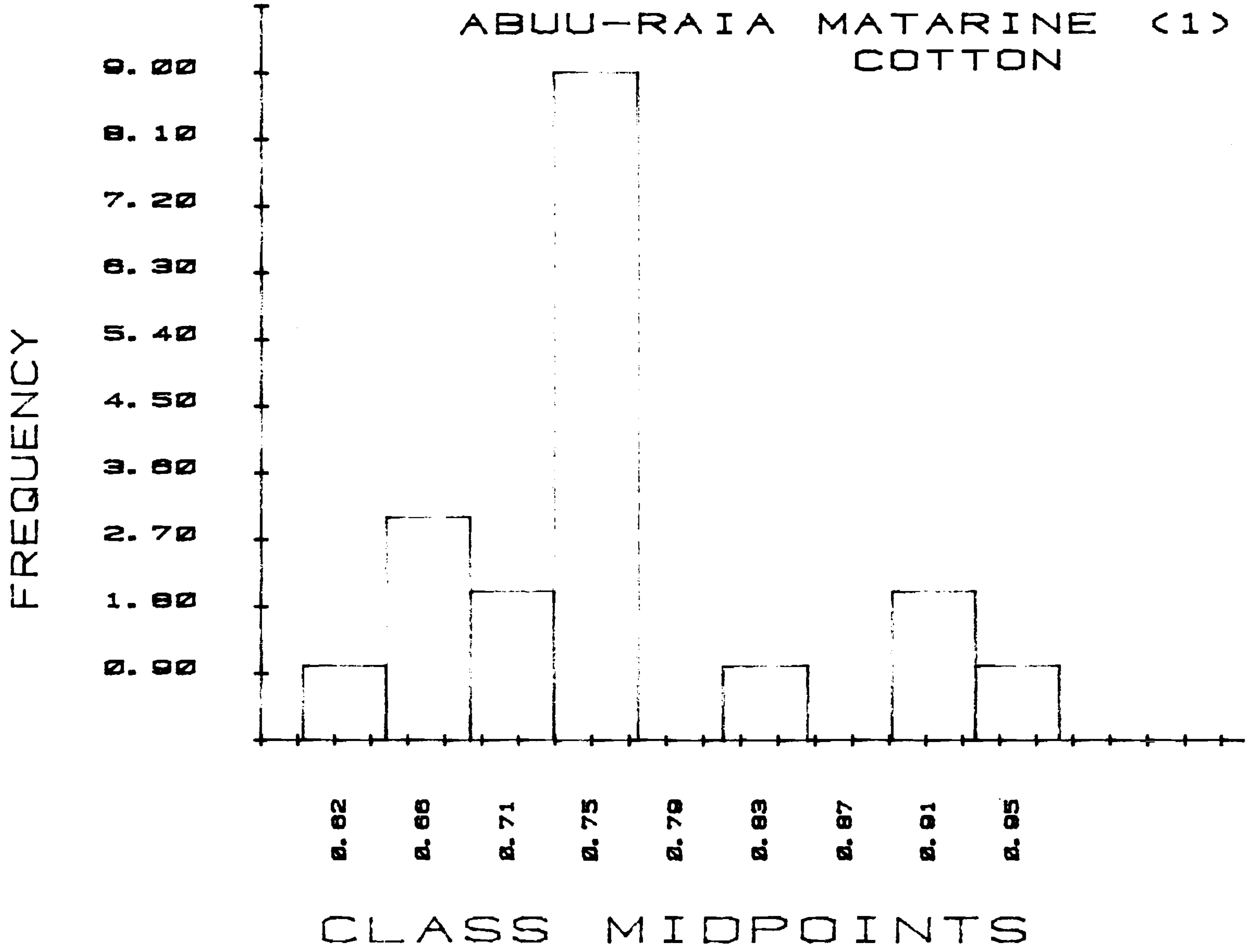

Fig. Al - Soil Phosphorus, PPM

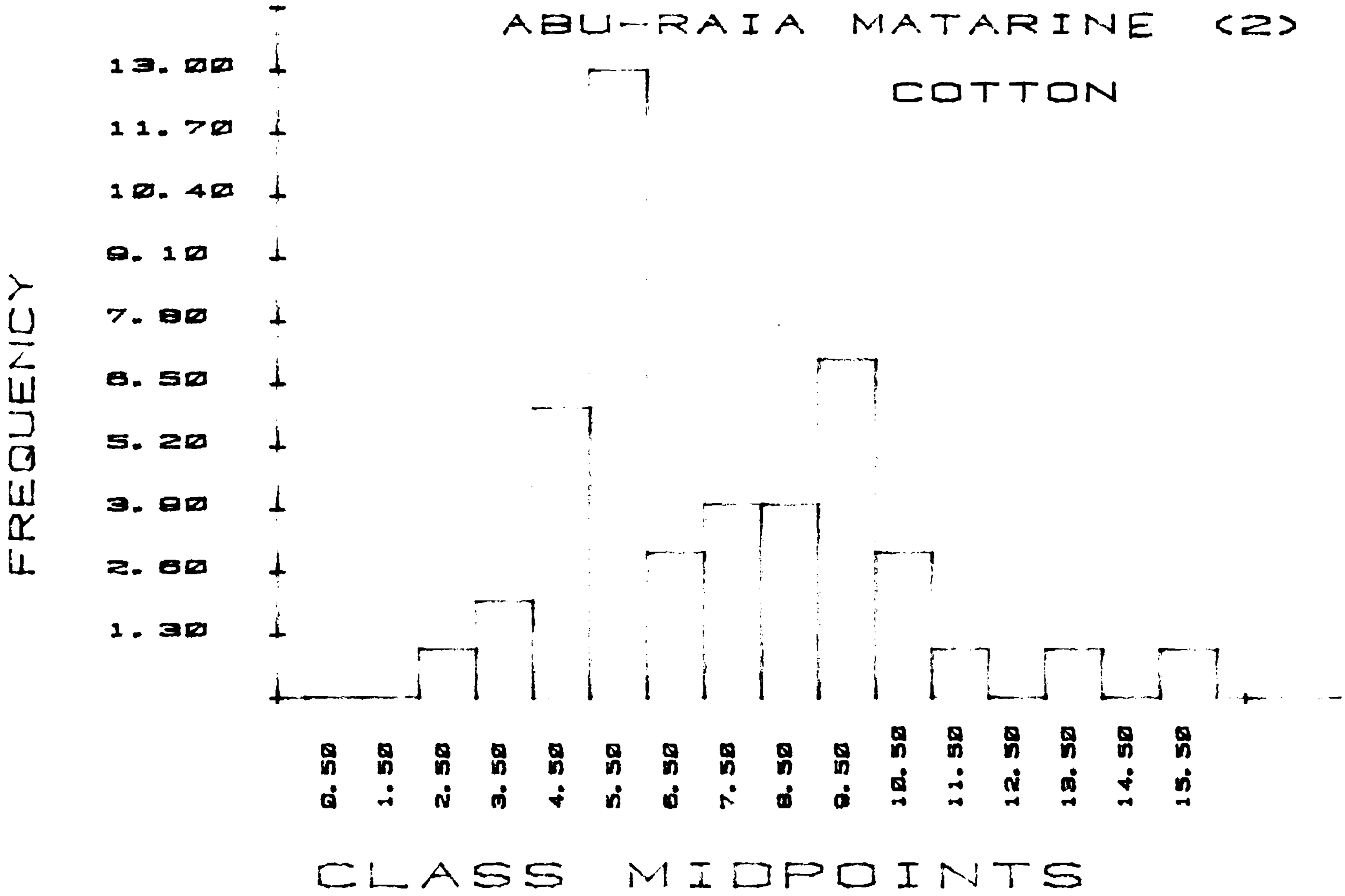

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Fig. A1 - Log of Soil Phosphorus Values in PPM

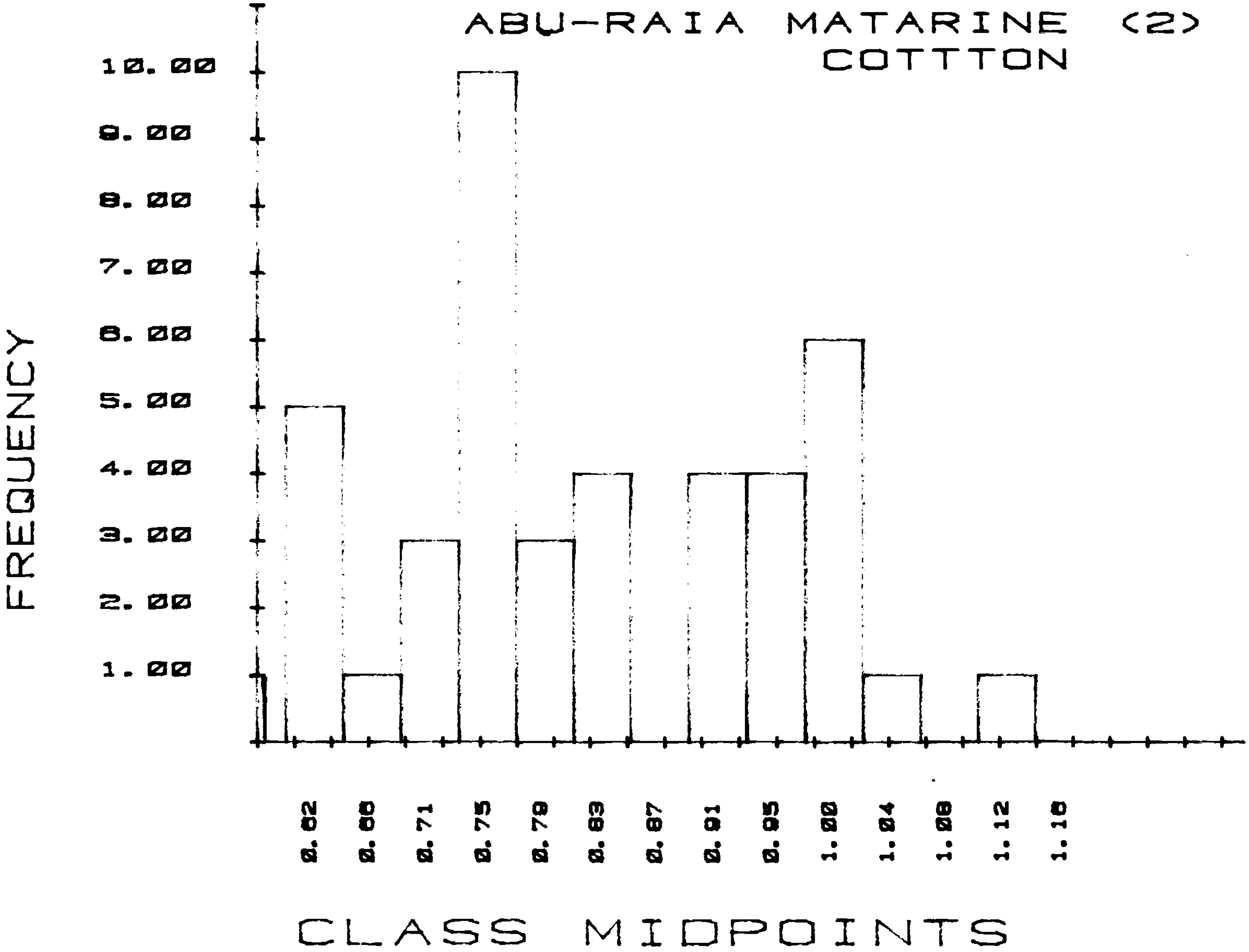

Fig. A1 - Soil Phosphorus, PPM

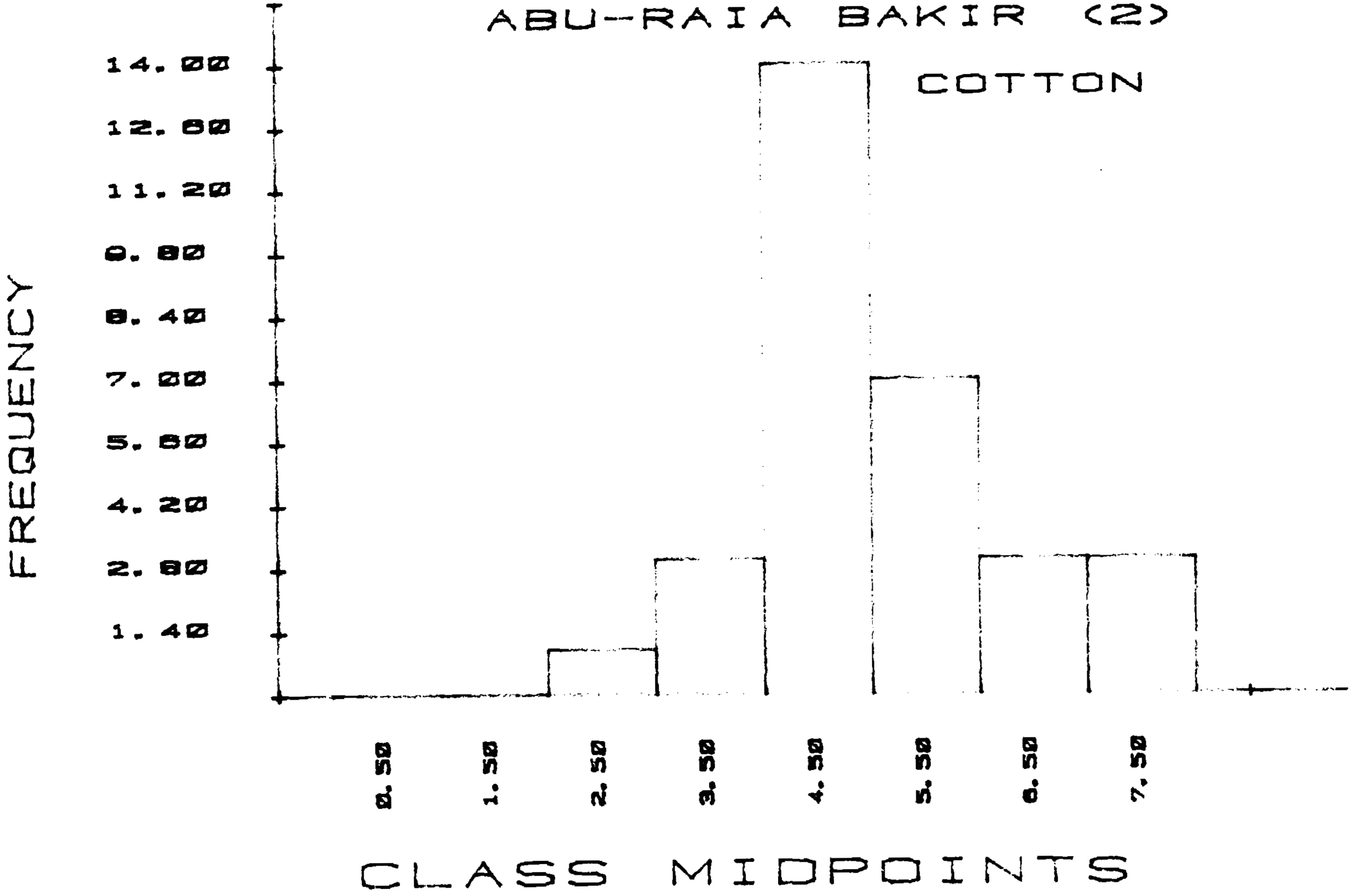

Fig. A1 - Log of Soil Phosphorus Values in PPM

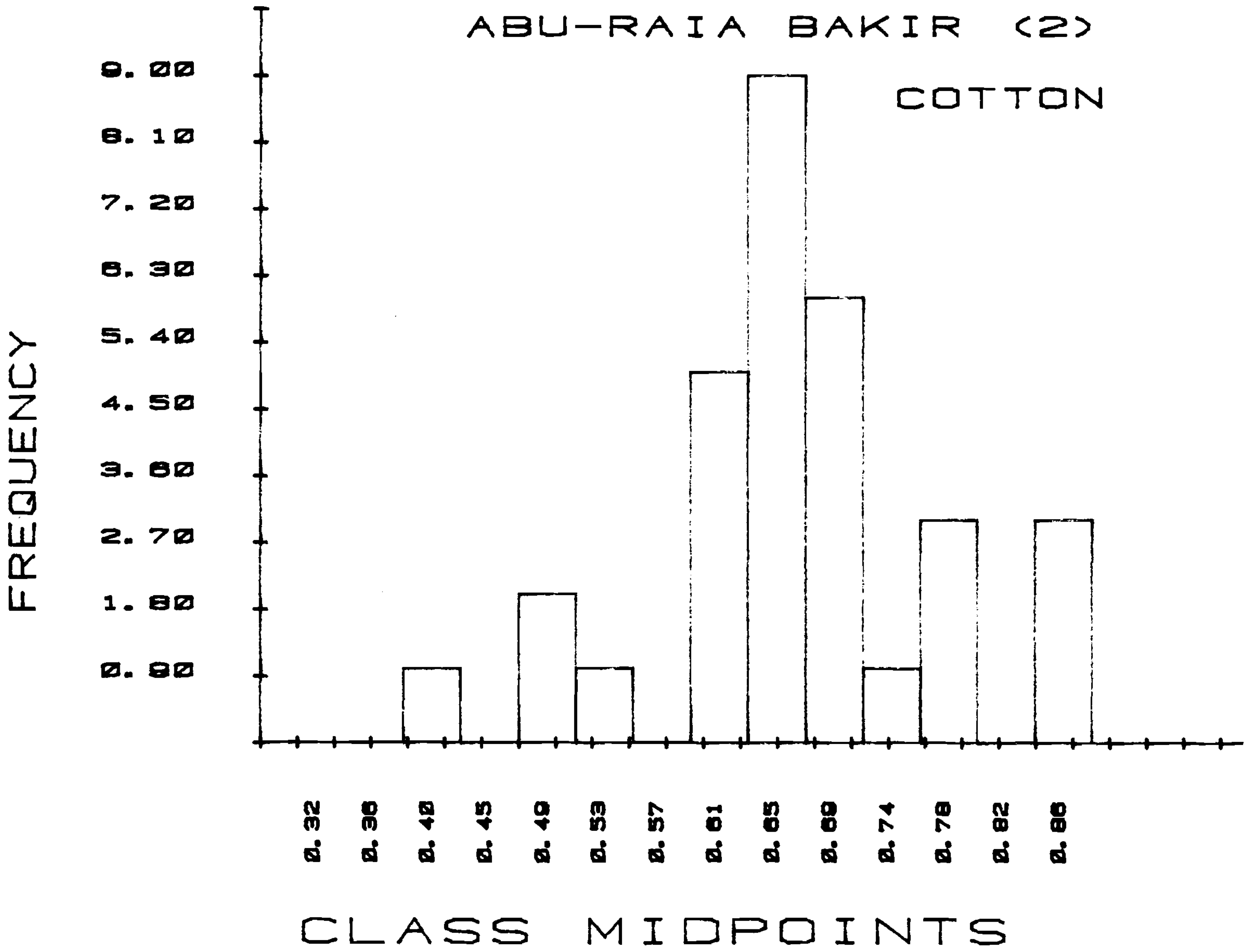

Fig. A2 - Log of Soil Phosphorus Values in PPM

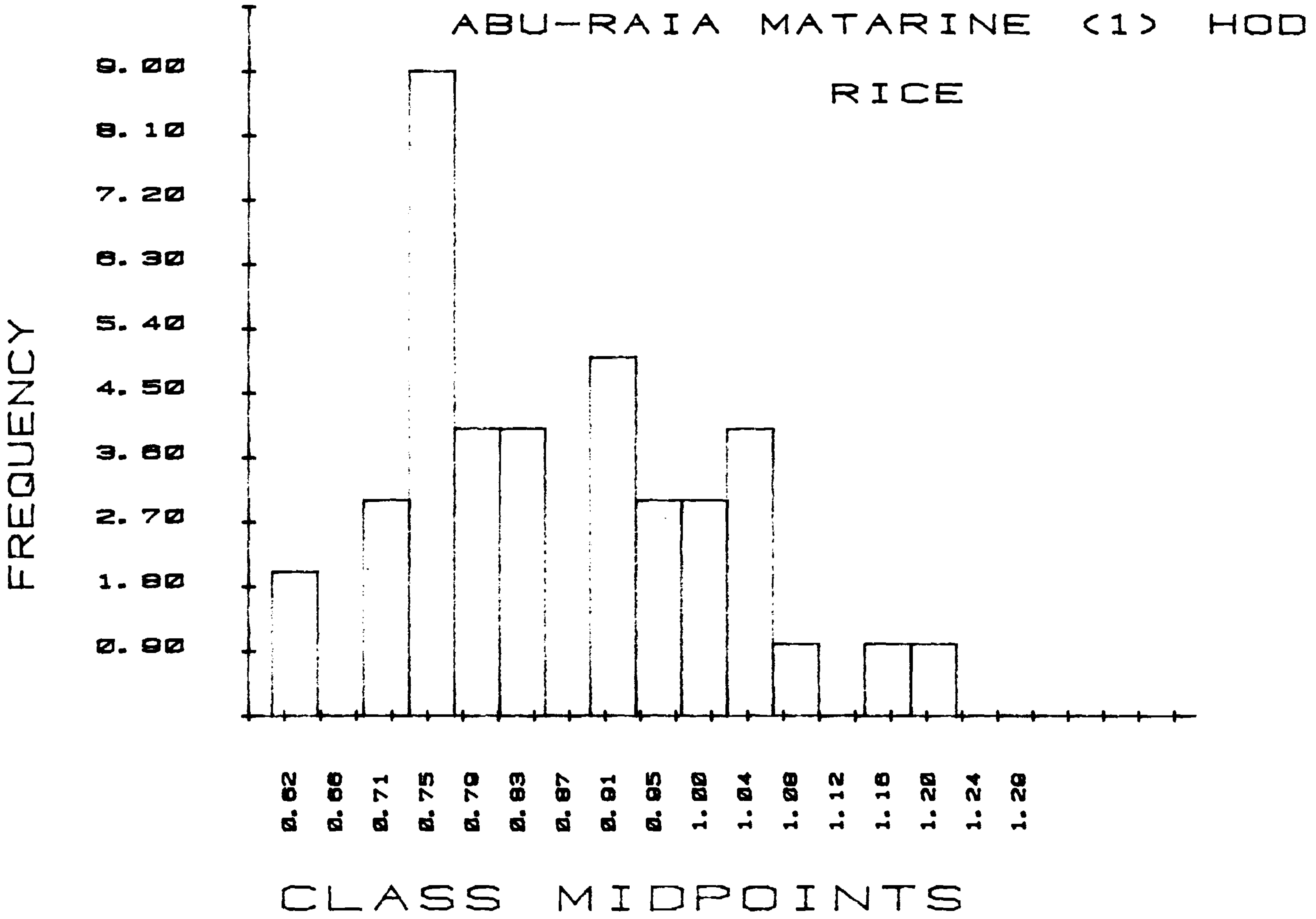

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Fig. A2 - Soil Phosphorus, PPM

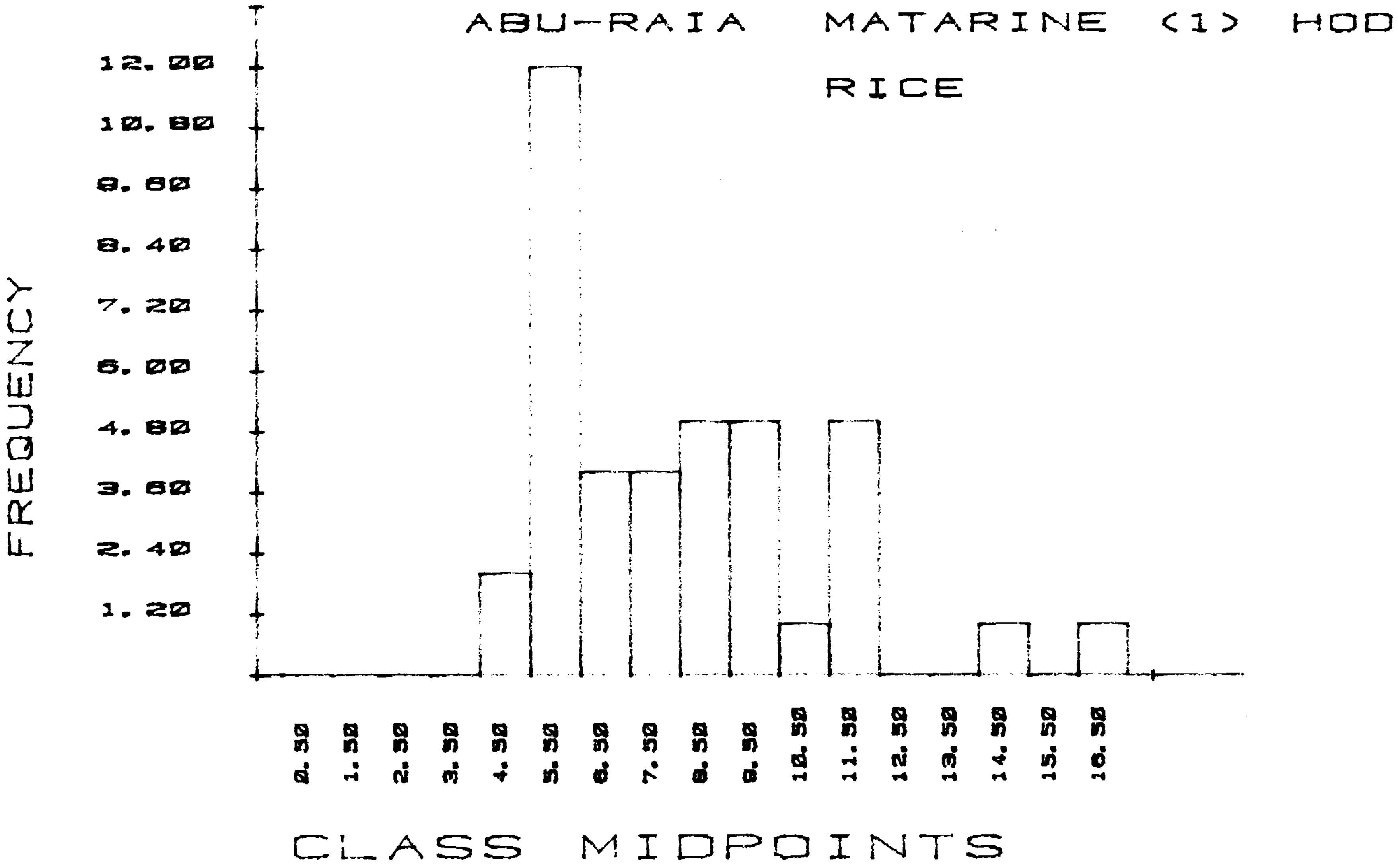


Fig. A2 - Soil Phosphorus, PPM

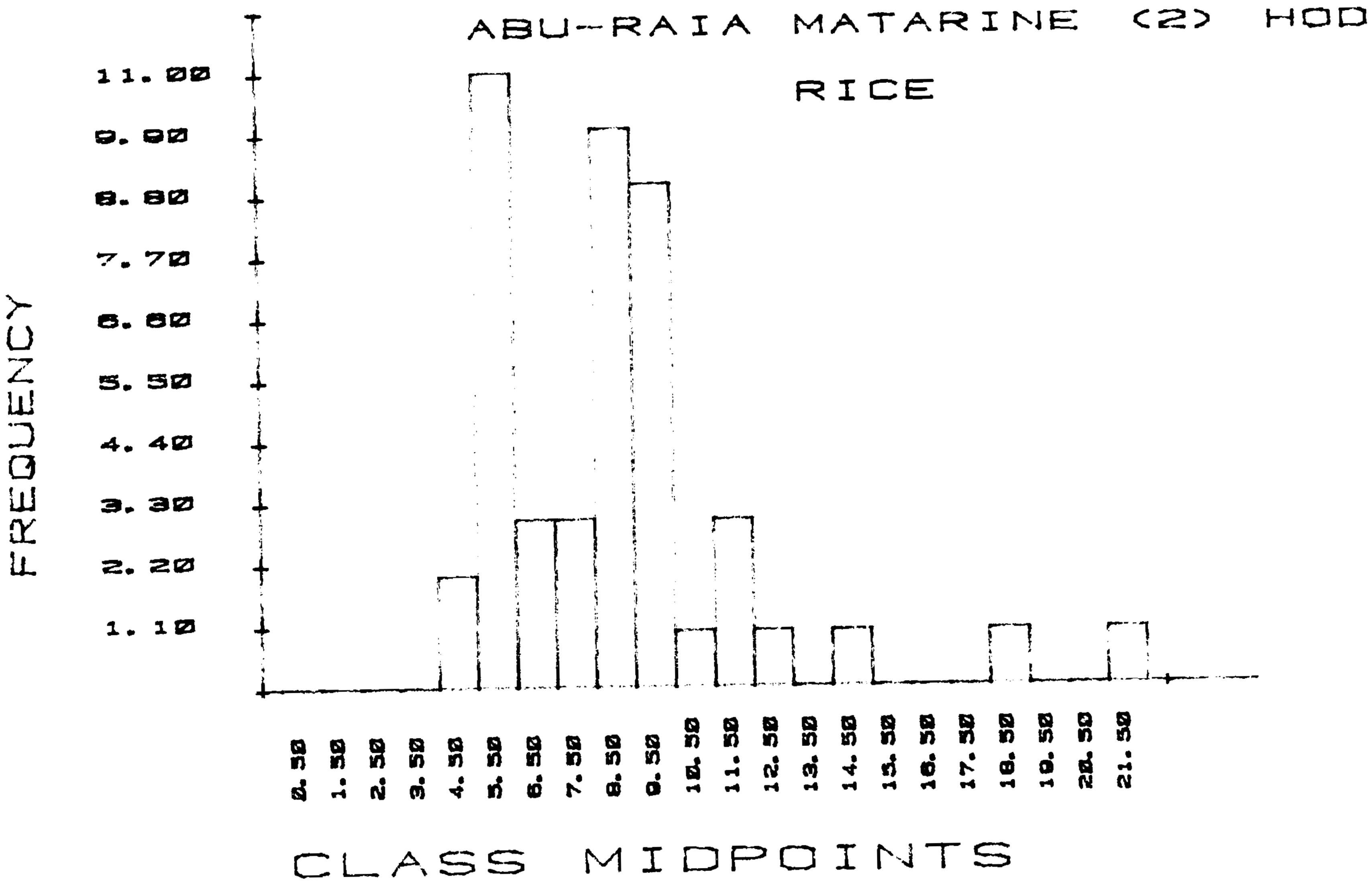


Fig. A2 - Log of Soil Phosphorus Values in PPM

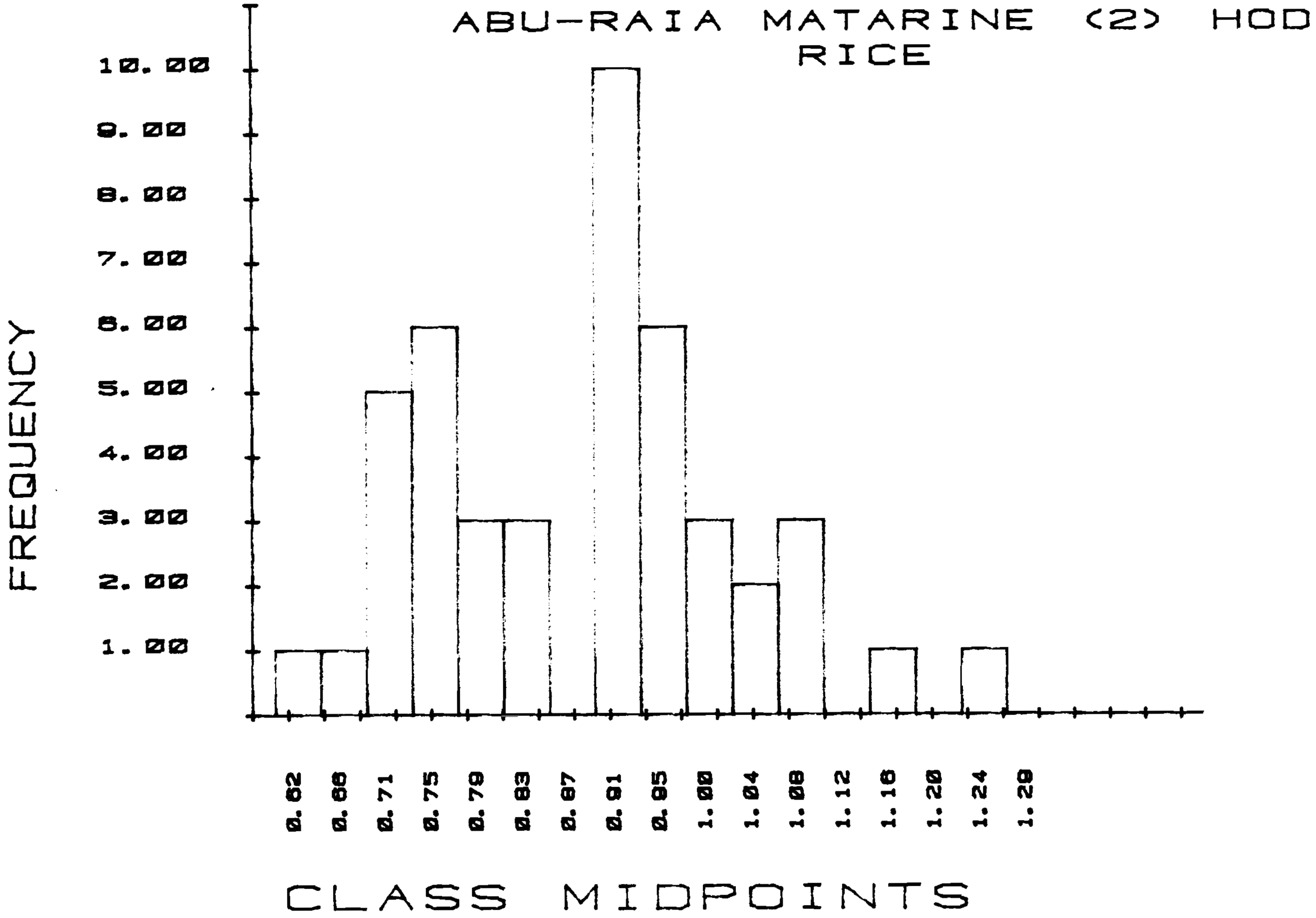


Fig. A2 - Soil Phosphorus, PPM

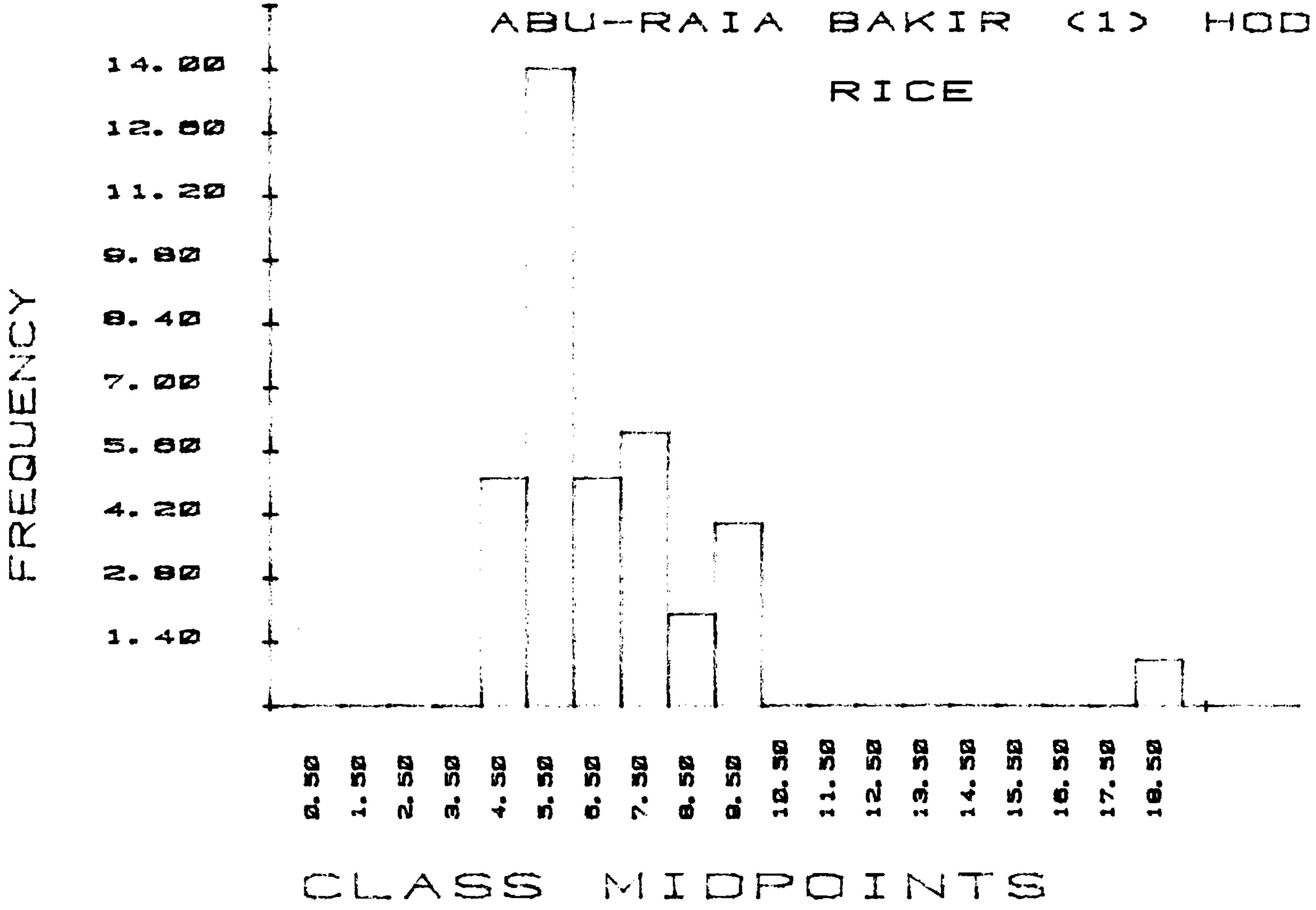


Fig. A2 - Log of Soil Phosphorus Values in PPM

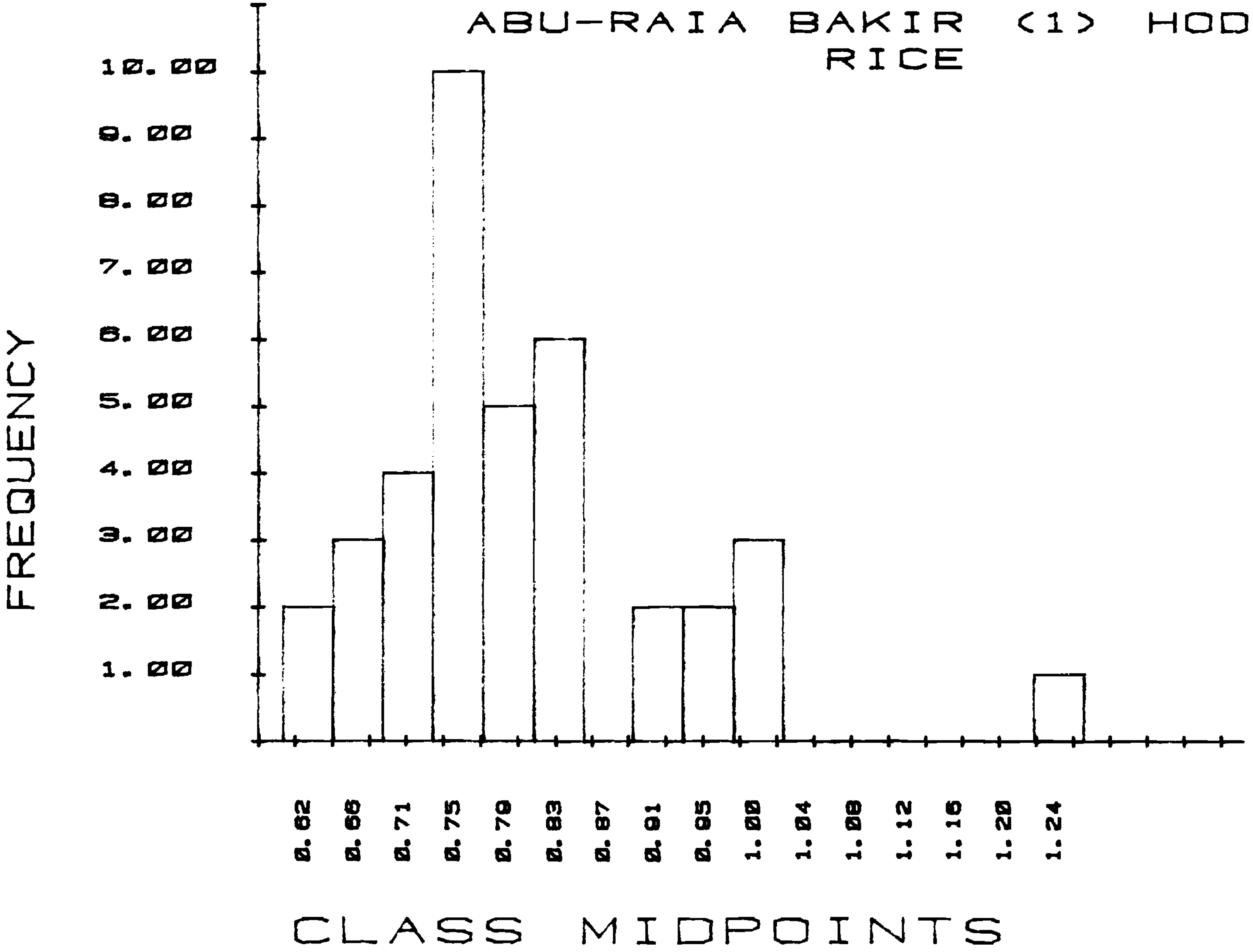


Fig. A2 - Soil Phosphorus, PPM

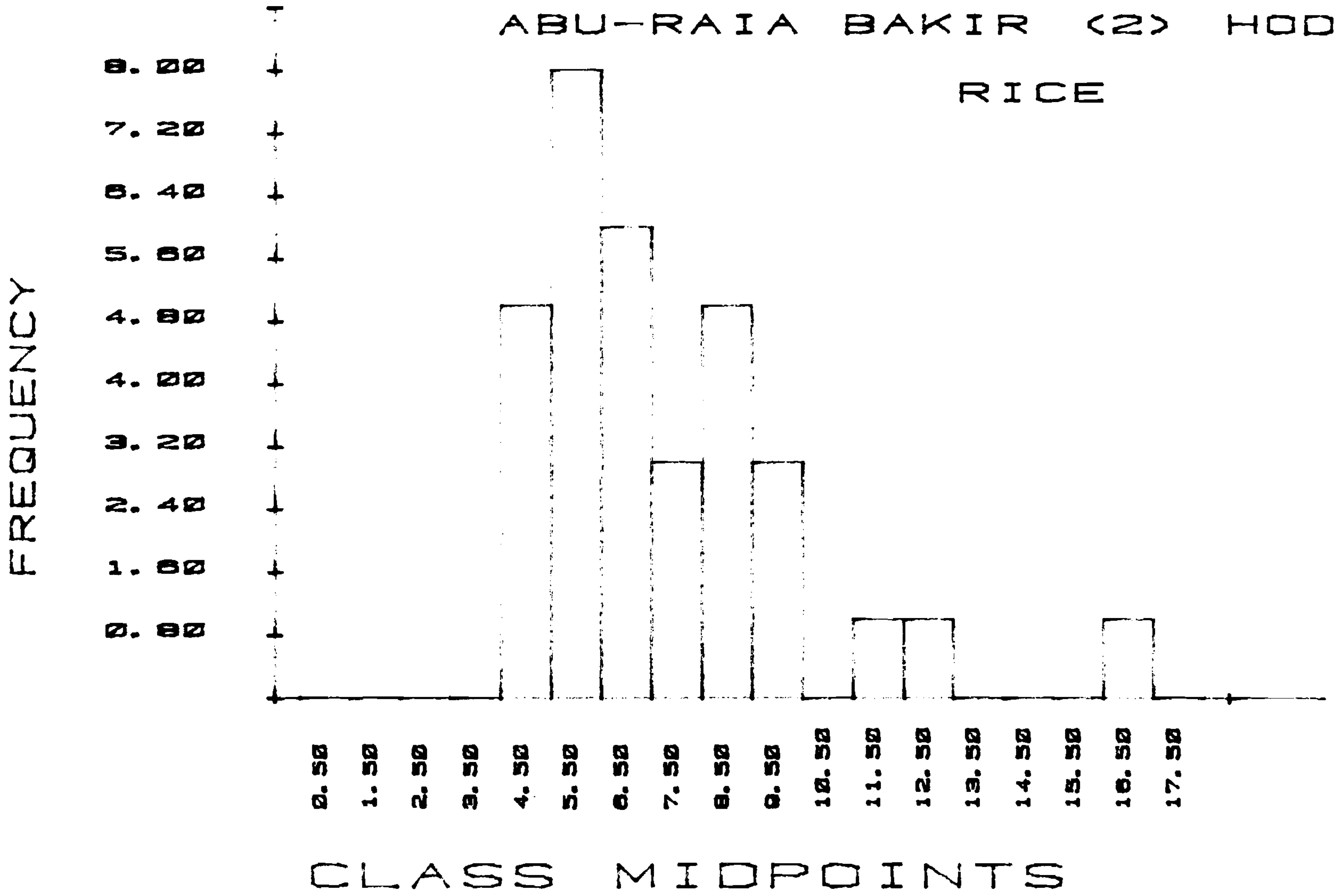
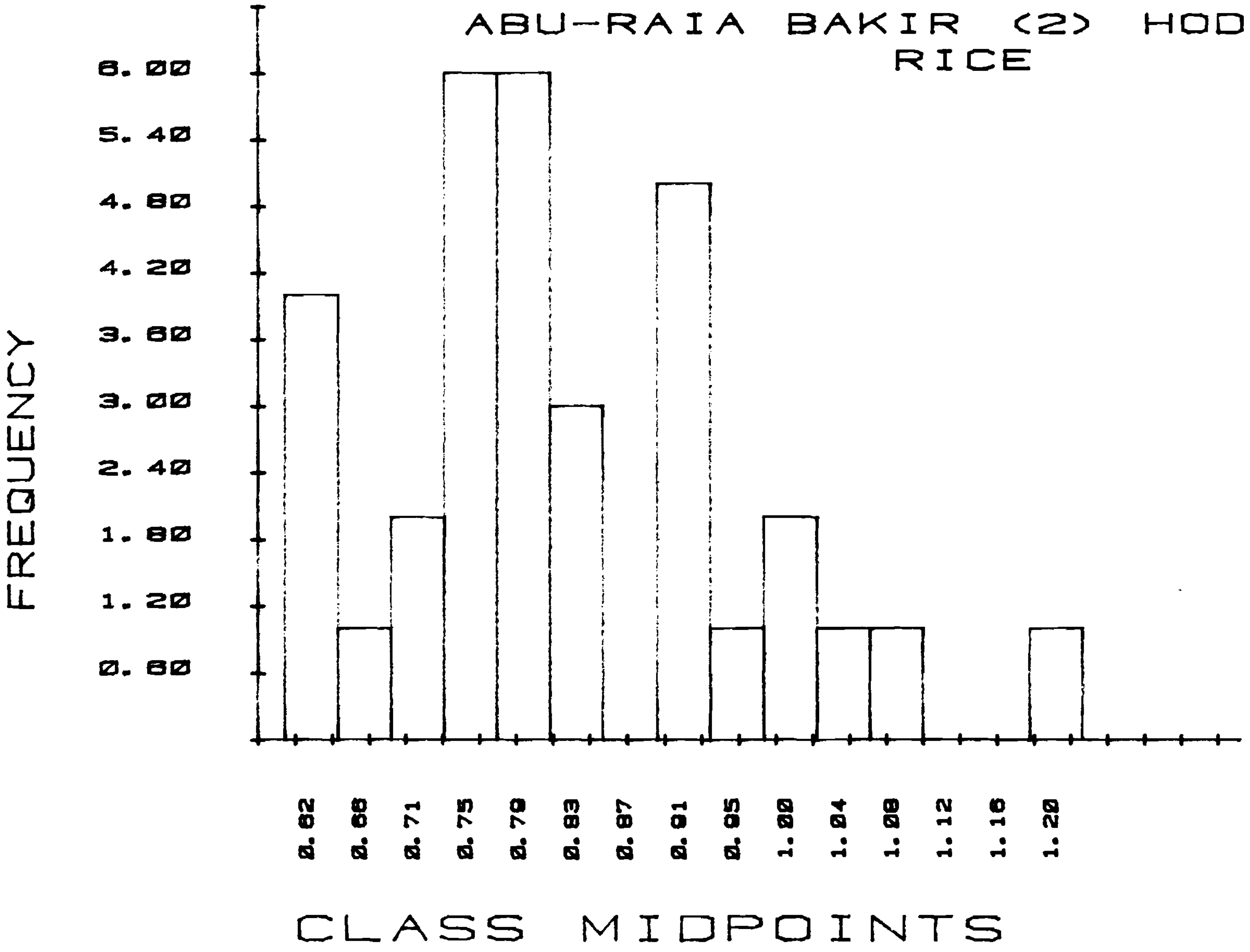


Fig. A2 - Soil Phosphorus Values in PPM



Staff Paper #44

SOIL AND LAND CLASSIFICATION

R. D. Heil

January, 1979

Introduction

A. Soil Classification

1. Soil and Land Classification Approach

At the present time, soils are being classified at the higher taxonomic categories and according to salinity, sodium, texture and depth to water table.

The concern of both Dr. Dotzenko and Mr. Ahmed was that although the above criteria are needed for assessing the opportunities and/or constraints soils offer relative to irrigated agriculture, some of these, namely, sodium, salinity and depth to watertable can change, and groupings of soils with major emphasis on these variables may not adequately reflect the cause of a problem or provide soil units needed for expressing more comprehensive interpretive information.

Mr. Ahmed recognized the significance of this factor, thus one of his first requests of me was to aid in classifying the soils at the lower taxonomic categories, i.e. families, series and/or phases.

These efforts revealed that present criteria for classifying soils at the family category are adequate for describing textural properties which are significant for assessing factors important to irrigation management, i.e., water retention, movement and overall drainage regime. Some soils having extreme stratification, i.e., several thin layers of materials with widely different textural properties, were not reflected very well at the family level. It is suggested that these soils be identified either at the series or phase level.

In addition to classifying soils at the family level, it appears that several soil properties which are presently being observed, but not being considered for grouping soils, should be considered for developing series and/or phases of soils. These properties and their significance for being considered are discussed below.

Slickensides

A large number of the fine textured soils exhibit a characteristic defined as "slickensides". Slickensides reflect a high degree of shrink-swell and a potential for what is know as "self churning". Soils and/or soil layers exhibiting this characteristic contain a high proportion of shrink-swell type clays and have the ability to crack both vertically and horizontally upon drying. They may crack to depths of 1 meter or more.

This factor may be significant based on the fact that the depth at which these slickensided layers occur varies among soils as well as their thickness within soils. This relationship may be important relative to the following:

1. May affect the rate at which water tables rise and fall.

2. If soils are cracked, excessive water may be required to wet these soils.

3. Irrigation of the soils when cracked causes the soil to wet from the bottom of the cracks upward and may influence salt movement within the profile.

4. High shrink-swell potential may affect the cost of installing and maintaining both closed and open drain systems.

In summary, the presence and/or absence and/or extent of cracking, both by degree and by depth may significantly effect the drainage, salinity, alkalinity and water movement characteristics in these soils.

Gypsum

Free gypsum has been described as being present within a depth of 150 cm in a number of soil profiles. This property may be useful for assessing the drainage relationships among soils.

Pores and Soil Structure

Many of the fine-textured soils, dependent on the particular horizons, are described as having many observable pores present in the soil structural units, particularly at lower depths in the profile. This property as well as the grade, type and size of structural units should be considered in terms of their potential relationship to permeability. Extent of pore space in these soils indicates a relatively high permeability not normally associated with soils being this fine-textured. Suggests a relatively high drainage potential.

Mottling and Presence of Manganese Concretions

Mottling, which is an indicator or poorly drained soil conditions appeared to be absent in most of the soils, although water tables are present at shallow depths.

Presently my interpretation of this is that first, although the soils are wet for long periods of time, oxygenated water being added is moving through the soil at a sufficient rate such that the soil water does not become de-oxygenated (this rationale seems to be supported by the fact that soil porosity and internal soil drainage potential is high). On the other hand, the inherent dark color of the soil, which results from the presence of dark minerals, may mask any evidence of "gleization" i.e., (evidence of reducing conditions by the presence of blue, bluish gray colors), and in fact reducing conditions are present for long periods of time. So much so that reddish colored mottler, which along with bluish, bluish gray colors reflect oxidation reduction cycles

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in soils, are absent indicating that reduction is the dominant process. This latter rationale seems to be supported by the presence of maganese concretions of varying amounts occuring at various depths in the soil which indicated that reducing conditions are the rule.

The presence and/or absence of mottling and manganese concretions should be considered initially to aid in determining potential soil wetness.

Root Distribution and Habit

Typically, root development in fine-textured soils and more so, in fine-textured soils exhibiting high shrink-swell properties as well as texture variation with depth can be adversely affected. Size, distribution and general root habit of crops being grown should be characterized whenever possible.

In summary, it appears that consideration of soil properties such as slickensides, structure, color, $CaCO_3$, gypsum, mottling, porosity characteristics, consistency and texture may be key to differentiating soil series and/or phases.

My suggestion is that the soils be described and classified first using characteristics such as these and then the salinity, sodium and depth to watertable characteristics be defined within each groups. If this is not done, then it becomes difficult to determine which factor or set of factors are contributing mostly to soil behavior, i.e., management, inherent soil properties, etc.

One concern relative to including or using the previously discussed factors for providing soil classification and subsequent interpretive groupings, is the question of whether or not some of the soil properties discussed are an expression of past or current day soil forming conditions or to particular soil characterics. For example, the variation in the degree and extent of slickenside development may be the result of differences in mineralogy, differences in degree of wetting and drying cycles - past and/or current conditions, or all or a combination of these factors. It will be important to keep this factor in mind when attempting to evaluate these properties in terms of being useful for developing interpretations applicable to the present day irrigation and crop management systems.

Mr. Ahmed and myself initiated efforts toward grouping soils according to the properties described. The significance of usefulness of these groupings only can be determined based on correlation of research observations and findings obtained from this study.

2. Recommendations for Soil and Land Classification Effort

Attached is a research paper entitled "Distribution Patterns of the Weld-Rago Soil Association in Relation to Research Planning and Interpretation" by Fly and Romine. The paper describes research efforts, the results of which illustrate the significance of quantifying soil property relationships both from the standpoint of their importance for

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evaluating soil management needs and for extrapolating and projecting research results.

Classification of soils on the basis of soil taxonomy is a necessary first step. However, in addition to this type of classification and subsequent development of specific property groups such as salinity, sodium and depth to watertable, it is necessary to evaluate the relationships between other potentially significant soil properties and crop production and/or irrigation management systems. This approach will make soil survey data more applicable to a given situation, i.e., more local interpretive value. The attached paper can serve as a basis for initiating this type of approach.

Initiation of this type of effort of course will mean more participation by Mr. Ahmed in the project. In addition, it would be very desirable for Mr. Ahmed to spend four to six weeks at Colorado State University to participate in on-going activities here which are directed toward using a "Quantitative Pedological" approach for developing "soil and/or land management interpretive" data. It is recommended that serious consideration be given to assigning Mr. Ahmed on a TDY basis to Colorado State University for a period of four to six weeks during late summer of 1979.

The main objective of this effort would be for Mr. Ahmed, using EWUP soil characterization and other data and utilizing mathematical and statistical programs available through our project, develop potential soil management interpretive groupings. Following this, efforts would be made to establish procedures for correlating data obtained from the research projects on the basis of specific soil groupings. This then will allow for defining meaningful soil interpretive groupings which would result based on the results obtained through the course of the research project.

This recommendation is made because it appears that the soils both on and among the different project areas are sufficiently different in their management potentials and/or constraints to warrant intensive study.

B. Field Survey Program

My observations were that Mr. Ahmed and his survey party are conducting a technically sound survey program. Survey progress is necessarily slow because of the number of observations required and soil conditions, which require that pits be opened in order to accurately observe, describe and sample the soils. Wet soil conditions almost preclude the use of augers or probes for studying the soils.

Mr. Ahmed and I visited extensively concerning the need for the number of observations being taken and concluded that the present effort is justified. The amount of detailed data now being collected will provide several things, namely, will allow for critically needed data to determine the variability of soils across landscapes and secondly to identify specific soil-site conditions which can serve as a basis for collecting and categorizing research results, i.e., provide a basis for describing the component parts of the system which affect experimental results.

Mr. Ahmed and I did discuss however, the possibility of developing an interim soil map and accompanying soil descriptive information based on the field survey immediately following the field investigations rather than wait until all laboratory data becomes available before providing soil survey information.

This could be done in several ways:

1. Provide a soil map and soil descriptions based on soil families, series and/or phases which are developed using soil characteristics described earlier in this report or,

2. Same as above, but in addition make available to the survey party a "Field Soil Chemical Test Kit" which would allow for a semi-quantative evaluation of sodium, salinity and pH. The advantage of this procedure is that in addition to providing added information in an immediate way, would also provide for a screening procedure to determine the number and kind of samples that would be submitted for further laboratory analyses. The Soil Conservation Service has employed this procedure for several years with favorable success.

Also, the soil survey program could be enhanced if the following resources were made available:

a. A supply of new color books which include color charts for describing poorly drained soils.

b. Copies of "Soil Taxonomy". Presently these are not available to the capability of the field party personnel in identifying and describing soil properties of significance to classification.

c. Hand Soil Probes - although the utilization of probes and/or augers is restricted because of wet soil conditions, Mr. Ahmed indicated that sometimes it would be possible to observe the soil below 150 cm. in depth if small hand probes were available for use. The information that could be gained would be useful.

d. Sand Augers - needed for use on extremely sandy soils.

e. Portable Chemical Soil Analysis Kits - "Hach" kits are available at a relatively low cost which would provide the capability previously discussed.

In summary, the following points emerge regarding the soil survey field program.

a. The field summary program is being carried out on a highly technically sound basis.

b. Efforts should be made to publish an interm soil survey report based on field investigations which would be useful in project planning.

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c. Additional resources, as described would enhance the ability of the soil survey program to contribute to the project.

GENERAL SUMMARY

The following overall points emerged as a result of this effort:

1. Classification of soils at the lower taxonomic categories should enhance the useability of soils data in project planning and interpretations.

2. Grouping of soils separately from taxonomic units on the basis of salinity, sodium and depth to watertable should be altered such that the above characteristics be defined within the framework of taxonomic groups, i.e., families and/or phases. The development of maps showing salinity, alkalinity and depth to watertable should be continued as they are critical for assessing present conditions. However, in terms of developing irrigation management guidelines which have long-term implications, these should be correlated as much as possible with soil groups based on more permanent properties. It would appear that if this is not done, there is a high risk of not being able to relate responses of treatments to different variables and to their interactions.

3. An effort should be made to develop potential "soil management groups" based on permanent slowly changeable properties using a "quantitative pedological" approach. These units could then be tested using data being collected through the course of this study which, in turn should provide in the final analyses, meaningful soil management interpretations significant to local conditions.

4. Soil conditions do vary considerably within and among the project areas. The significance of soil differences cannot accurately be assessed at this point in time. The same amount of resources and effort being directed to other phases of the study need to be applied to the soil survey program if the effects of basic soil conditions on the project efforts are to be recognized. Another dimension with respect to the significance of giving adequate attention to this phase of the project is the question of the extent to which the project areas typify the soil conditions of the Delta area.

In conclusion, I would like to express my sincere appreciation to all project staff for being most helpful in providing background information and for their hospitality. I was very much impressed with the amount of work accomplished. I am most appreciative to have had the opportunity to learn and interact with the fine people associated with the project.

yield was only 0.1 tons per acre with corn (SM) producing an average of 3.8 tons per acre compared with 3.7 tons per acre from corn (R). Generally, in years when rainfall during the growing season was above average, the yield from corn (SM) was lower than that from corn (R). However, this yield differential was compensated for by higher yields from corn (SM) during years when growing season rainfall was below average. Corn yield was higher from corn (SM) in 9 location-years, 6 of which were dry years.

The yield relationship is expressed by the equation

$$Y = 3.75 - 1.51X,$$

where X is departure from the average growing season rainfall and Y is yield difference in bushels per acre of corn (SM) as compared to corn (R). The coefficient of correlation, using 15 years of data, was 0.69 which is significant at the 1% level.

The presence of the mulch had no apparent effect on corn height or color at any time during the growing season over the 9-year period of study. This is in contrast to the data of Larson et al. (4), who found that mulches generally decreased the early growth of corn in northern United States and attributed this decrease to the lower soil temperatures under the mulch.

LITERATURE CITED

1. Hays, O. E., McCall, A. G., and Bell, F. G. Investigations in erosion control and the reclamation of eroded land at the Upper Mississippi Valley Conservation Experiment Station near La Crosse, Wis., 1933-43. USDA Tech. Bull. No. 973. 1949.
2. ————, and Taylor, R. E. Conservation methods for the Upper Mississippi Valley (Fayette Soil Area). USDA Farmers' Bull. No. 2116. 1958.
3. Kidder, E. H., Stauffer, R. S., and Van Doren, C. A. Effect on infiltration of surface mulches of soybean residues, corn stover and wheat straw. Agr. Eng. 24 (5):155-159. 1943.
4. Larson, W. E., Burrows, W. E., and Willis, W. O. Soil temperature, soil moisture, and corn growth as influenced by mulches of crop residues. Trans. Intern. Congr. Soil Sci. 7th Madison. 1:629-637. 1960.
5. Wischmeier, Walter H. A rainfall erosion index for a universal soil-loss equation. Soil Sci. Soc. Am. Proc. 23:246-249. 1959.

Distribution Patterns of the Weld-Rago Soil Association in Relation to Research Planning and Interpretation[1]

CLAUDE L. FLY AND DALE S. ROMINE[2]

ABSTRACT

This study is concerned with criteria for predicting applicability to other soils of research results obtained from key or benchmark soils. Soil-water-plant growth relations which affect yields under different levels of management were evaluated at Akron, Colo. Under 46 years of uniform management, wheat production levels varied from 73 to 120 among eight soil types identified in a 25-acre test field formerly mapped as one soil type. Soil differences induced wider variations under uniform treatment than did different treatments on a single soil type. When the detail of delineation and characterization of soils is comparable to the detail of the research plot layout, existing research fields and plot data may be used to associate soil qualities with response to treatment. The reliability of application of research findings to other areas will depend on adequate characterization and evaluation of the soil in each plot.

FOLLOWING REORGANIZATION of the Soil Conservation Service and the Agricultural Research Service in 1954, impetus has been given to the interpretation of soil surveys for use in various endeavors such as conservation, engineering, and urban and rural planning. Mapping and characterization of soils on state and federal experimental fields was speeded up to improve interpretations of soil surveys and to facilitate more exact application of research data to soil management.

Guidelines are needed in interpolating or extrapolating the results obtained by research processes from one soil to other soil and soil-climate situations (1). The applicability of research findings or conservation experience to other soils and climates is, at present, largely a matter of opinion.

This study was made to determine, first, if existing research data could be used to help interpret benchmark soils on which research had been performed; and second, whether reliable criteria for prediction of applicability of results could be effectively developed.

PROCEDURES

Priority was given to research fields having *(a)* long records of reasonably uniform management and *(b)* contrasting soil types. A plot area for study was selected on the USDA Central Great Plains Field Station, Akron, Colo. which included 56 dryland rotations and tillage treatments on 152 plots, 8 by 2 rods in dimensions. Research on most of the field dated from 1908 through 1954,[3] but additional plots were added in 1924, 1928, and 1930 (2). The 25-acre field appears relatively uniform on the surface, and as late as May 1944 (2) published reports described it as being of one soil type.

Plots were selected to represent the production of winter wheat by *(a)* continuous cropping, *(b)* fallow and wheat, and *(c)* wheat following corn in a 4-year rotation. A very detailed study of the distribution of soil types and phases within the 25-acre field was made using a power probe. Soils were sampled at intervals of 100 feet on a uniform grid. Color, thickness, texture, and structure of horizons, depths to zones of carbonate accumulation, and the presence or absence of buried soils were recorded.

Paired profiles of Weld[4] loam and Rago loam were excavated to a depth of 5 feet and samples were taken by horizons for

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[1] Joint contribution from the Soil and Water Conservation Research Division, ARS, USDA, and the Department of Agronomy, Colorado Agr. Exp. Sta. (Project 141). Presented before Div. VI, Soil Sci. Soc. Am., Ithaca, N. Y., Aug., 1962. Received Apr. 10, 1963. Approved Aug. 26, 1963.

[2] Soil Scientist, USDA, Fort Collins, Colo., and Associate Professor of Soils, Colorado State University, Fort Collins, respectively.

[3] Unpublished data examined included:
USDA Climatological Records of the Akron Dryland Field Station, Akron, Colo. 1908-62.
USDA Cooperative Cereal Grains Investigations, Ann. Rep., Akron Field Sta., Akron, Colo. 1910-54.
USDA Cooperative Dryland Crop Rotations Studies, Ann. Rep., Akron Dryland Field Sta., Akron, Colo. 1908-54.

[4] Series names based on final field correlation memorandum, SCS Soil Survey, 1961.

laboratory analyses. Analyses included particle size distribution, organic matter, $NaHCO_3$-soluble P, calcium carbonate, pH, cation-exchange capacity and exchangeable cation concentrations, moisture content at saturation and at ⅓- and 15-atm. tension, bulk density, and organic N.

In addition to surface examinations and laboratory data, the soil-boring grid map, the detailed soil map, and a topographic map (vertical interval = 0.2 feet) were used as overlays on a plot map of exactly the same scale in order to establish the composition of each plot. In this manner the specific composition of each plot with respect to percentage distribution of soil types and phases, the mean depth to the $CaCO_3$ horizons, and the dominant slopes were determined. Only the major soil types and depth groupings were used for final comparisons.

Crop yield and management records and climatic data were obtained from the daily records of the experiment station[3] and from the U. S. Weather Bureau (7, 8).

From long-time records of uniform normal treatment on plots composed of single soil types, it was possible to establish base productivity levels for thin, medium, and deep soils, respectively, and by statistical methods, to assign normal plot productivity values to the heterogeneous plots. Comparisons of actual yields of several treatments with computed plot yields under normal treatment (check plots) permitted differentiation of yield variations caused by soils and those caused by treatment.

RESULTS

Soil Distribution Patterns

From the initiation of the dryland experimental field in 1908 until 1938, there was no specific designation of the soil type or types on which the experiments were being conducted. The Akron Area soil survey, made in 1938 and published in 1947, designated this field as Rago silt loam (5). The 1950 detailed survey divided this 25-acre block into four types and one phase. The 1960 field correlation not only made major revisions in boundary lines, but changed textural classes for all types and changed names of two series. The 1961 detailed examination recognized four of these types and phases, but identified a total of 5 soil types and 3 phases occurring in a rather intricate pattern. Figure 1 indicates the chronological changes in soil boundary designation and soil identification, omitting the 1950 survey. Rago silt loam, shown as 100% of the 25-acre area up to 1950, did not occur on the 1960 or 1961 map. Of the three major types that were shown on the 1950 map, only one appeared on the maps made in 1960 and 1961. Soil variability was found significant in data interpretations, however.

Soil Descriptions

The soils studied are all derived from relatively recent aeolian deposits, chiefly of fine sands and silts, and are developing on relatively uniform topography under a shortgrass-midgrass complex in the semiarid climate of the Central Great Plains. Therefore, there is no great difference in origin. The primary differences are *(a)* stage of development; *(b)* microrelief, which, because of better water distribution, may have resulted in higher organic matter and deeper development in some soils than in others; *(c)* differential wind erosion with redeposition of the aeolian materials and surface soils; and *(d)* depth of deposition of $CaCO_3$. Major properties of Weld and Rago loams and the other soil types delineated in the detailed examination of plots are described briefly in table 1.

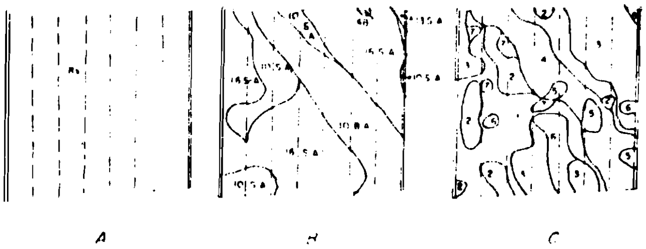

Figure 1—A study in progressive soil mapping of the dryland rotation plots, Akron Field Station, Akron, Colo.
A. Akron area soil survey (5), 1947: Rs=Rago silt loam.
B. Detail soil survey, 1960: 4B=Colby loam; 10S-A=Weld loam, thick solum phase; 10B-A=Rago loam; 13-A=Sligo loam; 16S-A=Weld loam.
C. Detail survey, 100 foot Grid, 1961: 1=Weld loam; 2=Weld loam, thick solum phase; 3=Weld loam, thin solum phase; 4=Rago loam; 5=Kuma loam; 6=Norka loam; 7=Norka loam, thick solum phase; 8=Sligo loam.

Table 1—Summary of major characteristics of soils in experimental field.

Series* names	Surface soil	Upper subsoil	Lower subsoil	Origin and position	Slope and aspect‡	Zone of calcium carbonate	
						Depth	Concentration
						in.	
*1 Weld loam	Loam 6-8 in., 10YR 4/2-3/2† mod. med. granular, abrupt boundary.	Clay or silty clay loam-4-8 in., 10YR 4/3-3/3, strong prismatic, density 1.55-1.60.	Clay loam to loam 10-15 in., calcareous, weak to mod. coarse prismatic, hard to firm.	Calcareous, loamy aeolian deposition; upland divides of smooth or convex slopes	0.1-1.6%, 0.4% dominant.	15-18	12-15% at 20-30 in.
*2 Weld loam Thick Solum Phase	Same, less abrupt boundary.	6-10 in. thick, less dense.	Similar but several inches deeper.	Same on slightly concave slopes	0.1-1.0%, 0.3% dominant.	20-24	less than above
*3 Weld loam Thin Solum Phase	Loam 3-6 in., 10YR 4/3-3/2, weak med. granular, smooth boundary.	Clay loam-3-5 in., 10YR 4/3-3/3, mod. prismatic, may be calcareous.	Loam 10-20 in., weak coarse subangular blocky, highly calcareous, soft, friable.	Same but on steeper or strongly convex slopes.	0.23-3.0%, 2.0% dominant	6-10	10-15% at 12-20 in.
*4 Rago loam	Loam-8-10 in., 10YR 4/2-3/3, mod. med. granular, smooth boundary.	Clay loam-4-6 in., 10YR 4/3-3/3, med. prismatic, density 1.45-1.50.	Silty clay loam-12-20 in., 10YR 4/1-2/1 and 4/2-3/2 (buried soil). Non-calcareous, subangular blocks, firm to friable.	Reworked, loamy aeolian materials; smooth divides, slightly concave slopes.	0.0-0.8%, 0.15% dominant.	25-30	2-4% at 28-40 in.
*5 Kuma loam	Loam 8-9 in., 10YR 4/2-3/2, mod. med. granular, gradual boundary.	Loam or light clay loam 10-12 in., 10YR 4/2-3/2, weak prismatic to subangular blocky.	Similar to buried soil of Rago, less dense and lower in clay content.	Similar to Rago.	0.15-0.8%, 0.2% dominant	25-30	2-4% at 28-40 in.
*6 Norka loam	Loam 6-8 in., 10YR 4/3-3/2 weak to mod. med. granular, smooth boundary.	Loam to light clay loam 3-5 in., 10YR 4/3-3/2, weak med. prismatic to subangular blocky.	Loam to vfsl., calcareous weak coarse prismatic to subangular blocky.	Same but thin on smooth to convex slopes; some fine gravel on surface.	0.18-2.0%, 0.15% dominant	8-13	less than in Weld soils
*7 Norka loam Thick Solum Phase	Loam-8-9 in., 10YR 4/3-3/2, weak to mod. med. granular, smooth boundary.	Loam to light clay loam 6-10 in., 10YR 4/3-4/2, weak med. prismatic to subangular blocky.	Loam to vfsl., 10YR 4/3-3/3, calcareous below 20 in., firm to friable.	Same on smooth flats or gentle slopes.	0.10-0.5%, 0.3% dominant.	20-24	less than in Weld soils
*8 Sligo loam	Loam-8-10 in., 10YR 4/2-2/1, mod. med. granular, gradual boundary.	Loam to light silty clay loam 10YR 4/1-2/1, weak med. subangular blocky.	Dark, loamy and friable to considerable depth.	Well drained swales in upland; gently concave slopes concentrate runoff water.	0.1-1.0%, 0.35% dominant.	Variable, low concentration, may be calcareous at surface or at 2-3 feet.	

* Soil series names are those used in field correlation and are subject to approval in final correlation of area.
† Color symbols by Munsell System. ‡ All soils on southeast and east exposures.

Soils Analyses

Comparative analyses of Rago loam and Weld loam are given in figure 2. No strongly unfavorable reactions were observed in any of the soils. Conductivity of saturation extracts of Rago and Weld loams was less than 1.0 millimho per cm., except in the C horizons which ranged from 0.9 to 1.7 millimhos per cm. The paste pH was 6.5 for all surface soils, 6.5 to 7.8 for progressively deeper subsoil horizons, and 7.6 to 8.1 in the C horizons. The 1:5 dilution pH rose slightly above 9.0 in the C horizon only. The two soils differ markedly in certain respects, however. The Rago soil has a buried profile, being underlain by a darker soil at relatively shallow depths. This "two-story" soil accounts for deeper accumulation of organic matter. Concentrations of $CaCO_3$ are only 2 to 4% at depths of 28 to 34 inches in the Rago loam whereas Weld loam has as high as 15% lime within the 20- to 30-inch layer. Total N to a depth of 5 feet computed from one sample of Rago loam was 11,500 pounds per acre as compared to 9,800 pounds computed from analysis of a sample of Weld loam; 1,400 pounds more N was found in the first 3 feet of the Rago loam. Bicarbonate-soluble P in the 5-foot profile of a sample of Rago loam was 218 pounds (500 pounds P_2O_5) and in the Weld loam was 120 pounds (275 pounds P_2O_5). The Weld loam has an abrupt change in texture and compaction between the plow layer and the B horizon, with a 10 to 15% increase in bulk density. The available moisture capacity above the zone of highest concentration of $CaCO_3$ is 3 inches greater in the Rago loam than in the Weld loam.

Relative Soil Productivity

The procedure for determining the characteristics of individual plots and of evaluating relative differences in response to treatments and crop sequences has been explained. Because of the difficulties involved in segregating an adequate number of plots of each soil type for the entire period, it was necessary to compare some types under similar levels of management for shorter periods and make adjustments in relative yields by comparison with soil types having the longer records.

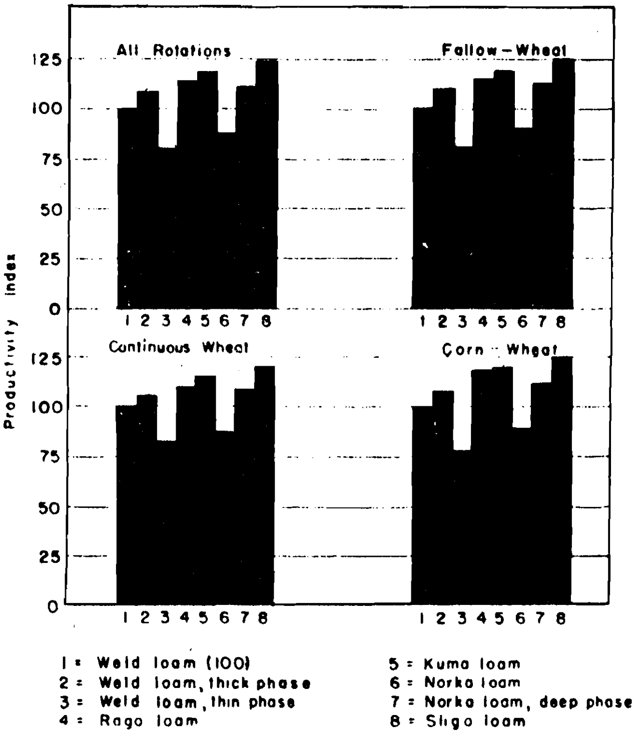

Figure 3—Productivity of winter wheat, Akron, Colo.

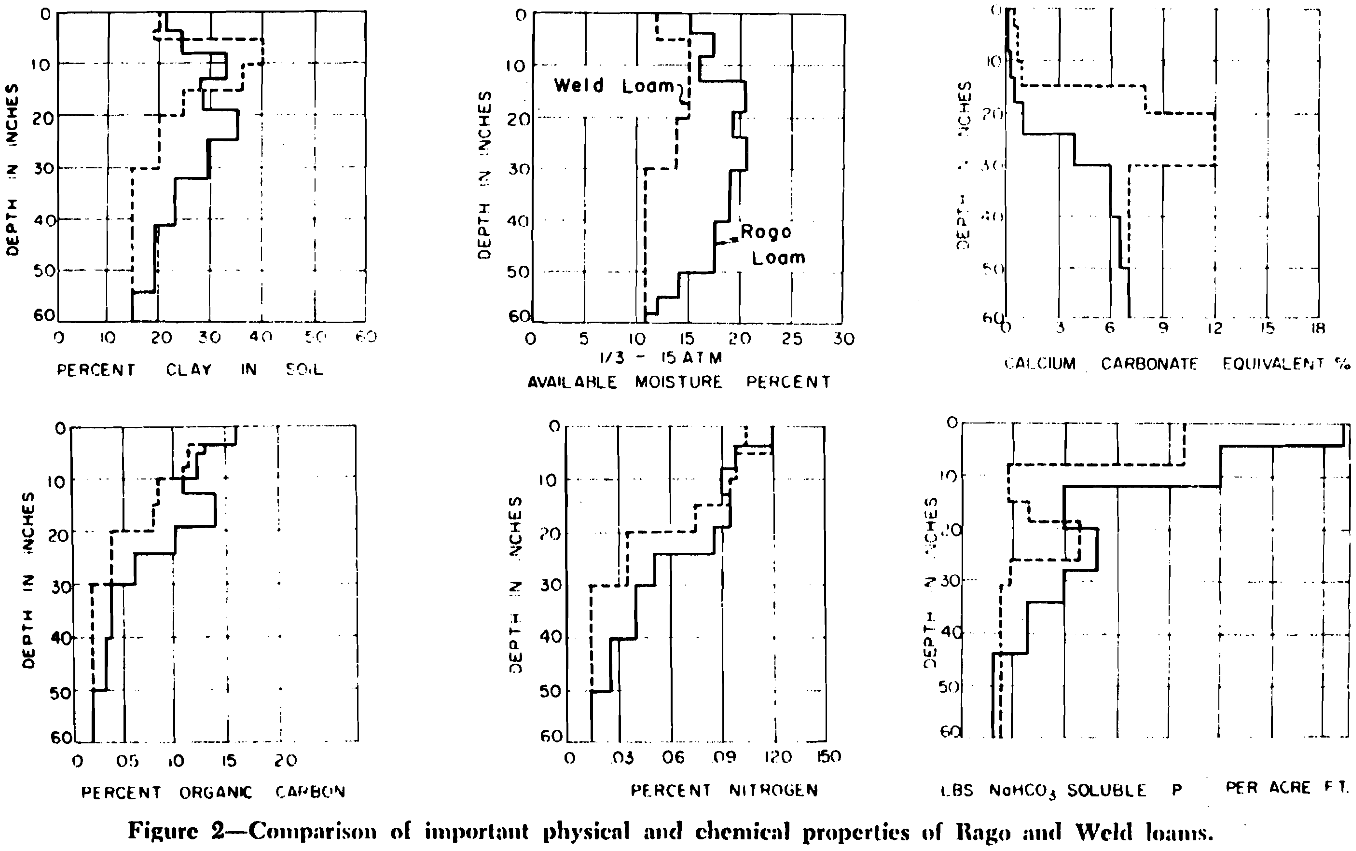

Figure 2—Comparison of important physical and chemical properties of Rago and Weld loams.

Figure 3 shows the relative productivity of the eight soil types for winter wheat at Akron, Colorado, using Weld loam as 100. The relative position of each type changes only slightly for different cropping systems, the deeper soils[5] being somewhat more responsive than thinner soils under a fallow-wheat program. "Relative productivity" is used on a percentage basis because quantity ratings in terms of bushels of wheat would be reliable only for a given period (1). During a 30-year period of wheat grown under continuous culture, the deep soils produced 20% more paying crops[6] and 55% more wheat above cost of production than did the thin soils in the same experimental field. During 47 years of record, the deep soils[5] produced 16% more paying crops and 52% more wheat above cost of production from corn-wheat rotations than did the thin soils. Where wheat was grown after fallow over a 29-year period, the deep soils produced 19% more paying crops and 64% more wheat above cost of production. These relationships could not have been determined without the detailed field and laboratory examination of soils in the experimental plots and association of plot response with soil properties and soil distribution patterns.

The Effect of Soil Type Variations on Interpretations of Dryland Rotation and Tillage Experiments

Where it was possible to segregate a representative number of plots for a single soil type, (Weld loam, thin solum phase) the six treatments used for growing continuous wheat, involving dates and types of tillage and seeding methods, were generally insignificant in their effects on wheat yield. The variation among treatments was no greater than the variation within the treatments. The mean yield of all continuous wheat on Weld loam, thin phase, was 342 pounds for 330 plot years with a mean variation of ± 8.4 pounds or 2.5% among treatments.

However, when all records were adjusted to a 46-year period on the basis of comparable years, and adjusted for years of production under different climatic situations, the mean average yield of wheat under continuous culture for the 46 years was Rago loam = 516 pounds; Weld loam = 450 pounds; and Weld loam, thin phase = 372 pounds. The productivity ratings were Rago loam = 114, Weld loam = 100, and Weld loam, thin phase = 83. It appeared from these data that significant differences in wheat yields reported in the past for certain rotations and treatments could be the result of soil differences rather than treatment.

To evaluate the effects of soil type distribution patterns on interpretation of results, the mean weighted productivity level for each plot was determined from the percentage distribution of soil types and the mean productivity levels under normal treatment for the deep, medium, and thin soils, respectively. Normal yield values were assigned to each plot for fallow-wheat, corn-wheat and wheat-wheat sequences. Calculated mean plot productivity values ranged from 77 to 114, and the soil distribution patterns ranged from 100% deep to 100% shallow soils. Comparisons of actual plot yields with yields computed from normal treatment and for the weighted soil productivity of each plot permitted differentiation between variations due to soils and those due to treatment (see procedure).

Table 2—A summary of rotations and treatments used in production of winter wheat at Akron, Colo. and interpretation of results with and without benefit of detailed soils evaluation.

Treatment or practice	Rotation & plot numbers	Actual plot yield avg.	Treatment minus check unadjusted	Potential yield adjusted for soils	Treatment minus check adjusted
		pounds/acre			
Time & frequency of plowing continuous wheat					
Check plots:Normal disked & seeded	571 B, 572 B, 573 B, -C, 568	342	0	342	0
Early fall disked	572-1-B	498	+156	468	+ 30
Early plowed & strip seeded	592	450	+108	402	+ 48
Early fall listed	MC F	444	+102	468	- 24
Early listed & seeded in lister furrow	572-1-A	390	+ 48	468	- 78
Subsoiled & plowed	MC E	378	+ 36	450	- 72
Early fall plowed	MC-B, -B', 572 A, 573 A	360	+ 18	340	+ 20
Late fall plowed	MC A	348	+ 6	366	- 18
No treatment, seeded in stubble	591	330	- 12	366	- 66
Manuring					
A. On fallow land:					
Check plots:No manure	267	954	0	954	0
Spring topdressed	269-1	1,050	+ 96	1,176	-126
Plowed under in spring	268	942	- 12	918	+ 24
Fall topdressed	269	912	- 42	912	0
B. On corn land:					
Check plots:No manure	252	546	0	546	0
Manure plowed under	251	552	+ 6	556	- 4
Crop rotation & sequence					
A. Wheat after fallow:					
Check plots:Alternate fallow-wheat	MC-C, -D, 267	1,038	0	1,038	0
Corn-oats-fallow wheat	28	1,092	+ 48	1,096	- 4
Wheat-fallow-wheat	568	852	-186	850	+ 2
B. Wheat after corn (All seeded on disked corn ground)					
Check plots Corn-wheat	252	552	0	552	0
Fallow-oats-corn-wheat	81	654	+102	630	+ 24
Rye-oats-corn-wheat	26	564	+ 12	620	- 56
Corn-wheat (manured)	251	546	- 6	654	-108
Peas-oats-corn-wheat	97	540	- 12	498	+ 42

The summary of treatment, tillage, and rotation practices is given in table 2, where the effects of correcting yield relations with respect to soil productivity differences among individual plots and rotations are shown. In several cases, the interpretation one would assume from reports of plot treatment averages is reversed when the relative plot productivity potentials are considered. This is clearly illustrated by rotation 269-1 where spring topdressing of wheat with manure appeared to have increased yields by 96 pounds. This particular plot consisted largely of deep, dark soils of much higher potential production than was obtained. After soil productivity correction, it would appear to be that spring topdressing actually depressed yields.

For 11 out of 21 practices and treatments, correcting for soil differences either reversed the original interpretation based on plot averages or made changes of 30 pounds or more in the yield values indicated. After correcting for soil differences, over one-half of the practices and treatments appeared to have negligible effects on yields of winter wheat. It can be seen, therefore, that where plot yields are not corrected for soil differences, rotations and treatments which are wholly or to a large extent on a thin soil may be unfavorably rated in comparison with those on deep soils.

DISCUSSION AND CONCLUSIONS

These studies indicate that, if research results are to be correlated with soil type characteristics, the detail of mapping should be comparable to plot layout and intensity of agronomic or other research performed. Successive changes in the concepts of soil mapping and soil identification and in the detail of soil mapping may also necessitate occasional re-examination of data interpretation.

Determination of the principal physical and chemical

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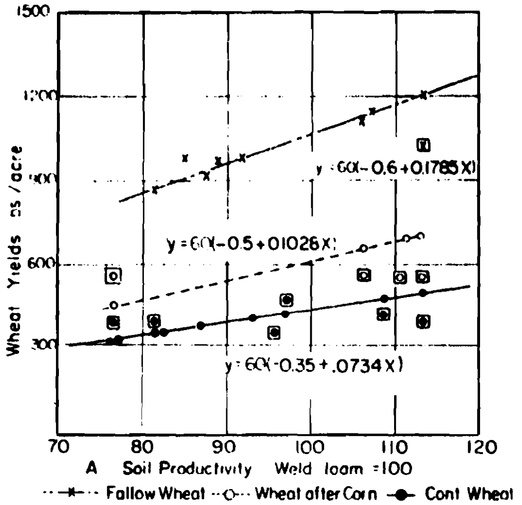
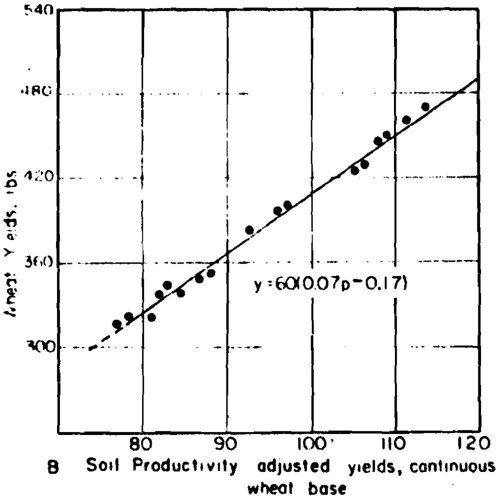
[5] Deep soils include Kuma, Rago, and Sligo loams, and Weld loam, thick solum phase; medium includes Weld loam, and thin soils include Norka loam and Weld loam, thin solum phase.

[6] Paying crops were considered as 600 pounds (10 bushels) or more from fallow-wheat, and 300 pounds (5.0 bushels) or more from continuous wheat or corn-wheat rotations.



A Soil Productivity Weld loam = 100



B Soil Productivity adjusted yields, continuous wheat base

Figure 4—Plot yields of winter wheat vs. soil productivity. Dryland rotation plots, Akron, Colo. Plots where treatment causes significant (18 lb. ±) difference from soil effect are shown in square, ⊡

soil properties responsible for plot heterogeneity and correlation of these with mappable soil units would aid interpretation of plot research results and furnish improved criteria for prediction of research applicability to other soil-climate areas. Any new plot layout should be very carefully aligned with soil variations encountered in order to provide for statistical examination of results by soil types. Such a procedure would not eliminate need for replication but would provide a basis for interpretation of results. When plot uniformity tests are being made to evaluate soil heterogeneity, a detail grid-type soil survey should be made and the soil type and phase map used as an overlay to (*a*) guide plot layout, (*b*) to serve as a plot sampling guide, and (*c*) to aid computation of mean plot productivity values.

Interpretation of the applicability of research to other soil areas and climates depends upon a thorough knowledge not only of the soil distribution patterns, but also of climatic influences during the important phenological growth periods of the crop. One must first know the micropattern of soil type and phase distribution and microclimatic effects within the research plots. Then one must know the "macro" soil patterns within the broader areas into which research results are to be interpolated.

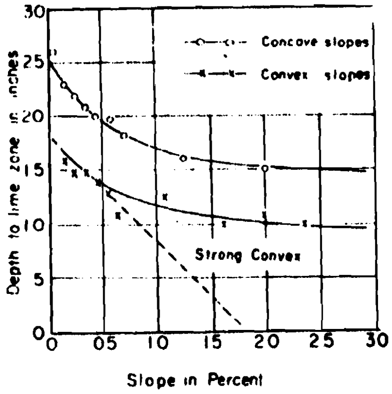


Figure 5—Depth of calcium carbonate as related to slope.

This procedure was applied to the Akron area by use of overlays and of planimetric measurement of similar soils and soil associations on three maps, viz., the detail soil survey of the 25-acre research field (scale: 1 inch = 200 feet), the Akron Area soil survey (1 inch = 1 mile), and the Great Plains Soil Association map (1 inch = 40 miles). Research results from the 25-acre block apply specifically and directly to 52% of the county. Based on soil variations from the regional soil association map, the research has specific application to 14% and general application to an additional 14.6% of a surrounding area of 40,000 square miles. It is recognized, however, that certain research findings or interpretations may apply generally over a larger area and to a number of soils under a given land use, while other findings may have direct application to only a few soil types or a local situation.

Developing Research Applicability Criteria

Mathematical expressions of soil criteria for predicting applicability of research results are not easily developed for a specific soil type or soil association. In this study the yields were adjusted to a common base in a subjective manner. This gives satisfactory results but is impractical or impossible on a large scale. Development of a mathematical model which will allow adjustments to be made by inexperienced personnel using modern statistical equipment would facilitate application of the effects of soil type distribution patterns to interpretation and use with field or field plot results.

Plot yields for dryland wheat production were associated with soil distribution patterns within the plots and regression lines computed for yields of fallow-wheat, corn-wheat, and continuous wheat at different levels of soil productivity (figure 4A). This allows quick evaluation of the relative levels of the three cropping systems and the effect of soil productivity on these levels. Fallow-wheat response to soil productivity is estimated to be 2.4 times that of continuous wheat as shown by the slopes of the regression lines. While moisture is the primary limiting factor in production of continuous wheat, crops respond more readily to increased moisture deposits in the deeper, more productive soils.

When all plot yields were reduced to the level of continuous wheat, the r value was 0.741 for the regression equation

$$Y\ [\text{yield}] = 60\ (.068\ P\ [\text{productivity index}] - .202).$$

When the yields were adjusted also to compensate for treatment effects and for micellaneous factors, such as hail, a correlation coefficient of $r^2 = .992$ was obtained (figure 4B) for the regression equation,

$$Y = 60\ (0.07\ P - 0.17).$$

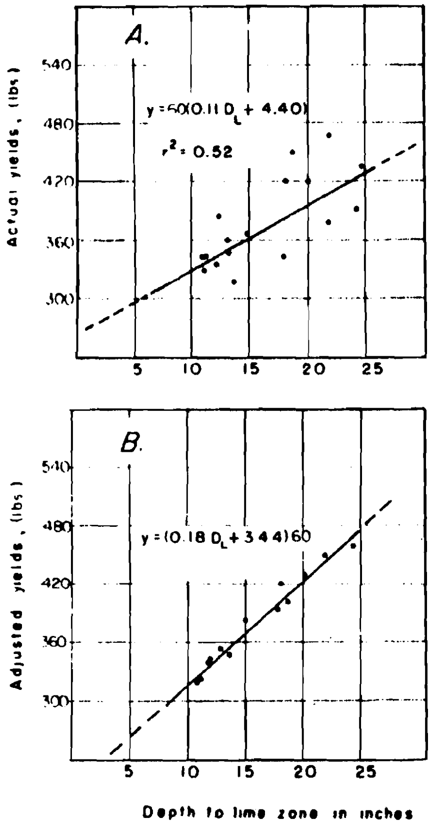


Figure 6—Depth of calcium carbonate as related to wheat yields.

A. Actual yields of continuous wheat vs. lime zone depth.

B. Adjusted yields of continuous wheat vs. lime zone depth.

Thus figures 4A and 4B provide one criterion for extrapolation of research results between soils of different productivity levels and also for comparing treatment effects where soils or more than one productivity level are involved.

Depth to the primary zone of $CaCO_3$ accumulation is often used by soil surveyors in the semiarid regions as a quick clue to soil development of medium- to fine-textured soils. At Akron, concave slopes, which tend to concentrate more than the normal flow of water across an area, generally had soils with lime zones 4 to 6 inches deeper than those soils developing on convex surfaces where greater runoff and surface soil loss was to be expected (figure 5). Microrelief appeared significantly connected, also, with other soil-forming processes such as organic matter accumulation, clay migration, and structural development. A direct comparison of lime zone depth to unadjusted plot yields (figure 6A) shows some scatter, perhaps caused by treatment variation and miscellaneous factors, with an r^2 value of 0.521 for the regression equation

$$Y \text{ [yield]} = 60 \ (0.11 \ D_L \text{ [depth to lime]} + 4.40).$$

When yields are adjusted for treatment differences and miscellaneous factors (such as hail or insect damage), the values fit rather closely the regression line

$$Y = 60 \ (.18 \ D_L + 3.44)$$

with an r^2 value of 0.988 (figure 6B). There is some justification in using a single, easily measured, soil property to quickly assess relative productivity of developed soils which are derived from similar parent materials and are developing under the same general influences of climate and vegetation. Such technique might not apply to recent alluvium or other undeveloped soils or to soils differently irrigated and fertilized.

LITERATURE CITED

1. Aandahl, A. R. Soil productivity—concepts and predictions. Trans. Intern. Congr. Soil Sci. 7th Madison. 4:365-370. 1960.
2. Brandon, J. F. and Mathews, O. R. Dryland rotation and tillage experiments at the Akron (Colorado) Field Station. USDA Circ. 700. 1944.
3. Brown, Lindsay A. A basis for rating the productivity of soils on the plains of eastern Colorado. Colorado Agr. Exp. Sta. Tech. Bull. 25. 1938.
4. Chilcott, E. C. The relations between crop yields and precipitation in the Great Plains area: I. Crop relations and tillage methods. USDA Misc. Circ. 81. 1931.
5. Knobel, E. W. et al. Akron Area Colorado soil survey. Series 1938, No. 14. Published 1947 by USDA, Bureau of plant Industry, Soil and Agricultural Engineering, and Colorado Agr. Exp. Sta., cooperating.
6. McMurdo, George A. Cereal experiments at the Akron Field Station, Akron, Colorado. USDA Bull. 402. Oct. 1916.
7. U. S. Weather Bureau. Monthly Review. 1906-1960.
8. U. S. Weather Bureau. Climatological Summaries, Colo. 1908-62.

NOTES

A RECORDING BALANCE FOR MEASURING UNSATURATED MOISTURE FLOW IN SOIL[1]

THE TRANSIENT OUTFLOW method for making unsaturated conductivity measurements, described by Kunze and Kirkham,[2] requires accurate measurements of the initial flow rate out of a soil sample. Green[3] found that the method also was applicable for transient flow into a soil sample. Both methods were adequate for most conductivity experiments, but apparently were unsatisfactory for some experiments in the near saturation range. In the investigations cited above, the flow rates were obtained by measuring the movement of an air bubble in a pipette. The air bubble technique has several limitations—*(1)* more force is required to move a column of water containing an air bubble than without it; *(2)* with fast outflow the bubble movement is too rapid to be recorded accurately with the eye; and *(3)* the initial surge effect

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[1] Contribution from the Soil and Water Conservation Research Division, ARS, USDA, in cooperation with the Minnesota Agr. Exp. Sta., St. Paul 1, Minn. Minn. Agr. Exp. Sta. No. *5041*. Received Apr. 17, 1963. Approved May 27, 1963.

[2] Kunze, R. J. and Kirkham, D. Simplified accounting for membrane impedance in capillary conductivity determinations. Soil Sci. Soc. Am. Proc. 26:421-426. 1962.

[3] Green, R. E. Infiltration of water into soils as influenced by antecedent moisture. Ph.D. Thesis, Iowa State University, Ames. 1962.

Staff Paper #45

OPTIMAL DESIGN OF BORDER IRRIGATION SYSTEMS

J. Mohan Reddy and Wayne Clyma

INTRODUCTION

Border irrigation systems, both graded and level, are widely practiced methods of surface irrigation. Effective designs of border systems have frequently been based on arbitrary constraints and performance criteria. The farmer, as the owner of the farm, is interested in the highest net benefits from crop production. Depending upon the amount of water available, the cost of production and the value of the produce, the farmer may or may not irrigate all the farm. He is not sure how much area he should irrigate to obtain maximum benefits. Hence, a procedure to analyze a given situation and to optimally design the irrigation system would facilitate effective on-farm water management. This paper presents a procedure for optimal design of border irrigation systems based on maximization of profit while incorporating system operation constraints and the variables of the operating system.

LITERATURE REVIEW

Hall (4) presented a simple procedure to optimize the design of border irrigation systems. But only maximization of the application efficiency was considered. Vierhout (11) applied differential calculus to the optimal design of border and furrow irrigation systems. Once again the criteria was to maximize application efficiency. Wu and Liang (12) presented a procedure to optimize only the length of run of a

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[1] Post-doctoral fellow, Civil Engineering Department; and Associate Professor, Agricultural and Chemical Engineering Department, Colorado State University, Fort Collins, Colorado, respectively.

furrow irrigation system. There are many other variables such as inflow rate, time of irrigation, and net depth of application which should be simultaneously included in the optimization to arrive at an optimal design for the system.

Marjai (7) developed a procedure to determine the optimum inflow rate into a border with the other variables remaining constant. The objective was to maximize uniformity along the length of the border. Karmeli (6) presented a procedure to optimize the irrigation quality parameters such as tailwater ratio, deep percolation ratio, and water requirement efficiency for furrow irrigation. Though it is not difficult to extend the same procedure to border irrigation, the procedure becomes highly tedious and lengthy as the number of combinations of the variables increase. Besides, this procedure does not allow for system constraints. Recently, Reddy and Clyma (8) presented a procedure to optimize furrow irrigation system design based on minimum costs and considering the design variables, performance parameters, and incorporating the system constraints. A similar approach for borders is presented here considering maximization of profit after deriving the relationship between the design variables and the quality parameters.

SYSTEM RELATIONSHIPS BY SIMULATION

In irrigated agriculture maximum profit is obtained when the losses are minimum and the water requirement efficiency is at an optimum. Water requirement efficiency is defined as a ratio in percent of the amount of water made available for plant use to the water requirement at the time of irrigation (5). Both can be obtained simultaneously with proper design and appropriate management of the system. If losses are high, excess costs are incurred in providing irrigation water. Yields are reduced if the water requirement met by each irrigation is less than optimal. Hence, there is a trade-off between maximizing water requirement efficiency and minimizing losses. Therefore, the irrigation system should be designed for optimum net benefits.

A relationship between yield and design variables must be established to optimize the system design. This was achieved by a two-step process. First, a relationship was obtained between water requirement efficiency and the design variables using a hydraulic model. Second, a relationship between yield and water requirement efficiency using a crop production model and the hydraulic model. Later, these two relationships were combined with a mathematical programming technique to optimize the design of freely draining graded border and level basin irrigation systems.

Performance and Design Variables

Hydraulic simulation of the applied water is an important component of this optimization model. Conceptually the hydraulic model represents accurately the operational conditions of the irrigation system. Actually the hydraulic model provides the volumes (depth) of water that enters the root zone, goes to deep percolation, and runs off the field. The hydraulic model simulates these volumes for given conditions of intake, slope, and design depth and different combinations of the design variables such as length of run, unit inflow rate, and time of irrigation.

All the system variables can be constrained to specified limits for given field conditions. The constraints were as follows:

$$Q_u \leq Q_{u,max} \tag{1a}$$

$$Q_u \geq Q_{u,min} \qquad (1b)$$

$$T_i \leq T_{max} \qquad (1c)$$

$$n_\ell L = L_F \qquad (1d)$$

where Q_u = unit inflow rate into the border, L/s; T_i = time of inflow into the border, min; L = length of irrigation run, m; $Q_{u,max}$ = maximum non-erosive stream size, L/s; $Q_{u,min}$ = minimum flow rate required, L/s; T_{max} = maximum time available per irrigation, min; L_F = length of the field, m; and n_ℓ = number of lengths of run. After defining these limits, the values of the variables were discretized to a finite number and simulated by using the appropriate hydraulic model. The models used in this study were those of Strelkoff and Katopodes (10), and Clemmens and Strelkoff (1). Finer discretizations increase the cost of simulation. The length variable was discretized into a limited number because there are a limited number of acceptable alternatives, i.e., the length of run may be halved or reduced to one-third. For each combination of the variables, the water requirement efficiency, the volume of runoff, and the deep percolation volume were calculated. Here, only freely draining graded borders, and level basins are considered.

Graded Borders

Graded borders are well suited to soils of moderate intake characteristics and slopes. Efficient irrigation is possible by balancing the advance and recession of water. In graded borders, the water frequently is freely draining at the downstream end of the field. Hence, runoff water becomes an important component of the irrigation system design. Under some circumstances detrimental effects of deep percolation also may be incorporated as a design constraint.

After simulating for a set of given conditions and various combinations of the design variables--length of run, unit inflow rate, and time of irrigation--the values of the quality parameters such as water requirement efficiency, and deep percolation and tailwater ratios were obtained. By a statistical analysis of the data, the following types of relationships were defined with a high degree of correlation, between the quality parameters and the design variables. They are:

$$E_r = K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} \tag{2}$$

$$R_t = K_2 Q_u^{a_2} T_i^{b_2} L^{c_2} \tag{3}$$

and

$$R_p = K_3 Q_u^{a_3} T_i^{b_3} L^{c_3} \tag{4}$$

where R_t = tailwater ratio or the volume of runoff divided by the total volume applied; R_p = deep percolation ratio or the volume of deep percolation divided by the total volume applied; and K_1 to c_3 are constants which are site dependent. For given conditions and constraints, these equations provide the relationships between system performance and design variables for graded borders.

Level Borders

A level border or basin was defined as an irrigation unit of zero slope with the downstream end diked. The tailwater ratio was zero because there was no runoff. Here, an approach similar to the one in the previous section was followed. An additional variable, the water requirement at the time of irrigation, is added in defining the water requirement efficiency. Hence, the relationship is given as:

$$E_r = K_4 Q_u^{a_4} T_i^{b_4} L^{c_4} D_u^{d_4} \qquad (5)$$

in which D_u = water requirement at the time of irrigation; and d_4 = a constant. This adds one more variable to the optimization process.

In level border irrigation the water requirement efficiency relationship is sufficient to describe the quality parameters. There is no runoff. Hence, deep percolation is the only loss in the field. Thus, the deep percolation ratio can be derived easily from the water requirement efficiency. The derivation is as follows:

$$V_p = Q_u T_i - LD_u\ (E_r/100) \qquad (6)$$

where V_p = volume of deep percolation. The deep percolation ratio is given as:

$$R_p = V_p/(Q_u T_i) \qquad (7a)$$

$$= \frac{Q_u T_i - LD_u(E_r/100)}{Q_u T_i} \qquad (7b)$$

$$= 1 - \frac{LD_u E_r}{100 Q_u T_i} \qquad (7c)$$

$$= 1 - \frac{K_4 Q_u^{a_4} T_i^{b_4} L^{c_4} D_u^{d_4} LD_u}{100 Q_u T_i} \qquad (7d)$$

or

$$R_p = 1 - (K_4 Q_u^{a_4 - 1} T_i^{b_4 - 1} L^{c_4 + 1} D_u^{d_4 + 1})\ /100 \qquad (8)$$

Equations (5) and (8) provide the relationships between system performance and design variables for given conditions and constraints. Now, a relationship between system performance and yield is developed.

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Yield and Performance

Evaluation of the optimum level of crop production for a given irrigation system requires a crop production model which defines yield as a function of system performance at each irrigation during the season. The system performance at each irrigation in each section of the field is obtained from the hydraulic model. The model used in simulating the yield is presented elsewhere (9). The depth of water applied was assumed constant for each irrigation during the season. Any other sequence of depth of irrigations may be specified including empirical or experimental approaches to defining the depth and/or the sequence. Once the optimal depth of irrigation and the crop production model are given, the relative yield of the crop as a function of a constant water requirement efficiency at each irrigation during the season was simulated. Different combinations of yield and water requirement efficiency were obtained by varying the design variables: inflow rate, length of run, and time of irrigation. Other variables such as slope, intake family, or design depth may be considered. A yield versus water requirement efficiency function can be developed from the above simulation data. For a given set of field conditions, the relationship of relative yield to water requirement as obtained from the simulation is shown in Fig. 1. The relationship was quadratic as follows:

$$Y_R = -27.89 + 2.49E_r - 0.01212E_r^{2.0} \tag{9}$$

in which E_r = water requirement efficiency in percent; and Y_R = percent relative yield, and is defined as:

$$Y_R = 100 \cdot Y_a/Y_{max} \tag{10}$$

where Y_a = actual yield, kg/ha; and Y_{max} = potential yield under optimum conditions, kg/ha. A high coefficinet of correlation (r^2=0.96) was obtained between relative yield and the water requirement efficiency.

PROBLEM FORMULATION

Problem formulation is an important component of any optimization. The problem is defined in terms of an objective function (either minimization or maximization) and related constraints. For this problem, the objective was to maximize the profit, i.e., searching for a particular value of water requirement efficiency and the corresponding values of the design variables that give the optimum net benefit. The profits were due to crop production in a particular field. The costs associated with irrigation system design are: labor, water and energy, ditch construction, and any negative effects of runoff and deep percolation. If no direct costs of runoff or deep percolation can be quantified, then their costs are included in the increased amounts of water required. After the cost coefficients and the mathematical relationships of the quality parameters are obtained, the problem can be formulated as shown below:

$$\begin{aligned} \max G_o = {} & \underbrace{P_c\, Y_R\, L n_\ell\, W\, n_w}_{\text{value of the produce}} - \underbrace{C_1\, Q_u\, T_i\, W\, n_i\, n_w\, n_\ell}_{\text{cost of water}} - \underbrace{C_2\, \alpha\, T_i\, n_i\, n_w\, n_\ell}_{\text{cost of labor}} \\ & \underbrace{C_3\, n_\ell\, W_F}_{\text{cost of ditch construction}} - \underbrace{C_4\, L\, n_\ell\, W\, n_w}_{\text{cost of production}} - \underbrace{C_5\, f_1(Q_u,T_i,L)}_{\text{cost of runoff}} - \underbrace{C_6\, f_2(Q_u,T_i,L)}_{\text{cost of deep percolation}} \qquad (11) \end{aligned}$$

where P_c = profit coefficient, \$/ha; C_1 = cost of water, \$/ha-m; C_2 = cost of labor, \$/h; C_3 = cost of ditch construction, \$/lin m; C_4 = cost of production, \$/ha; C_5 = cost of runoff water, \$/ha-m;

C_6 = cost of deep percolated water, \$/ha-m; α = fraction of the time labor is utilized during the irrigation time; n_i = number of irrigations per season; n_w = number of borders in the width direction; W = width of the border, m; W_F = width of the field, m; f_1 = function of runoff volume; and f_2 = function of deep percolated volume.

After substituting the yield-water requirement efficiency relationship (Eq. 9) into Eq. 11, and neglecting the cost of runoff and deep percolated volumes the objective function becomes:

$$\max G_o = \underbrace{P_c\,[-27.89 + 2.49\,E_r - 0.01212\,E_r^2]\,\frac{L\,n_\ell\,W\,n_w}{10{,}000}}_{\text{value of the produce}} - \underbrace{C_1 Q_u T_i W\,n_i\,n_\ell\,n_w}_{\text{cost of water}}$$

$$- \underbrace{C_2\,\alpha\,T_i\,n_i\,n_\ell\,n_w}_{\text{cost of labor}} - \underbrace{C_3\,n_\ell\,W_F}_{\text{cost of ditch construction}} - \underbrace{C_4\,\frac{L\,n_\ell\,W\,n_w}{10{,}000}}_{\text{cost of production}} \qquad (12)$$

By substituting the relationship between the design variables and the water requirement efficiency (Eq. 2) into Eq. 12, the objective function is given as:

$$\max G_o = \underbrace{P_c[-27.89+2.49\,K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} - 0.01212\,(K_1 Q_u^{a_1} T_i^{b_1} L^{c_1})^2]\,\frac{L\,n_\ell\,W\,n_w}{10{,}000}}_{\text{Value of the produce}}$$

$$-\underbrace{C_1\,Q_u\,T_i\,n_i\,W\,n_w\,n_\ell}_{\text{cost of water}} - \underbrace{C_2\,\alpha\,T_i\,n_i\,n_w\,n_\ell}_{\text{cost of labor}} - \underbrace{C_3\,n_\ell\,W_F}_{\text{cost of ditch construction}} \qquad (13)$$

$$-\underbrace{C_4\,\frac{n_\ell\,n_w\,L\,W}{10{,}000}}_{\text{cost of production}}$$

and the constraints are given as:

$$K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} \le 100 \quad \rightarrow G_1 = K_1 Q_u^{a}1 T_i^{b}1 L^{c}1/100 \le 1 \tag{14a}$$

$$Q_u \le Q_{u,max} \quad \rightarrow G_2 = Q_u/Q_{u,max} \le 1 \tag{14b}$$

$$Q_u \ge Q_{u,min} \quad \rightarrow G_3 = Q_{u,min}/Q_u \le 1 \tag{14c}$$

$$L \ge L_{min} \quad \rightarrow G_4 = L_{min}/L \le 1 \tag{14d}$$

$$L \le L_{max} \quad \rightarrow G_5 = L/L_{max} \le 1 \tag{14e}$$

$$Q_u\ W = Q_F \quad \rightarrow G_6 = Q_F/(Q_u\ W) \le 1 \tag{14f}$$

$$n_\ell\ n_w\ T_i \le T_{max} \quad \rightarrow G_7 = n_\ell\ n_w\ T_i/T_{max} \le 1 \tag{14g}$$

$$n_\ell\ L = L_F \quad \rightarrow G_8 = L_F/(n_\ell L) \le 1 \tag{14h}$$

$$n_w\ W \le W_F \quad \rightarrow G_9 = n_w W/W_F \le 1 \tag{14i}$$

$$W \ge W_{min} \quad \rightarrow G_{10} = W_{min}/W \le 1 \tag{14j}$$

$$W \le W_{max} \quad \rightarrow G_{11} = W/W_{max} \le 1 \tag{14k}$$

where W_{min} = minimum width of the border, m; W_{max} = maximum width of the border, m; L_{min} = minimum length of the run, m; L_{max} = maximum length of the run, m; and Q_F = total flow rate available at the farm, L/s.

OPTIMIZATION TECHNIQUE

Generalized geometric programming, which is applicable to engineering design problems of this type, is most appropriate for the above problem. The same technique was presented by Reddy and Clyma (8) for furrow irrigation systems. Generalized geometric programming (GGP) is formulated with an objective function of the form:

$$G_o(\bar{X})_{min} = P_o(\bar{X}) - Q_o(\bar{X}) \tag{15}$$

with K constraints of the form:

$$G_k(\bar{X}) = P_k(\bar{X}) - Q_k(\bar{X}) \leq 1.0, \; k = 1,2,3, \ldots K \tag{16}$$

in which $\bar{X}$ = the vector of variables to be considered $(x_1,x_2,x_3,\ldots x_M)$; M = the number of variables; and P_k and Q_k = posynomial functions of the form:

$$P_k(\bar{X}) = \sum_{i=1}^{I} U_{ik}(\bar{X}); \; k = 0, 1,2,3, \ldots K \tag{17}$$

$$Q_k(\bar{X}) = \sum_{j=1}^{J} V_{jk}(\bar{X}); \; k = 0, 1,2,3, \ldots K \tag{18}$$

where U_{ik} and V_{jk} = terms with positive and negative coefficients, respectively, in the objective function and the constraints; I = number of terms in the objective function or the constraints with positive coefficients $(P_k(\bar{X}))$; and J = number of terms in the objective function or the constraints with negative coefficients $(Q_k(\bar{X}))$. The terms U_{ik} and V_{jk} are defined as follows:

$$U_{ik} = C_{ik} \prod_{m=1}^{M} x_m^{\varepsilon_{ikm}} \; ; \; \begin{array}{l} k = 0,1,2, \ldots K \\ i = 1,2,3, \ldots I \end{array} \tag{19}$$

$$V_{jk} = C_{jk} \prod_{m=1}^{M} x_m^{\varepsilon_{jkm}} \; ; \; \begin{array}{l} k = 0,1,2, \ldots K \\ j = 1,2,3, \ldots J \end{array} \tag{20}$$

where C_{ik} and C_{jk} = coefficients; ε_{ikm} and ε_{jkm} = exponents of the variables in the objective function and the constraints; and x_m = system variable.

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Equations (15) and (16) are called signomials. A signomial is defined as the difference of two posynomials. The major step in the formulation of GGP is the transfer of the signomials into posynomials with one term, called monomials. This is accomplished by a process of condensation as defined by Dembo (2). After the monomials are obtained, the constraints and the objective function are linearized by taking the natural logarithm of the monomial function. This set of equations is solved by linear programming. Convergence of the solution to the original problem is obtained by additional constraints called 'cuts' to the original problem. By solving the linear program a finite number of times, an optimum solution is obtained to the original nonlinear problem. Being a nonlinear programming problem, global solution cannot be guaranteed. Different local optima are obtained by starting at different initial feasible solutions. The maximum of all the optima is considered the global solution to the problem. A signomial geometric programming code has been developed to solve the problem.

The values of the variables obtained from the above technique are continuous (non-integer). In the design of an irrigation system some of the variables such as the number of lengths of run, number of sets, number of borders in the width direction should have integer values. Therefore, a different technique was attached to the above procedure to obtain an optimal solution in terms of integers for the above variables. The branch-and-bound (3) technique was chosen to express the related variables in an integer form.

OPTIMAL SYSTEM DESIGN

The generalized geometric programming technique presented above was applied to the optimal design of border irrigation systems: graded borders and level basins. The two cases are discussed separately as an example with specific conditions.

Example 1 - Graded Border

The data for this problem is presented in Table 1. Using this data the hydraulic model was simulated for different combinations of the design variables as presented in Table 2. A relationship of the following form was obtained between water requirement efficiency and the design variables:

$$E_r = 27.16\ Q_u^{0.07678}\ T_i^{0.28299}\ L^{-0.04829} \tag{21}$$

A very good correlation ($r^2 = 0.99$) was obtained between the predicted and actual water requirement efficiency. A comparison of actual versus predicted water requirement efficiency is shown in Fig. 2.

After obtaining the relationships between the design variables and the irrigation quality parameters, the problem was formulated in terms of the cost coefficients, system constraints, system constants and the design variables. In the present study, the effect of deep percolation and tail water are not considered. But when appropriate cost coefficients are available, they can be incorporated into the optimal design process. For the given situation P_c was calculated by

$$P_c = \frac{Y_{max}(m^3/ha)\cdot\$/m^3}{100}$$

$$= \frac{17.41\ m^3/ha}{100} \cdot (56.8\$/m^3) = \$9.89/ha \tag{22}$$

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Table 1. Cost coefficients, system constants and system constraints for a freely draining border.

Parameters	Value
Cost Coefficients	
Value of produce, \$/m^3	56.8
Cost of production, \$/ha	494.0
Maximum production, m^3/ha	17.41
Cost of labor, \$/h	3.00
Cost of water, \$/ha-m	40.0
Cost of ditch construction, \$/lin m	3.25
System Constants	
Length of the field, m	805.0
Width of the field, m	402.0
Slope of the field, m/m	0.001
Roughness of the field	0.024
Depth of requirement, mm	76.0
Infiltration constants, $z = kt^a$	
k, mm/min^a	18.0
a	0.2716
Number of irrigations per season	5
α	1
System Constraints	
$Q_{u)max}$, L/s	11.20
$Q_{u)min}$, L/s	0.92
Q_F, L/s	158.0
T_{max}, min	3600.0
L_{min}, m	67.0
L_{max}, m	402.0
W_{min}, m	9.0
W_{max}, m	30.5

Table 2. Relationship between the design variables and the water requirement efficiency for a freely draining border.

Inflow rate, in liters per second (1)	Time of inflow, in minutes (2)	Length of run, in meters (3)	Water requirement efficiency, in percent (4)
3.28	40.00	91.50	67.80
3.28	60.00	91.50	76.33
3.28	80.00	91.50	82.74
3.28	100.00	91.50	87.98
3.28	150.00	91.50	98.22
4.16	40.00	91.50	69.05
4.16	60.00	91.50	77.29
4.16	80.00	91.50	83.58
4.16	100.00	91.50	88.76
4.16	150.00	91.50	98.93
5.58	40.00	183.00	68.02
5.58	60.00	183.00	76.99
5.58	80.00	183.00	83.55
5.58	100.00	183.00	88.87
5.58	150.00	183.00	99.22
7.41	40.00	183.00	69.88
7.41	60.00	183.00	78.31
7.41	80.00	183.00	84.67
7.41	100.00	183.00	89.90
7.41	150.00	183.00	99.97
4.62	80.00	366.00	75.96
4.62	100.00	366.00	83.68
4.62	120.00	366.00	89.37
4.62	150.00	366.00	96.05
4.62	180.00	366.00	99.88
6.04	70.00	366.00	76.51
6.04	90.00	366.00	83.96
6.04	120.00	366.00	91.85
6.04	150.00	366.00	98.07
6.04	180.00	366.00	100.00

After substituting Eq. 22 and the cost coefficients into Eq. 11, and neglecting the coefficients of runoff and deep percolation, the objective function becomes:

$$\max G_o = \underbrace{9.89\, Y_R \frac{L\, n_\ell\, W\, n_w}{10{,}000}}_{\text{Value of produce}} - \underbrace{0.0012 Q_u\, T_i\, W\, n_\ell\, n_w}_{\text{cost of water}}$$

$$\underbrace{-0.25\, T_i\, n_\ell\, n_w}_{\substack{\text{cost of}\\ \text{labor}}} - \underbrace{3.95\, W\, n_\ell\, n_w}_{\substack{\text{cost of ditch}\\ \text{construction}}} \underbrace{-0.0494\, L\, n_\ell\, W\, n_w}_{\substack{\text{cost of}\\ \text{production}}} \qquad (23)$$

By substituting Eqs. 9 and 21 into Eq. 23 and simplifying, the result becomes:

$$\max G_o = -0.02758\, L\, n_\ell\, W\, n_w + 0.06688\, Q_u^{0.07478}\, T_i^{0.283} L^{0.9517} n_\ell\, W\, n_w$$

$$- 0.0884\, Q_u^{0.1496} T_i^{0.566}\, L^{0.9034} n_\ell\, W\, n_w - 0.0012\, Q_u\, T_i\, W\, n_\ell\, n_w$$

$$- 0.25\, T_i\, n_\ell\, n_w - 3.25\, n_\ell\, W\, n_w - 0.0494\, L\, n_\ell\, W\, n_w \qquad (24)$$

The system constraints are given as follows:

$E_r \leq 100 \rightarrow$ $G_1 = 0.2716\, Q_u^{0.07478} T_i^{0.28299} L^{-0.04829} \leq 1$ (25a)

$n_\ell\, L = L_F \rightarrow$ $G_2 = 0.001242\, L\, n_\ell \leq 1$ (25b)

$n_w\, W \leq W_F \rightarrow$ $G_3 = 0.002487\, W\, n_w \leq 1$ (25c)

$L \leq L_{max} \rightarrow$ $G_4 = .003727\, L \leq 1$ (25d)

$L \geq L_{min} \rightarrow$ $G_5 = 67\, L^{-1} \leq 1$ (25e)

$W \leq W_{max} \rightarrow$ $G_6 = 0.0328\, W \leq 1$ (25f)

$$W \geq W_{min} \rightarrow \qquad G_7 = 9.146\ W^{-1} \leq 1 \qquad (25g)$$

$$Q_u W = Q_F \rightarrow \qquad G_8 = 151.42\ Q_u^{-1} W^{-1} \leq 1 \qquad (25h)$$

$$n_\ell\ n_w\ T_i \leq T_{max} \rightarrow \qquad G_9 = .0002778\ n_\ell\ n_w\ T_i \leq 1 \qquad (25i)$$

$$Q_u \leq Q_{u,max} \rightarrow \qquad G_{10} = 0.1350\ Q_u \leq 1 \qquad (25j)$$

$$Q_u \geq Q_{u,min} \qquad G_{11} = 0.92\ Q_u^{-1} \leq 1 \qquad (25k)$$

The generalized geometric programming technique was applied to the solution of the above problem. The following optimal values of the design variables are obtained:

Q_u = 4.98 L/s $\qquad$ T_i = 122 min
L = 269 m $\qquad$ n_ℓ = 2
W = 31 m $\qquad$ n_w = 13

The water requirement efficiency (E_r) obtained was 91 percent. The net profit was $9,833 for the field which equals $304/ha. At the optimum, the cost of design was $186/ha. The application efficiency for the optimum was 51 percent. In fact, when the criteria is to maximize net benefits, much emphasis cannot be given to application efficiency. The technique presented here selects the optimal water requirement efficiency and yield without directly considering the application efficiency.

In defining the constraints, care must be exercised in selecting proper limits for the variables. These limits should not be different from the limits used in simulating the hydraulic model; if so, the relationships developed may not be valid. If a wide range of alternatives for the design variables are considered, these same limits should be included in the hydraulic simulation model.

Example 2 - Level Basin

The optimization technique was applied for a level basin. The system cost coefficients, constants, and constraints are given in Table 3. The hydraulic model was used to simulate the relationships between the quality parameters and the design variables. The different combinations of the design variables used in the simulation are presented in Table 4. For the given situation, the following relationships were obtained between the quality parameters and the design variables:

$$E_r = 3103\ Q_u^{0.8232} T_i^{0.9182} L^{-0.8393} D_u^{-0.9201} \tag{26}$$

or

$$E_r = 85\ Q_u^{0.8232} T_i^{0.9182} L^{-0.8393}, \quad D_u = 50 \text{ mm} \tag{27}$$

and the equation for R_p is given as:

$$R_p = 1\text{-}31\ Q_u^{-0.1768} T_i^{-0.0818} L^{0.1607} D_u^{0.0799} \tag{28}$$

or

$$R_p = 1\text{-}0.85\ Q_u^{-.1768} T_i^{-.0818} L^{0.1607}, \quad D_u = 50 \text{ mm} \tag{29}$$

A good correlation ($r^2 = 0.96$) between the actual and predicted water requirement efficiency was obtained. A comparison of predicted versus actual water requirement efficiency is presented in Fig. 3. The above relationship was used to formulate the problem.

The profit coefficient for the given situation is calculated as:

$$P_c = \frac{Y_{max}(\text{kg/ha})}{100} \times \$/\text{kg}$$

$$= \frac{2500 \times 1}{100} = \$25/\text{ha} \tag{30}$$

Table 3. Cost coefficients, system constants, and system constraints for a level basin irrigation system.

Parameter	Value
Cost Coefficients	
Value of produce, \$/kg	1.00
Cost of production, \$/ha	1482.0
Maximum production, kg/ha	2500.0
Cost of ditch construction, \$/lin m	6.56
Cost of labor, \$/h	3.0
Cost of water, \$/ha-m	4.0
System Constants	
Length of the field, m	335
Width of the field, m	302
Slope of the field, m/m	0.0
Roughness of the field	0.15
Depth of requirement, mm	50
Infiltration constants, $z = kt^a + ct$	
k, mm/h^a	28.52
a	0.1088
c, mm/h	2.25
System Constraints	
$Q_{u,max}$, L/s	11.20
$Q_{u,min}$, L/s	0.92
Q_F, L/s	52.0
T_{max}, min	3600.0
L_{max}, m	168
L_{min}, m	67
W_{max}, m	30.5
W_{min}, m	9

Table 4. Relationship between the design variables and the water requirement efficiency for a level basin irrigation system.

Length of run, in meters (1)	Inflow rate, in liters per second (2)	Time of inflow, in minutes (3)	Water requirement depth, in millimeters (4)	Water require-efficiency, in percent (5)
67	1.87	25.00	58	68.00
67	1.87	25.00	76	52.00
67	1.87	25.00	89	44.50
67	1.87	40.00	76	86.00
67	1.87	56.00	102	91.00
67	1.87	56.00	114	81.00
134	3.76	25.00	76	58.00
134	3.74	33.00	76	69.00
134	3.74	45.00	76	97.00
134	4.66	30.00	114	53.00
134	3.76	50.00	76	100.00
168	3.74	40.00	102	52.00
201	2.79	50.00	76	66.00
201	3.74	65.00	76	92.00
201	4.66	45.00	127	49.00
201	4.66	50.00	102	66.00
268	2.79	100.00	76	80.00
268	3.74	80.00	76	87.00
268	4.66	60.00	76	79.00
268	5.58	50.00	89	68.00

After substituting the cost coefficients (from Table 3) and Eq. 27 into Eq. 12 and simplifying, the objective function becomes:

$$\begin{aligned}\max G_o = {} & -0.06973\ L\ n_\ell\ W\ n_w + 0.529\ Q_u^{0.8232} T_i^{0.9182} L^{0.1607} n_\ell\ W\ n_w \\ & -0.2189\ Q_u^{1.646} T_i^{1.836} L^{0.6786} n_\ell\ W\ n_w - 6.56\ n_\ell\ W\ n_w \\ & -0.1482\ L n_\ell\ W\ n_w - 0.0012\ Q_u\ T_a\ n_\ell\ n_w - 0.25\ T_i\ n_\ell\ n_w \end{aligned} \qquad (31)$$

and the system constraints are given as:

$$E_R \leq 100 \rightarrow \qquad G_1 = 0.85\ Q_u^{.8232} T_i^{.9182} L^{-0.8393} \leq 1 \qquad (32a)$$

$$n_\ell\ L \leq 335 \rightarrow \qquad G_2 = .00298\ L\ n_\ell \leq 1 \qquad (32b)$$

$$n_w\ W \leq 302 \rightarrow \qquad G_3 = .00331\ n_w\ W \leq 1 \qquad (32c)$$

$$Q_u\ W \leq Q_F \rightarrow \qquad G_4 = 0.01929\ Q_u W \leq 1 \qquad (32d)$$

$$n_\ell\ n_w\ T_i \leq T_{max} \rightarrow \qquad G_5 = .00022\ T_i n_\ell n_w \leq 1 \qquad (32e)$$

$$W \leq 45.7 \rightarrow \qquad G_6 = 0.05263\ W \leq 1 \qquad (32f)$$

$$W \geq 24.4 \rightarrow \qquad G_7 = 9.15\ W^{-1} \leq 1 \qquad (32g)$$

$$Q_u \leq 11.2 \rightarrow \qquad G_8 = 0.0894\ Q_u \leq 1 \qquad (32h)$$

$$Q_u \geq 0.918 \rightarrow \qquad G_9 = 0.918\ Q_u^{-1} \leq 1 \qquad (32i)$$

$$L \leq 167 \rightarrow \qquad G_{10} = 0.005988\ L \leq 1 \qquad (32j)$$

By applying the generalized geometric programming technique, the following optimal values of the design variables were obtained.

Q_u = 1.20 L/s
L = 168 m
W = 43.3 m

T_i = 110 min
n_ℓ = 2
n_w = 7

The water requirement efficiency satisfied at the optimum was 100 percent. The maximum net profit at the optimum was $5797/per field or $573/per ha. The application efficiency found at the optimum was 93 percent. The application efficiency with level basin irrigation systems was higher than for the graded border.

In the analysis, the cost of runoff and deep percolation water was included indirectly in the cost of water provided in excess of the requirement in the root zone. But, the negative effects of these parameters (runoff and deep percolation) were not considered because of lack of appropriate cost coefficients for these parameters. The cost coefficient for runoff includes the cost of removing the excess water from the field, and the negative effects on water quality. Similarly, the cost coefficient for deep percolation must take into account the effects of waterlogging and fertilizer leaching on crop yield. The cost coefficients should be given in terms of dollars/unit volume of water. Once these coefficients are available, they can be incorporated into the optimization process. This would help in evaluating different management practices in controlling the quality of irrigation return flow while increasing agricultural production.

An implicit assumption in the problem was that the farmer applies the total available flow rate on one border. No consideration was given to irrigating more than one border at a time. This was not considered in the problem to reduce the number of variables considered, but can be incorporated into the optimization process if desired. It was also assumed that the relationship between the yield and water requirement efficiency was identical under graded and level basin irrigation systems.

SUMMARY AND CONCLUSIONS

A combination approach of simulation and mathematical programming was used to develop an optimal system design. First, the irrigation quality parameters were developed in terms of the application system design variables using a hydraulic simulation model. Second, a relationship was developed between crop yield and the system quality parameters (water requirement efficiency) using a crop production function. Maximization of net benefits was the objective. The value of the produce, and the costs of labor, water, ditch construction, and crop production were considered in the objective function. The negative effects of runoff and deep percolation were not considered. The problem was defined in terms of system variables, cost coefficients and system constraints, and the generalized geometric programming technique was applied to the optimal design of border and level basin irrigation systems. The design variables considered were the inflow rate, time of inflow, length of the run, number of lengths of run, width of the border and number of border widths. The procedure gives an optimal design under given field conditions. In addition, the procedure shows the possibility of combining simulation and mathematical programming techniques in optimizing system designs. The technique presented provides guidelines for improving existing on-farm irrigation systems for better management of the scarce resources of agricultural production.

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APPENDIX I.-REFERENCES

1. Clemmens, A. J., and Strelkoff, T. S., "Dimensionless Advance for Level-Basin Irrigation," Journal of the Irrigation and Drainage Division, ASCE, Vol. 105, No. IR3, Sept., 1979, pp. 259-273.
2. Dembo, R. S., "Solution of Complementary Geometric Programming Problems," thesis presented to the Israel Institute of Technology at Haifa, Israel, in 1972, in partial fulfillment of the requirements for the degree of Master of Science (Hebrew).
3. Garfinkel, R. S., and Nemhauser, G. L., Integrer Programming, John Wiley and Sons, Inc., New York, N.Y., 1972.
4. Hall, W. A., "Design of Irrigation Border Checks," Agricultural Engineering, Vol. 41, July, 1960, pp. 439-442.
5. Hart, W. E., Irrigation System Design, Dept. of Agri. & Chem. Engr., Colorado State University, Fort Collins, Colorado, 1975.
6. Karmeli, D., "Distribution Patterns and Losses for Furrow Irrigation," Journal of the Irrigation and Drainage Division, ASCE, Vol. 104, No. IR1, March, 1978, pp. 59-68.
7. Marjai, G., "Theoretical and Practical Problems of Water Dosaging in Sprinkling Stripe-Irrigation," Kulonlenyomat a Kiserletugyi Kozlemenyek, LXIV/A Novenytermesztes, 1-3, 1971, pp. 65-82 (Hungarian).
8. Reddy, J. M., and Clyma, W., "Optimal Design of Furrow Irrigation Systems," presented at the June 15-18, 1980, ASAE Summer Meeting held at San Antonio, Texas (#80-2071).
9. Reddy, J. M., "Irrigation System Improvement by Simulation and Optimization," thesis presented to the Colorado State University at Fort Collins, Colorado, in 1980, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

10. Strelkoff, T. S., and Katopodes, N. D., "Border Irrigation Hydraulics with Zero-inertia," Journal of the Irrigation and Drainage Division, ASCE, Vol. 103, No. IR3, Sept., 1977, pp. 325-342.

11. Vierhout, M. M., "Een Mathematische Methode Voor het Optimaal Ontwerpen Van Border or Furrow Irrigatic-Systemen (Flow Irrigation)," thesis presented to the Agricultural University at Wageningen, The Netherlands, in 1971, in partial fulfillment of the requirements for the degree of Master of Science (Dutch).

12. Wu, I-Pai, and Liang, T., "Optimal Design of Furrow Length of Surface Irrigation," Journal of the Irrigation and Drainage Division, ASCE, Vol. 96, No. IR3, Sept., 1970, pp. 319-332.

APPENDIX II.-NOTATION

The following symbols are used in this paper:

a = infiltration exponent

a_1, b_1, c_1
a_2, b_2, c_2 = exponents in irrigation quality parameter equations
a_3, b_3, c_3
a_4, b_4, c_4, d_4

c = constant in the infiltration function

C_1 = cost of water, \$/ha-m

C_2 = cost of labor, \$/h

C_3 = cost of ditch construction, \$/lin m

C_4 = cost of production, \$/ha

C_5 = cost of runoff water, \$/ha-m

C_6 = cost of deep percolation, \$/ha-m

E_r = water requirement efficiency in percent

G_o = objective function in terms of cost coefficients, profit coefficient and the system variables

G_k = system constraints in terms of system variables

I = number of terms in the objective function or the constraints with positive coefficients

J = number of terms in the objective function or the constraints with negative coefficients

k = constant in the infiltration function

K = number of constraints in the problem

K_1, K_2, K_3, K_4 = proportionality constants in the irrigation quality parameter equations

L = length of irrigation run, m

L_F = length of the field, m

L_{max} = maximum length of the run, m

L_{min} = minimum length of the run, m

M = number of variables in the problem

n_i = number of irrigations per season

n_ℓ = number of lengths of run

n_w = number of borders in the width direction

P_c = profit coefficient, \$/ha

P_k, Q_k = posynomial functions in the objective function and the constraints

Q_F = total flow rate available at the farm, L/s

Q_u = unit inflow rate into the border, L/s

$Q_{u,max}$ = maximum non-erosive stream size into the border, L/s

$Q_{u,min}$ = minimum flow rate into the border, L/s

r^2 = correlation coefficient

R_p = deep percolation ratio

R_t = tail water ratio

t = time variable, min

T_i = time of inflow into the border, min

T_{max} = maximum time available per irrigation, min

U_{ik}, V_{jk} = terms in the objective function and the constraints

V_p = volume of deep percolation, m^3

W = width of the border, m

W_F = width of the field, m

W_{max} = maximum width of the border, m

W_{min} = minimum width of the border, m

x_m = system variable

y_a = actual yield, kg/ha

Y_R = relative yield in percent

Y_{max} = potential yield under optimum conditions, kg/ha

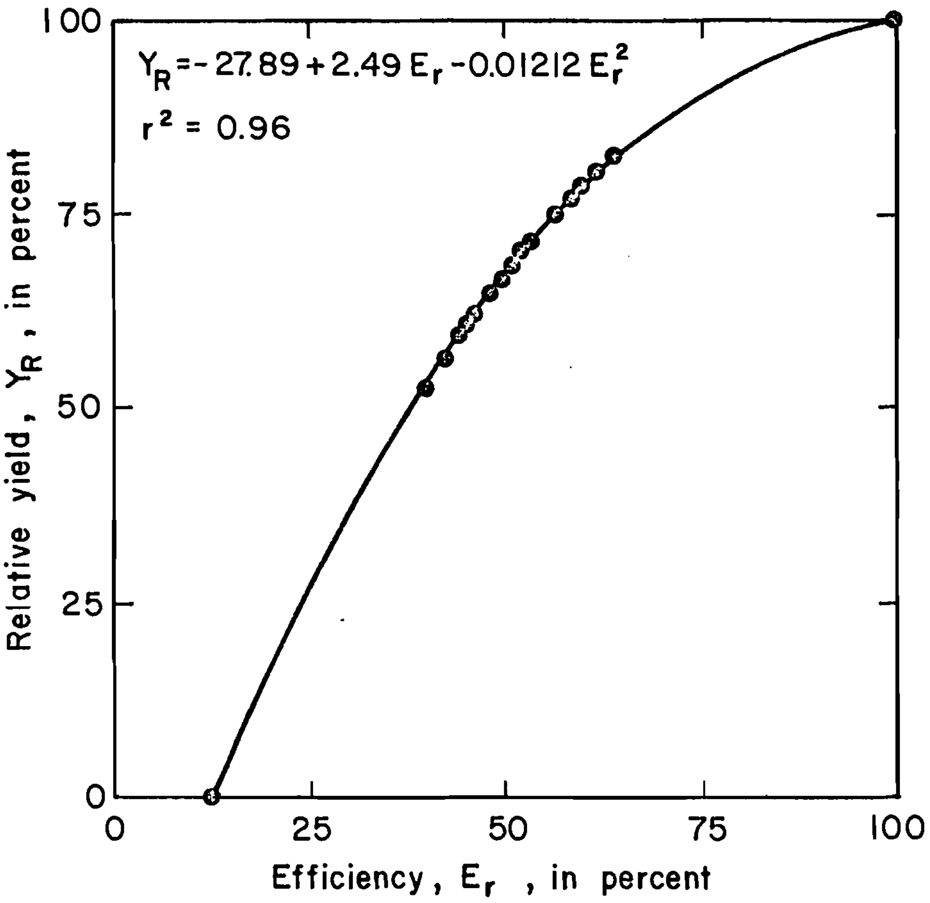
z = cumulative infiltration, mm

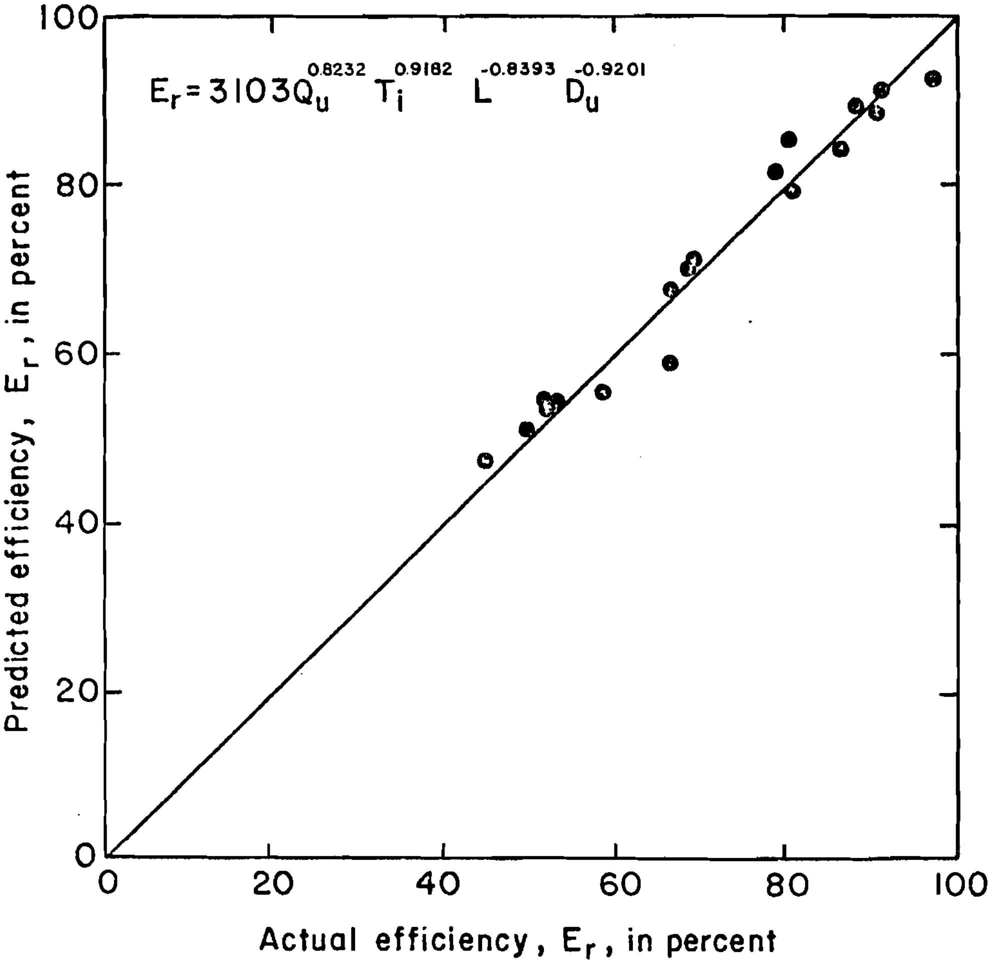
α = fraction of the time labour is utilized during the irrigation time

$\varepsilon_{ikm}, \varepsilon_{jkm}$ = exponents of the system variables in the objective function and the constraints

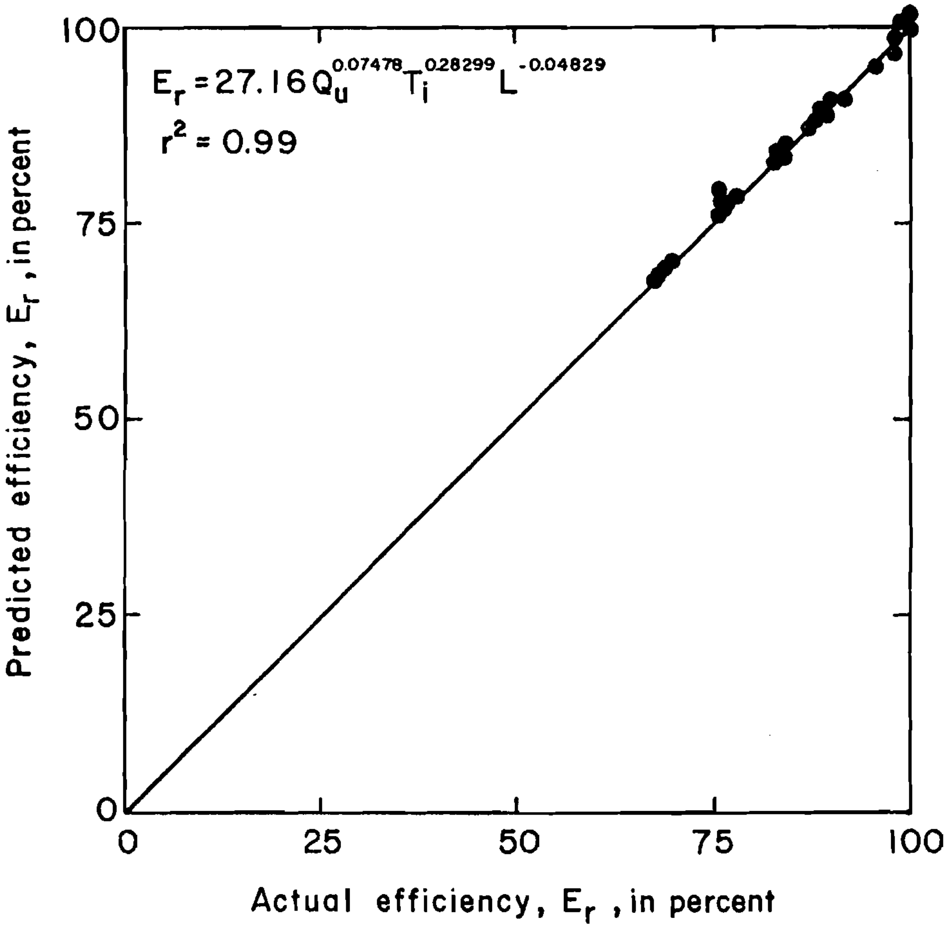
LIST OF FIGURE CAPTIONS

1. Relationship between water requirement efficiency and relative yield of wheat crop.
2. Actual versus predicted water requirement efficiency for a freely draining border.
3. Actual versus predicted water requirement efficiency for a level border.


$Y_R = -27.89 + 2.49\,E_r - 0.01212\,E_r^2$
$r^2 = 0.96$
Relative yield, Y_R, in percent
Efficiency, E_r, in percent
0
25
50
75
100
0
25
50
75
100



$E_r = 3103 Q_u^{0.8232} T_i^{0.9182} L^{-0.8393} D_u^{-0.9201}$
Predicted efficiency, E_r, in percent
Actual efficiency, E_r, in percent
0
20
40
60
80
100
0
20
40
60
80
100


$E_r = 27.16 Q_u^{0.07478} T_i^{0.28299} L^{-0.04829}$
$r^2 = 0.99$
100
75
50
25
0
0
25
50
75
100
Predicted efficiency, E_r, in percent
Actual efficiency, E_r, in percent

Staff Paper #46A*

IRRIGATION SYSTEM IMPROVEMENT BY SIMULATION AND OPTIMIZATION: 1, THEORY

J. Mohan Reddy and Wayne Clyma

INTRODUCTION

In crop production the crop water requirements, in excess of rainfall, must be met by irrigation water. Water is one of the scarce resources of agricultural production. The demand for water is growing as a result of population increase, improvement of living standards, and competing industrial development. The losses in storage, conveyance, distribution, and application of the water aggravate the dwindling water supplies. Though, on the basis of present level of technical development, fully automatic and remote controlled irrigation systems are conceivable and feasible, in order to save most of the losses, there is still a long way to go before economic and sociological conditions are achieved under which such optimum equipment becomes widespread. For the present, attempts must be made to improve the existing traditional systems with a view to a higher level of efficiency (Garbrecht, 1979). Investments in improving the conveyance, application, and use of water must be economically justified. A thorough understanding of the irrigation system is a must for efficient and economical utilization of the available resources. This paper presents the theory and concepts for evaluation of improvement alternatives based on simulation and optimization of the irrigation system.

LITERATURE REVIEW

An irrigation system basically consists of four different subsystems. They are:

*Draft copy subject to revision.

1. The conveyance subsystem (canals, pipes).
2. The application subsystem (border, basin, furrow, sprinkle, trickle, subsurface).
3. The water use subsystem (rootzone storage, evapotranspiration and crop growth).
4. The water removal subsystem (surface and subsurface drainage).

A considerable amount of research has been conducted on each component of an irrigation system. Consideration usually was not given to the interrelationships between the different components. There are only a few research works such as Anderson and Maass (1974), and Rydzewski and Nairizi (1979) where a complete irrigation system was considered, but with unrealistic assumptions.

The benefits are realized from crop production on the farm. So Benefits from proposed improvement of any component of the irrigation system must be evaluated in terms of increased crop production in the area under consideration. A conveyance subsystem improvement saves water. But the cost of improvement must be weighed in terms of increased production either for increase in the area of cultivation or yield per unit area. Similarly, the increase in yield from uniformly distributed water due to land leveling must be weighed against the cost of land leveling. In order to evaluate the economics of improvement alternatives, all the distinct components of the irrigation system must be integrated into a single management model.

A mathematical simulation model incorporating three distinct components of the irrigation system-the conveyance, application, and water use subsystems-was developed. The water removal subsystem was not considered in this analysis. The theory, development, and verification of the irrigation system model is presented in this paper. The theory of simulation and optimization as related to irrigation is discussed. Available models of water application and conveyance are utilized. A multiplicative production function was developed for wheat. All these models were verified with available data. In addition, an approach for the optimal design of surface (border and furrow) irrigation systems was developed and incorporated into the irrigation system model. Application of the optimal design to a specific case was presented by Reddy and Clyma (1980).

SIMULATION AND OPTIMIZATION THEORY

The simulation and optimization theory used in this paper involves the following sequential steps:

1) Definition of a system simulation model that adequately represents the detailed structure of the irrigation system.

2) Use of the simulation model to define the relationships between:

   a) System performance and system design variables.

   b) Crop yield and system performance.

3) Use of the mathematical relationships from 2(a) and 2(b) combined with optimization theory to develop an optimal system design.

4) Use of the simulation model in 1 calibrated for the actual operating system and the optimally designed system to evaluate alternative levels of system improvement based on economic benefits and costs.

The simulation model defined in step 1 should adequately represent the internal structure of the system. In some instances, optimal policies have been recommended based on relationships between yield and seasonal amount of water applied ( ) ( ). Yet an important feature of the irrigation system is the seasonal distribution of

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water that creates shortages during critical growth stages. In other instances the field distribution of water is variable resulting in significant yield variations in space on a field. These examples represent important aspects of a system that, when present, must be represented in the internal structure of the irrigation system simulation model. Other factors are important under given conditions and must be represented in the simulation model if results are to be appropriate.

The relationships defined in step 2 may be those as defined for this study or they may involve other factors important in a given instance. For example, a careful analysis of deep percolation costs and benefits may consider in more detail the time and spatial distribution of infiltrated water than in this study. The important concept is that an adequate simulation model can be used to develop system performance and system variable relationships which are subsequently used for evaluation of optimal alternatives.

In evaluation of optimal alternatives, step 3, optimization theory in the past has used system relationships that assume internal structures for the system that are unrealistic. Typical of these assumptions are constant performance levels for the irrigation system in time and space and crop-yield as a function of seasonal water applied. Optimal system design should also consider how the various system variables interrelate at differing levels to result in the optimal values for each variable and based on realistic system constraints. For example, length of the field, time of application and inflow rate are all related and an optimal combination should be selected. The optimization theory used here has expanded the number of variables and constraints considered but further improvement of the optimal design can be achieved.

Optimal design, if implemented, would be the obvious selection for the level of system operation. In fact, farmers do not operate systems according to design. The purpose of the 4th step is to evaluate the benefits and costs of different levels of system operation. This allows a determination of the benefits of system improvement even when the improvements do not result in optimal operation. Simulation can be used to represent realistic operating conditions for the system. By evaluating the value of differing levels of improvement, strategies and their cost can be evaluated against the benefits. The latter emphasis on simulation permits realistic representation of the system while evaluating the benefits of different levels of improvement.

The above four steps use the best theory available from irrigation hydraulics, crop models for yield and evapotranspiration or other appropriate variables, optimization theory, and knowledge about system operation and improvement alternatives to develop an appropriate strategy. The theories available are numerous and useful. The knowledge about system operation and improvement alternatives are limited or frequently nonexistent. Evaluation and improvement of irrigation system needs more effective useful theory but also understanding of how systems operate and can be improved.

The conveyance system carries water from the headgate to the field. The amount of water delivered at the field is a function of the length of the canal, and the type of lining material. Any model, that gives the flow rate at the field, given the inflow rate into the canal, the loss rate in the canal, and the length of the canal, is appropriate for this analysis.

The performance of the application system depends upon several variables, such as the inflow rate into the field, length of run, time of inflow, roughness, slope and infiltration characteristics of the field. The model should be able to simulate the spatial and temporal distribution of water on the field. Using this model, relationships can be developed between system performance parameters and the design variables. The application system also provides the depths of water infiltrated in different sections of the field at each irrigation.

The water use system model consists of two submodels: the evapotranspiration model and the crop growth model. The evapotranspiration model provides the soil-water depletion before each irrigation, in addition to the ratios of actual to potential evapotranspiration for each growth stage of the crop. The crop growth model relates yield to these ratios. The crop growth can be simulated in different sections of the field to consider the effect of nonuniformity of applied water on yield. The depths of water applied at each irrigation are obtained from the hydraulic model. A relationship can be developed between crop yield and the irrigation performance parameter.

WATER CONVEYANCE SUBSYSTEM

The water conveyance system deals with the delivery of water from the head gate of the canal to the farm outlet, considering losses along the length of the canal. Losses in canals are due to seepage, spillage, and cuts in the banks, and many random phenomena that contribute to the losses. There are analytical (Reddy and Basu, 1976), finite difference (Jeppson and Nelson, 1970), and finite element techniques to estimate seepage depending upon the hydraulic conductivity of the medium. These equations are very complex. In addition, they cannot be directly used to estimate conveyance losses, because they do not consider losses that occur in the field during actual operating conditions. Hence, actual field data are the most realiable. If actual field data are available, empirical equations can be developed that relate outflow from the canal to the inflow into the canal, canal length, and the loss rate in that section of the canal, considering other operational and random losses along the length. Trout (1979) has developed such an equation using data from Pakistan. It is given as

$$L\% = \{1 - \frac{1}{Q_M} [Q_I^{(1-P)} - (\frac{Q_{LFB}}{Q_I^P}) (1-P) D_{FB}]^{1/(1-P)}$$

$$+ [.0047L_W - (\frac{.05L_D}{Q_M}) - 0.005L_D] \frac{1}{T_i} \} \times 100 \qquad (1)$$

where

$$Q_I = [Q_M^{(1-P)} - (\frac{Q_{LSK}}{Q_M^P}) (1-P) D_{SK}] (\frac{\overset{\uparrow}{1}}{1-P}) \qquad (2)$$

in which $L\%$ = percent loss; Q_M = watercourse inflow rate; Q_I = flow rate from government canal outlet to the farmer's branch; D_{SK} = length of government canal; D_{FB} = length of farmer's branch; L_D = length of channel drained; L_W = length of channel wetted; P = loss rate exponent; T_i = irrigation turn time; Q_{LFB} = loss rate in the initial section of the farmer's branch; and Q_{LSK} = loss rate in the initial section of the government canal.

Equations (1) and (2) are derived from actual field data under the given set of conditions such as the flow rates in the channels, and dimensions of the channels. The above equations calculate both the steady state and transient loss rates. In the present analysis only the steady state losses are considered. The input to this model are: the inflow rate into the channel, lengths of government and farmer's channels, initial section loss rates in the government and farmer's channels, and the loss rate exponent for that particular location. The output from this model is the flow rate at the farm.

Later, the conveyance system model is verified. Data reported by Johnson, Kemper, and Lowdermilk (1979) is utilized in the verification processes. The data is presented in Table 1. It is clear from Table 1 that the performance of the model is very good in predicting the loss rates in the canals. Hence, the model will be calibrated and applied to a specific condition.

Table 1. Comparison of Actual and Predicted Loss Rates of the Conveyance System.

Tubewell Number and Improvement Condition	Inflow Rate liters per second	Percent Loss Rate Measured	Predicted
TW 56 before improvement	113.28	6.56	6.62
TW 56 after improvement	152.93	4.03	4.78
TW 51 before improvement	133.10	3.76	3.66
TW 51 after improvement	141.60	2.53	2.98

WATER APPLICATION SUBSYSTEM

The water application subsystem deals with the spatial distribution of the applied water in the field. An extensive amount of research has been done in the area of predicting the spatial distribution of applied water in the field. In the present analysis only level basins are used. But the methodology described here can be used for any kind of application system. A model of surface irrigation hydraulics was developed to estimate the spatial distribution of applied water.

The surface irrigation hydraulics model calculates the advance and recession phases of irrigation. The zero inertia model which is given below is used for the advance phase:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} + \frac{\partial z}{\partial t} = 0 \qquad \text{continuity} \qquad (3)$$

$$\frac{\partial y}{\partial x} = S_o - S_f \qquad \text{momentum} \qquad (4)$$

in which q = flow rate in the border; y = depth of flow; $\frac{\partial z}{\partial t}$ = infiltration rate; S_o = slope of the border; and S_f = energy slope. These equations were linearized and solved by Strelkoff and Katopodes (1977) using Preissman double-sweep technique. At the end of advance phase, the water is ponded in the case of basins. The depletion and recession phases commense after the time of cutoff. Simultaneous recession throughout the length of the basin is assumed for the present purpose. Clemmens (1979) has verified the zero-inertia model. The performance of the model is good. Hence, the model is not verified here. Clemmens and Strelkoff (1979) have assumed simultaneous recession for ponded borders. This assumption is verified with the help of a zero inertia model. It seems to be a reasonable assumption. This model is used in the analysis.

At the end of irrigation, the depth of water infiltrated at different points in the field is calculated by

$$z_i = k\tau_i^a \qquad (5)$$

in which z_i = cumulative infiltration at point i; a and k = constants; and τ = infiltration opportunity time at point i. Once the net depth of irrigation is defined, the irrigation quality parameters can be defined as shown below:

$$\bar{Z} = \frac{\sum_{i=1}^{N} Z_i(x)}{N} \tag{6}$$

$$V_p = \sum_{i=1}^{N-1} (\bar{Z}_i(x) - D_u)dx_i, \text{ if } \bar{Z}_i(x) \geq D_u \tag{7}$$

$$V_D = \sum_{i=1}^{N-1} [D_u - \bar{Z}_i(x)]dx_i, \text{ if } \bar{Z}_i(x) \leq D_u \tag{8}$$

$$E_a = k \frac{L \, D_u \cdot E_r}{Q \, T_a} \tag{9}$$

$$E_r = \frac{[(N-1) \, D_u \, L - V_D]}{(N-1)D_u \, L} \times 100 \tag{10}$$

$$UCC = [1 - \frac{\sum_{i=1}^{N} \bar{Z}-Z_i(x)}{NZ}] \tag{11}$$

in which $\bar{Z}$ = average amount infiltrated into the root zone; N = number of stations in the field; $\bar{Z}_i$ = average depth infiltrated in section i; V_p = volume of water deep percolated; V_D = volume of deficit in the field; D_u = requirement depth in the root zone; E_r = water requirement efficiency; and UCC = Christiansen's coefficient of uniformity. For a given situation, the slope, infiltration characteristics, roughness, and farm boundaries are fixed. Therefore, the design variables are the flow rate, time of irrigation, and the length of run. The hydraulic model is simulated for different combinations of these three variables. Relationships of the following form were obtained between the design variables and the quality parameters:

$$E_a =$$

$$E_R = K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} \qquad (12)$$

and

$$R_p = K_2 Q_u^{a_2} T_i^{b_2} L^{c_2} \qquad (13)$$

in which R_p = deep percolation ratio; K_1, K_2 = proportionality constants; and a_1 to c_2 = exponential constants. K_1 to c_2 are site specific because their values are dependent upon other variables such as slope, roughness, and infiltration rates also. These relationships were obtained by polynomial regression analysis.

WATER USE SUBSYSTEM

The water use subsystem deals with the actual use of water in the field for crop production. Crops transpire water in response to the atmospheric demand. During the same process, the crops build up their tissues and finally produce grain. The plant water requirements must be met by either rainfall or irrigation. Plants suffer due to water stress if less water than required is provided to the crop. Root zone aeration is restricted if too much water is added. Both effects reduce yields. Hence, the water requirements of the plants must be met if the best irrigation practice is to result. A relationship between yield and the water requirements of the crop is needed to manage water efficiency.

Evapotranspiration

There are many equations to calculate the evapotranspiration requirements of a given crop (Jensen, 1973). Any one could be used depending upon the location, accuracy needed, and climatic data available. The modified Jensen-Haise equation is used in the present study to calculate the potential evapotranspiration, ET_{pr}, of a reference crop (Jensen, Robb, and Franzoy, 1970). The potential evapotranspiration of a crop is given by

$$ET_p = K_{co}\ ET_{pr} \tag{14}$$

where ET_p = potential evapotranspiration of a given crop; and K_{co} = crop coefficient of the given crop. The ET_p values are calculated under no stress conditions. Under actual field conditions, the crop experiences some degree of stress. Hence, the predicted actual evapotranspiration will be less than potential depending upon the soil-water content. A soil stress factor must be taken into account. The soil stress factor, K_s, is defined as:

$$K_s = \frac{\ell n(100\ \theta_s/\bar{\theta}+1)}{\ell n(101)} \tag{15}$$

where $\bar{\theta}$ = soil water content at field capacity; and θ_s = actual soil water content. In the model, the evapotranspiration values are calculated for each day. Then, they are averaged over the particular growth stage. The soil water content on any particular day is given by the following relationship:

$$\theta_i = \theta_{i-1} + R_i + I_i - ET_{ai} \tag{16}$$

in which θ_i = soil water content at the end of ith day; θ_{i-1} = soil water content at the end of (i-1)th day; R_i = rainfall on ith day; I_i = depth of irrigation on ith day; and ET_{ai} = actual evapotranspiration on ith day. If there was no rainfall or irrigation on any day, the values of R_i and I_i are set equal to zero. Immediately after rainfall, the soil surface will be wet. The evapotranspiration rate will be more than the potential. Therefore, a factor, K_r, must be added to the stress factor. K_r is defined as:

$$K_r = \begin{cases} 0.8 & \text{first day after rainfall} \\ 0.5 & \text{second day after rainfall} \\ 0.3 & \text{third day after rainfall} \\ 0.0 & \text{for all other days} \end{cases}$$

Therefore, the total stress coefficient, K_c, is given as:

$$K_c = K_{co}K_s + K_r(.90 - K_{co}K_s),\ K_r = 0 \text{ if } K_{co}K_s \geq 0.90 \qquad (18)$$

<u>Crop Production Function</u>

A relationship between evapotranspiration and yield will help plan irrigations on the farm. Several relationships are currently available. Yaron (1971) developed a polynomial production function. But these kinds of production functions do not consider the differential sensitivity of different growth stages. Multiplicative production functions of the type reported by Jensen (1968) are more useful (Rydzewski and Nairizi, 1979). A multiplicative production function was developed for wheat. The production function is of the form:

$$Y_R = \prod_{i=1}^{N_G} (ET_a/ET_p)_i^{\lambda_i} \qquad (19)$$

where Y_R = relative yield of given crop; λ_i = crop sensitivity factor; and N_G = number of growth periods considered in the analysis.

In the development of the model, data reported by Chauhan, Hukkeri, and Dastane (1970) are utilized. The available data and the assumptions are presented below.

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1. Soil Factors

The wheat crop was grown on a silt loam soil. The mean soil-moisture content at field capacity and wilting point were 17.51 and 7.32 percent, respectively. The bulk density of the soil was 1.45 grams/cc. The depth of the root zone was 3.33 feet (1.02 m). Moisture content of the soil at the time of planting of the crop is assumed to be at field capacity.

2. Plant Factors

The crop was planted on November 26, 1966 and was harvested on April 16, 1967. The maximum depth of rooting occurrs at about 60-85 days after planting (Hagan, Haise, and Edminster, 1967). The phenological stages of the crop are given in Table 2. This breakdown seems to be reasonable. Arnon (1972) reported that tillering stage starts at about 30-40 days after planting. This is very close to the value given in Table 2, which is 45 days.

3. Irrigation Scheduling and Yield

To evaluate the effect of water stress in different growth stages, irrigation water was not applied at the particular growth stages. The different treatment combinations are given in Table 2. No rainfall was reported during the crop growth period, except until after 120 days of planting. The amount recorded was 12 mm. As far as the amount of irrigation is concerned it is assumed that the gross application depth was sufficient to fill the root zone. It is not an uncommon practice. Significant differences in the yield of the crop were observed among the different treatments, as shown in Table 2.

Table 2. Effect of Varying Schedule and Frequency of Irrigation on the Yield of Wheat (Sonora-64).

S. No.	Treatment	Days after sowing						Total Number of Irrigations	Grain yield (q/ha)	Relative yield %
		25 days (crown root)	45 days (tillering)	65 days (jointing)	85 days (flowering)	105 days (milk ripe)	120 days (dough)			
1	A	-	-	-	-	-	-	0	9.29	100
2	B	+	-	-	-	-	-	1	30.41	327
3	C	-	-	+	-	-	-	1	20.61	222
4	D	-	-	-	-	+	-	1	10.54	113
5	E	+	-	+	-	-	-	2	34.18	363
6	F	-	-	+	-	+	-	2	26.05	280
7	G	+	-	-	-	+	-	2	31.59	340
8	H	+	-	+	-	+	-	3	35.41	381
9	I	+	+	+	-	+	-	4	41.77	450
10	J	+	-	+	+	+	-	4	42.75	460
11	K	+	-	+	-	+	+	4	37.57	404
12	L	+	+	+	+	+	-	5	47.75	514
13	M	+	+	+	-	+	+	5	43.27	466
14	N	+	-	+	+	+	+	5	43.45	468
15	P	+	+	+	+	+	+	6	51.09	550
Rainfall (mm)		-	-	-	-	0.8	12.0			

'+' indicates irrigation application
'-' indicates no irrigation
S. Em. = ± 2.09 q/ha
C.D. at 5% = 6.05 q/ha
C.D. at 1% = 8.17 q/ha

4. Potential Evapotranspiration

Dastane (1969) has given potential evapotranspiration values for the Delhi area. These values were calculated using the Penman equation and were given in graphical form by the author. These values are supported by Hargreaves (1977) values for the Delhi area. So the required values of potential evapotranspiration are obtained from Dastane's (1969) paper.

OPTIMAL DESIGN OF APPLICATION SYSTEM

Optimal design of irrigation application systems involves either minimization of costs or maximization of profits. Maximization of profits is the most realistic way of optimizing the irrigation system design. A crop production function is needed to maximize the profits under irrigation. In the design of the system, a relationship must be obtained between the design variables and the yield. This can be obtained by a two-step process: a relationship must be developed between water requirement efficiency and the design variables, as presented earlier, and another relationship between water requirement efficiency and yield, as shown below.

Yield Versus Water Requirement Efficiency

Crop yield is related to a performance parameter of irrigation system. Yield is dependent upon the amount of water provided in the rootzone at each irrigation. The depths of irrigation provided in each section at each irrigation are obtained from the hydraulic model. Using these seasonally constant depths, crop yield is simulated in different sections of the field. After defining the optimal depths of irrigation, the water requirement efficiency is calculated using the irrigation depths in different sections of the field. Here, the depths of irrigation are related to water requirement efficiency, and to yield. Therefore, yield is related, indirectly, to the water requirement efficiency. The relationship developed is as follows:

$$Y_R = \beta_0 + \beta_1 E_R + \beta_2 E_R^2 \qquad (20)$$

where β_0, β_1, and β_2 = regression constants. The water requirement efficiency can be related to the system design variables, as shown earlier. Therefore, now, the yield is related to the system design variables.

The yield in the field is affected by the nonuniform application of water. This reduction in yield must be taken into account in designing irrigation systems. The following relationship (Varlev, 1976) was suggested between yield and nonuniformity of the applied water:

$$Y_{nun} = \alpha_0 + \alpha_1 D_a + \alpha_2 D_a - \alpha_2 F_{nun} D_a^2 \qquad (21)$$

in which Y_{nun} = yield due to nonuniformity; α_0, α_1, and α_2 = regression coefficients; D_a = average depth of water applied in the field; and F_{nun} = coefficient of nonuniformity, which is defined as

$$F_{nun} = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{D_i}{D_a} - 1\right)^2 \qquad (22)$$

In the present analysis, the nonuniformity is taken into account by simulating the crop growth in different sections of the field. The average yield of all the sections is taken as the yield of the crop. The yield is simulated for different levels of water requirement efficiency by changing the combinations of the design variables.

Problem Formulation and Solution

Maximization of net profit is the objective of the optimal design. The gross returns from the crop production and the cost of production must be considered. The costs of production include, the cost of labor, water, construction of headland facilities, and some fixed costs of production. The costs must be considered in the design of an irrigation system. The difference between the gross returns and the costs, i.e., the net benefits must be maximized. The problem is formulated with an objective function of maximizing net benefits. The constraints also must be incorporated into the design process. For details on problem formulation see the papers of Reddy and Clyma (1980), and Reddy and Clyma (1980a).

After formulating, the problem is solved by applying the generalized geometric programming technique. This technique is very useful in design problems, and examples abound in the general area of engineering design. Extensive use of this technique has not been made in irrigation. Vast amount of literature is available on the subject. For a brief discussion of the technique see Reddy and Clyma (1980), and the references therein. This technique gives the optimal values of the design variables, along with the optimum profit under the given set of conditions.

IMPROVEMENT CONCEPTS

Once the model has been developed based on the theory presented earlier, several improvement concepts can be simulated and evaluated for their feasibility and economic justification. A few improvement concepts are presented here: O: As the amount of water delivered at the

> farm, given the inflow rate into the headgate, is dependent upon the canal lining material, the economics of several lining materials (including earthen improvement) can be evaluated.

0: The uniformity of applied water in the field, and the application efficiency are a function of the slope of the field, also. Hence, the economics of land leveling in changing the existing slope of the field to a slope that is optimum under the given set of conditions can be evaluated.

0: The effect of optimal design (as explained earlier) in increasing the net benefits can be estimated.

0: Crop yield in the command area is a function of the total area of cultivation and the yield per unit area. The yield per unit area depends upon the frequency of irrigation or the stress criteria used. For a fixed supply of water at the farm, the water could be distributed optimally on the farm so that maximum net benefits are realized from the farm. The model developed could be utilized in determining either the optimal frequency of irrigation, such as a 1-, 2-, 3-, and 4-week interval, if it is a rotational irrigation system, or the optimal stress criteria, if it is an on-demand method of water delivery system.

0: The infiltration characteristics of the soil change seasonally. This affects the performance parameters such as the application efficiency, tail water ratio, deep percolation ratio, water requirement efficiency, and the distribution uniformity. These in turn affect the crop yield and the net returns. This effect can be simulated using the mathematical model developed above.

0: Under canal irrigation system, the seasonal inflows into the field change. The effect of seasonal changes on crop yield, and the performance of the irrigation system can be evaluated.

SUMMARY

The theory (concepts) of simulation and optimization as applied to irrigation systems improvement is presented. The mathematical models of water conveyance (Trout, 1979), and water application (Strelkoff and Katopodes, 1977, and Clemmens and Strelkoff, 1979) are presented. A multiplicative production function was developed for wheat using data from Delhi, Inida. All the three models were verified using available data. A procedure to optimize the design of surface irrigation systems was also presented. Finally, some system improvement concepts such as the improvement of the conveyance system and the application system, irrigation scheduling, optimal design, simulation for the seasonal variation of inflow rate into the field, and the seasonal variation in the infiltration characteristics of the soil were discusssed.

REFERENCES

Anderson, R. L. and A. Maass, A simulation of irrigation systems, Techni. Bull. 1431, U.S. Dept. of Agri., Washington, D.C., 1974.

Arnon, I., Crop production in dry regions: systematic treatment of the principal crops, Leonard Hill, London, 1972.

Chauhan, D. S., S. B. Hukkeri, and N. G. Dastane, Intensive versus extensive irrigation in wheat, Indian Jour. of Agron., 15, 46-48, 1970.

Clemmens, A. J., Verification of the zero-inertia model for border irrigation, Transactions, Amer. Soc. of Agri. Engnrs, 22(6), 1306-1309, 1979.

Clemmens, A. J. and T. Strelkoff, Dimensionless advance for level-basin irrigation, Journ. Irri. and Drain., Amer. Soc. of Civil Engineers, 105 (IR3), 259-273, 1979.

Dastane, N. G., New concepts, practices, and techniques in the field of water use and management, Proc., All India Symp. on Water Mangt., 109-113, 1969.

Garbrecht, G., Increasing of irrigation efficiencies under the conditions of developing countries, Journ. Assoc. of Engrs. and Archit. in Israel, (10/11), 47-67, 1979.

Hagan, R. M., H. R., Haise, and T. W. Edminster, (eds.), Irrigation of agricultural lands, Monograph 11, Amer. Soc. of Agro., Madison, Wisconsin, 1967.

Hargreaves, G., World water for agriculture: climate, probabilities, and adequacies for rainfed agriculture, Utah State University, Logan, Utah, 1977.

Jensen, M. E., Water consumption by agricultural plants, Water Deficits and Plant Growth, 2, Academic Press, New York, 1968.

Jensen, M. E., D. C. N. Robb, and C. E. Franzoy, Scheduling irrigations using climatic-crop-soil data, Journ. Irri.. and Drain., Amer. Soc. of Civil Engrs., 96(IR1), 25-38, 1970.

Jeppson, R. W. and R. W. Nelson, Inverse formulation and finite difference solution to partially saturated seepage from canals, Proc. Soil Sci. Soc. Amer., 34(1), 9-14, 1970.

Johnson, S. H., W. D. Kemper, and M. K. Lowdermilk, Improving irrigation water management in the Indus Basin, Water Resour. Bull., Amer. Water Resour. Assoc., 15(2), 473-495, 1979.

Karmeli, D. and G. Oron, Analysis of closed conduit irrigation system and its subdivision, Journ. Irrig. and Drain. Div., ASCE, 105(2), 187-196, 1979.

Reddy, A. S. and U. Basu, Seepage from trapezoidal canal in anisotropic soil, Journ. Irri. and Drain., Amer. Soc. of Civil Engrs., 102 (IR3), 349-361, 1976.

Reddy, J. M., Irrigation system improvement by simulation and optimization, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, 1980.

Reddy, J. M. and W. Clyma, Optimal design of furrow irrigation systems, Transactions, Amer. Soc. of Agri. Engrs, (submitted for publication).

Reddy, J. M. and W. Clyma, Optimal design of border irrigation systems, Journ. Irri. and Drain., Amer. Soc. of Civil Engrs., (submitted for publication).

Reddy, J. M. and W. Clyma, Irrigation system improvement by simulation and optimization, 2, Applications, Water Resour. Res., (submitted for publication).

Rydzewski, J. R. and S. Nairizi, Irrigation planning based on water deficits, Water Res. Bull., 15(2), 316-325, 1979.

Strelkoff, T. and N. D. Katopodes, Border irrigation hydraulics with zero inertia, Journ. Irri. and Drain., Amer. Soc. of Civil Engrs., 103 (IR3), 325-342, 1977.

Trout, T. J., Factors affecting losses from Indus basin irrigation channels, Water Managt. Techn. Report 50, Colorado State University, Fort Collins, Colorado, 1979.

Varlev, I., Evaluation of nonuniformity in irrigation and yields, Journ. Irri. and Drain., Amer. Soc. of Civil Engrs., 102 (IR1), 149-164, 1976.

Yaron, D., Estimation and use of water production functions in crops, Journ. Irri. and Drain., Amer. Soc. of Civil Engrs., 97 (IR2), 291-304, 1971.

Staff Paper #46B*

IRRIGATION SYSTEM IMPROVEMENT BY SIMULATION AND OPTIMIZATION: 2, APPLICATION

J. Mohan Reddy and Wayne Clyma

INTRODUCTION

The performance of the irrigation system in Pakistan was not satisfactory. After evaluation of the on-farm irrigation system data, it was realized that the performance of the existing irrigation system could be improved by lining the canals, reconstructing the old canals, proper sizing and designing of the canals, design of the application systems to minimize deep percolation and runoff losses, land smoothing and land leveling operations. The cost and effectiveness of each of these alternatives may be different. The most beneficial alternative is desirable. The benefits are realized in terms of increased crop production in the command area. Therefore, improvement of any component of the irrigation system must be related to the resulting increase in crop production. An integrated model incorporating all the distinct components of an irrigation system was developed (Reddy and Clyma, 1980). This model was later calibrated and applied to a specific situation in Pakistan. The economics of improving the efficiency of the conveyance system and the application system is presented. The performance of the improved application system with optimal design under precision land leveling, and the conveyance system after canal lining and earthen improvement is compared with the performance of the existing system. The performance under the conjunctive improvement of the application and conveyance system is also evaluated.

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DESCRIPTION OF THE STUDY AREA

The model developed in Part 1 of this paper (Reddy and Clyma, 1980a) was applied to a specific location in Pakistan on a farm near Bhalwal in the Sargodha district. This farm is located on Watercourse No. 106 under tubewell 78. The area of the farm considered is 3.24 ha. Data for this study were obtained from Sargodha and studies of the Mona Reclamation Experimental Project at Bhalwal.

The soils at the site are silty loams. Some soils are saline but the majority of the area is non-saline. The bulk density of the soils was 1.52 grams/cm^3. The permanent wilting point and the field capacity of the soils was 6.9 percent and 18.6 percent, respectively. The infiltration characteristics of the soils at Bhalwal are presented in Table 1, as obtained from Haider, Farooqui, and DeMooy (1975).

The growing season of Spring (<u>Rabi</u>) wheat is from October to April. The values of potential evapotranspiration, irrigation treatments, and the wheat yield data for the Spring season of 1974-75 were obtained from Haider, Farooqui, and DeMooy (1975). The common irrigation practices, the farm sizes and the related application efficiencies of the fields in the Sargodha district area, as reported by Freeman, Lowdermilk and Early (1978), are given in Table 2. The fields are level but with uneven slopes and low and high spots. The roughness of the fields (Mannings n) was assumed to be 0.15 (SCS-USDA, 1974).

Table 1. Infiltration data from Bhalwal area (Haider, Farooqui and DeMooy, 1975).

Time, minutes	Cumulative Infiltration, mm
60	24.6
120	33.0
180	38.6
240	42.7
300	45.2
360	47.5

Table 2. Average operating conditions of watercourse 106 command area in Sargodha District, Pakistan (Early, Lowdermilk and Freeman, 1975).

	Location of the farm on the mogha		
Parameter	Head	Middle	Tail
Nakka discharges (lps)	65.4	59.47	59.47
Irrigation frequency (days)	7	24	27
Area of the basin (ha)	0.20	0.20	0.24
Time of irrigation (min)	.24	54	120
Depth of irrigation (mm)	46	84	114
Soil moisture deficiency (mm)	--	84	69
Irrigation delivery efficiency (%)	41	38	51
Watercourse length (m)	476	777	1073
Application efficiency (%)	--	72	61

CALIBRATION OF THE MODEL

The irrigation system model has been verified in Part 1 of this paper. The model must be calibrated in order to be applicable to a given area. Site specific data must be available to calibrate the model. The data required are the input and output variables of each subsystem considered in the Simulation Study. The input values were used to generate output from the simulation models. The output from the simultion of the subsystem models was compared with actual output from the subsystem. If the difference was significant, then the parameters of the system were adjusted until the output from the simulation models agreed very closely with the actual (given) output of the system. The calibrated model was then used to evaluate different management alternatives.

Water Conveyance System

In the calibration of the conveyance model, the data reported by Early, Lowdermilk and Freeman (1978) were used. The parameters of the system are presented in Table 3. The length of the canal considered in the present analysis was 777 m. The values deviated from actual field (nakka) discharges, as shown in Table 3.

Table 3. Performance of the conveyance system model before and after calibration.

Condition	Inflow Rate lps	Loss Rate, lps	Field Outlet Discharges, lps Head Actual	Head Predicted	Middle Actual	Middle Predicted
Before Calibration	97.43	29.74	65.14	58.90	59.48	41.63
After Calibration	97.43	22.70	65.14	66.84	59.48	51.83

In the verification part of the model, actual field measurements for a given section of a canal in the same region were used. Changing the loss rate to 22.65 lps/305 m improved the performance of the model as shown in Table 3. The result improved prediction at the head by percent and at the middle by __ percent. Considering the random variability of the actual measurements, the performance of the model was assumed adequate.

Water Application System

The water application system model is calibrated here. The values of the application system parameters are given as follows:

soil type: silty loam
length of the border: 67 m
width of the border: 30.5 m
inflow rate into the field: 1.86 lps/m
infiltration function: $z = 5.33\ t^{.38}$
Manning's roughness factor: 0.15
time of irrigation: 56 minutes
depth of requirement, D_u: 76.2 mm

The application system model developed in Part 1 of this paper was used to simulate the flow in level basins. The recession time was found to be 34 hours which seemed too high to infiltrate 89 mm of irrigation water. This might have been due to the use of the Kostiakov (1932) infiltrtion function which does not have a constant term for longer times. Therefore, an adjustment was made in the equation to include a constant for longer times. An infiltration function of the following type was developed:

$$z = Kt^a + Ct \tag{1}$$

Infiltration rate at the end of ten hours was taken as the basic intake rate, and this value was set equal to C in Eq. 1. Using linear regression, the following equation was obtained:

$$z = 28.5\ (\mathrm{mm/hr}^a)t^{0.1087} + 2.25\ t \qquad (2)$$

Using this equation, the recession time was found to be 10 hours, which is more reasonable than the previous value of 34 hours. Hence, Eq. 2 was assumed adequate for the present analysis. The application efficiency was found to be 70 percent, which is more than the average value reported by Clyma and Ali (1977). But considering the fact that the application efficiency was related to a level field condition as opposed to an uneven topography under the actual field conditions, and the specific set of data presented here, the performance of the model was assumed to be sufficient.

Water Use System

The water use system model consists of two sub-models: the evapotranspiration model and the crop growth model. The evapotranspiration model was calibrated by Clyma and Chaudhry (1975), hence it is not calibrated here. In addition, calculated potential evapotranspiration values were available for the crop season from Reuss et al. (1976).

Using the multiplicative production function model developed for wheat in Part 1 of this paper, the ratios of actual to potential evapotranspiration were calculated. Then, the relative yield of the crop was also calculated using the sensitivity coefficients developed in the previous paper (Reddy and Clyma, 1980a). The predicted relative yields were compared with the relative yields reported in Table 4. A good correlation ($r^2 = 0.90$) was found between the predicted and actual yield of the crop as shown in Fig. 1. The crop was irrigated at 1, 2 and 4 bars tension in the top 15 cm of soil in the field; hence, most of the time the ratios of actual to potential evapotranspiration were high. It was difficult to calibrate the sensitivity coefficients under moderate

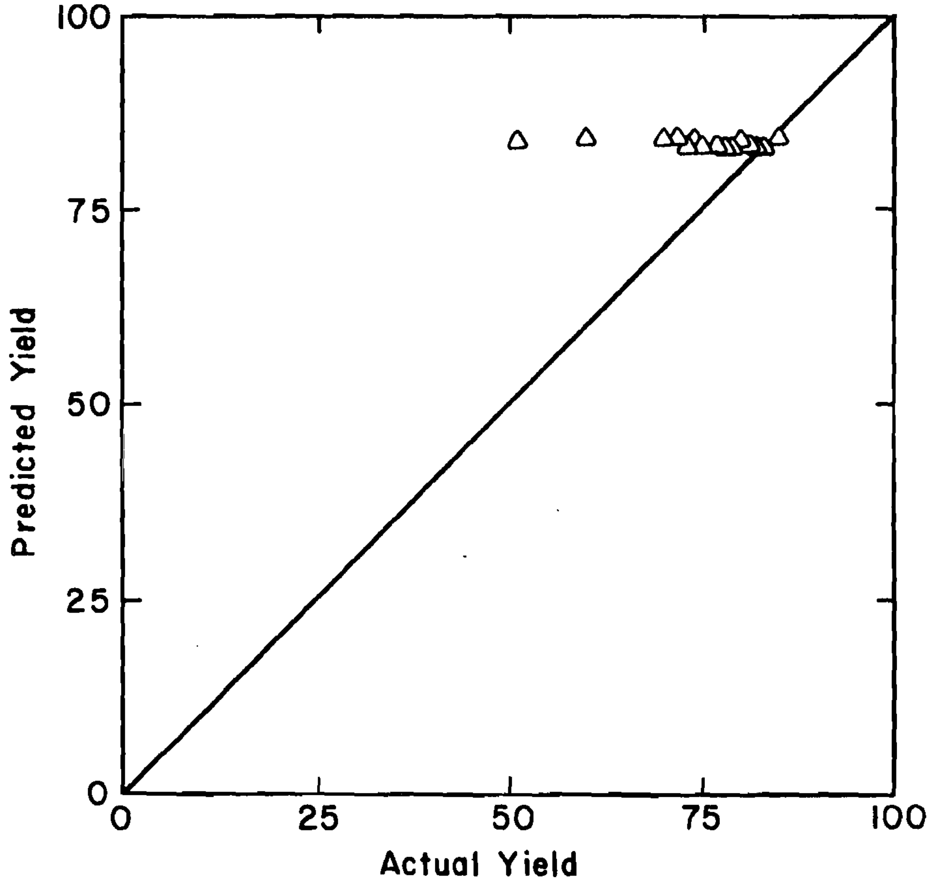

Figure 1. Comparison of actual versus predicted wheat yield for data from Pakistan (r^2 = 0.90)

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to severe stress conditions because of lack of sufficient data. Hence, the model developed here was assumed valid for the given area.

These three subsystem models: conveyance, application and water use, were combined into a single model and applied to the particular situation to evaluate the existing system and the different improvement alternatives.

PERFORMANCE OF THE TRADITIONAL IRRIGATION SYSTEM

The model was first applied to simulate the performance of the system under existing operating conditions. The depths of irrigation applied at each turn were obtained from Clyma (1978). The irrigation depths as reported in Table 4, and the potential evapotranspiration values as reported by Reuss et al. (1976) for the Spring season of 1975-76 were used in simulating the ratios of actual to potential evapotranspiration. The crop production model developed earlier was used in predicting the relative yield of the crop. The depths of irrigation, the requirements at each irrigation, and the relative yields of seven different treatments are presented in Table 5. Clearly, the existing system was operating at an application efficiency of 39 percent with a relative yield of only 0.64. This application efficiency is close to the application efficiency reported by Clyma and Ali (1977) which is 35 percent. The conveyance efficiency of the existing system was found to be 53 percent. This reveals the potential for increasing the efficiency of the irrigation system and the crop yield.

The yield levels under the existing system were low. The reduced yields were related to the nonavailability of water for the crops at each turn. When the irrigation system was designed, it was supposed to operate under a specific set of operating rules. But, the farmer

Table 4. Allocation of water (ha-mm/ha) on Farm No. 4 for Rabi 1975-76 at TW 78, Mona Reclamation Experimental Project (Clyma, 1978).

		Date of Warabundi Turn (day/mo.)																
Field #	Crop	16/10	23/10	30/10	6/11	13/11	20/11	27/11	4/12	11/12	18/12	25/12	1/1	8/1	15/1	22/1	29/1	5/2
168/3E	Wheat				50									105				
168/9N	Wheat			59	50									90				
168/(21,22)$_N$	Wheat/Rouni				59							102						
168/18N	Fallow	135																
168/18S	Fallow/Rouni																	
168/13N	Berseem		28															
168/13S$_1$	Berseem		48	39														
168/13S$_1$	Berseem		33															
168/8E	Wheat				50									82				
168/8W$_1$,W$_2$	Shaftal			59														
168/14N	Fallow																	
168/14S	Wheat		50											30				
176/1B$_1$	Berseem	111		67		50		85			165							
174/1B$_2$	Berseem	111		31	50			74			165							
174/2A$_1$	Berseem	111		30	50	50		76			165							
174/2A$_2$	Berseem	111		30	50	50		78			165							
173/10W	Berseem		52						28									
168/3W	Wheat				50									56				
168/(21,22)$_S$	Wheat				59							160						
TOTAL		580	211	315	469	150		314	28		660	262		362				
RAINFALL													1.25		33	10	8	6

1/Estimated

		Date of Warabundi Turn (day/mo.)														
Field #	Crop	12/2	19/2	26/2	4/3	11/3	18/3	25/3	1/4	8/4	15/4	22/4	29/4	6/5	13/5	20/5
168/3E	Wheat									33						
168/9N	Wheat															
168/(21,22)$_N$	Wheat/Rouni							39							181	
168/18N	Fallow											70				87
168/18S	Fallow/Rouni											208				
168/13N	Berseem								13			50				
168/13S$_1$	Berseem								13			50				
168/13S$_2$	Berseem								13			50				
168/8E	Wheat															
168/8W$_1$,W$_2$	Shaftal								77	91		50	130		49	
168/14N	Fallow															87
168/14S	Wheat								50							
174/1B$_1$	Berseem							40		93		109	57	23	73	
174/1B$_2$	Berseem							40		93		109	57		73	
174/2A$_1$	Berseem							40		93		109	57		73	
174/2A$_2$	Berseem							40		93		109	57		73	
173/10W	Berseem							40					57			18
168/3W	Wheat									33						
168/(21,22)$_S$	Wheat							39						135		
TOTAL								278	165	530		914	424	158	525	191
RAINFALL			8	33	13	11	34	3	34	13	14		8	26		10.0

Table 5. Irrigation interval, net depths, irrigation depths and application efficiency under traditional system.

Fields	Interval, Days	D_a,[a] mm	D_u,[b] mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Relative Yield
1	21	50.8	16.6	32.6	63	106.7	74.4	69.7	91	33.5	0.0	0.0	--	--	--	--	.667
2	14	60.0	12.1	20.2	7	50.8	7.1	13.9	63	90.0	73.4	80.7	--	--	--	--	.650
3	21	60.2	16.6	27.5	49	103.4	53.9	52.1	91	39.6	12.6	31.8	--	--	--	--	.681
4	21	50.8	16.6	32.6	63	83.3	74.4	89.3	--	--	--	--	--	--	--	--	.667
5	7	50.8	7.1	13.9	77	30.5	82.4	100.0	84	50.8	13.5	26.5	--	--	--	--	.515
6	21	50.8	16.6	32.6	63	56.6	74.4	100.0	91	33.5	0.0	0.0	--	--	--	--	.667
7	21	60.2	16.6	27.5	49	162.3	53.9	33.2	91	39.6	12.6	31.8	42	37.4	12.6	9.2	.681

Average relative yield = .648.
Average application efficiency, E_a = 39 percent.

[a] D_a = depth of application

[b] D_u = depth of requirement in the root zone.

follows his own set of rules. Under some circumstances, the irrigation system does not operate the way it was supposed to operate. The behavior of the system is probabilistic. The improvement alternatives will be simulated under the given set of operating conditions that were set at the time of designing the system. Therefore, the existing system performance must also be simulated under similar conditions for a better and direct comparison with the improvement alternatives. It was assumed that the farmer at least applies 50 mm per irrigation under the traditional level conditions. Under these conditions it was found that the farmer can irrigate 0.96 ha each time with a 3-week interval, to be within the range of application efficiency he was obtaining under traditional operating conditions with a 3-week. interval, the farmer can irrigate about 3 x 0.96 ha = 2.88 ha. The relative yield under this condition was found to be 0.97 with an application efficiency of 37 percent. The application efficiencies ranged from 13-64 percent. With a potential yield of 2594 kg/ha the farmer could obtain 2516 kg/ha. Only wheat crop was considered in this comparative study of improvements.

PERFORMANCE OF THE IMPROVED IRRIGATION SYSTEM

Two alternatives were considered in improving the existing system: improvement of the application system and improvement of the conveyance system. These are discussed separately below.

Improvement of the Application System

Optimal design of the application system along with precision land leveling was considered in the improvement of the application system. In optimal design it was assumed that the farmer was able to apply 38 mm of water efficiently at each irrigation. The generalized geometric programming technique was applied to the optimal design of the application system (Reddy and Clyma, 1980). It was found that the farmer can now irrigate 1.28 ha per turn instead of 0.98 ha under the traditional operating conditions. The optimal design gives the optimal rate of inflow, time of irrigation and dimensions of the irrigation unit. An application efficiency of 60 percent could be obtained under precision leveled conditions (Clyma, Kemper and Ashraf, 1977). Therefore, the irrigation intervals must be adjusted under the improved application system to get 60 percent application efficiency. By simulation it was found that the following relative yields and application efficiencies can be obtained by practicing different irrigation schedules:

Irrigation Schedule	Relative Yield	Application Efficiency
2-weeks	0.98	41 percent
3-weeks	0.97	49 percent
4-weeks	0.93	61 percent

So, the farmer must irrigate at a 4-week interval to be at the 60 percent application efficiency obtained by the farmers in the given area under precision level conditions. The application efficiencies ranged from a low of 19 percent to a high of 100 percent.

Johnson, Khan and Hussain (1978) reported that the farmers in Pakistan were getting a yield of 1927 kg/ha (1681+246) with precision land leveling, under traditional canal operating conditions. As mentioned earlier, the relative yield under the traditional operating conditions was 0.64. Therefore, the estimated potential yield under precision level conditions becomes 2974 kg/ha. The yield obtainable under improved design of the application system becomes 2766 kg/ha (2976 x 0.93).

A comparison of benefits under the traditional leveled and precision level with optimal design revealed that the benefits can be increased from Rs 2612 under traditional level to Rs 3625 under precision level conditions. The total benefits depend upon the area irrigated and the yield per unit area. A relationship between the frequency of irrigations, and the relative yield, application efficiency, and total yields is presented in Figure 2. It is obvious from Figure 2 that the net benefits can be increased by spreading out the irrigation frequency. But, after a particular frequency, the benefits start declining because of reduced relative yield and fixed costs of production per unit area. Therefore, an optimal area of cultivation must be chosen in order to obtain maximum benefits. For the given situation, 4-week interval is optimal in terms of total net benefits from the farm.

Improvement of the Conveyance System

Canal lining and earthen reconstruction were considered in the improvement of the conveyance system. The cost and effectiveness of each of these alternatives was evaluated. The life of a lined canal was assumed to be 20 years and that of an earthen improved system to be 8 years (Clyma, Kemper and Ashraf, 1977). An interest rate of 15 percent was used.

The total length of channels (main, branches and field channels) in the watercourse command area of 212 ha was 27,423 m (Freeman, Lowdermilk and Early, 1978). At the rate of Rs 6.56/m, the cost of earthen improvement becomes Rs 179896. The annual cost of earthen improvement was calculated to be Rs 188/ha. Similarly, the annual cost of canal lining is Rs 2446/ha. An annual maintenance cost of Rs 44/ha and

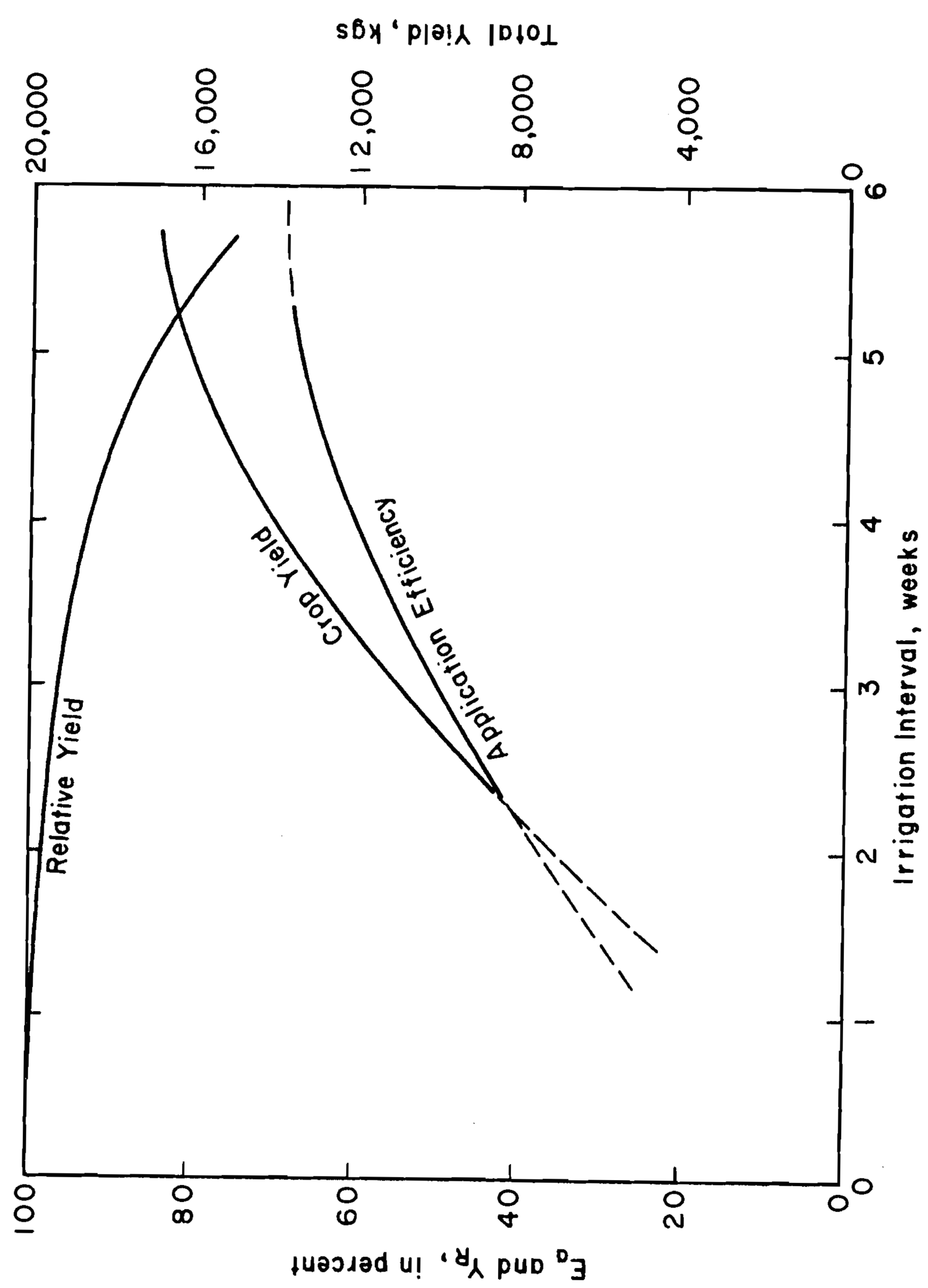

Figure 2. Relationship between irrigation interval, and relative yield, seasonal application efficiency and total yield.

Rs 12/ha (Clyma, Kemper and Ashraf, 1977), respectively, must also be added to the cost of canal lining and earthen improvement. The characteristics of conveyance system improvement alternatives are presented in Table 6.

A comparison of the improvement alternatives is presented in Table 7. Apparently, canal lining is more expensive than earthen improvement. But to make an economic comparison, the total yields under each improvement must be compared. A comparison of costs and benefits of the different improvements are also presented in Table 7. Clearly, earthen improvement is more economical than other alternatives. The benefits under earthen improvement are Rs 3304 as against Rs 2612 under traditional field supply.

Under the improved conveyance system more area is brought under irrigated cultivation. An area of 4.64 ha can be irrigated under earthen improvement as against 2.88 ha under the traditional canal system. This amounts to an increase of 61 percent in the area. Under the traditional simulated system, the yield levels were near potential (a relative of 0.98). Hence, most of the increased supply was applied on additional area.

The above discussion reveals that earthen improvement is more economical than canal lining. The dependability of the supply may also have been a factor in the increased benefits. Under the traditional system some of the area in the command area is always fallowed. So, this additional field supply was used to increase the irrigated area by bringing the fallowed land under irrigation.

Table 6. Characteristics of the conveyance system improvement alternatives.

Type of Improvement	Loss Rate Before Improvement lps/hm	Loss Rate After Improvement lps/hm	Cost of Improvement Rs/metre	Canal Inflow Rates lps	Field Supply Rate, lps
No improvement	7.43	--	--	97.42	51.81
Earthen Improvement	7.43	1.95	6.56	97.42	83.0
Canal lining	7.43	0.46	98.4	97.42	93.86

hm - hectametre = 100 metres.

Table 7. Operating characteristics and net benefits from conveyance system improvement alternatives.

Type of Improvement Characteristic Parameter	Traditional System	Earthen Improvement	Canal Lining
Life of the system (years)	--	8	20
Annualized cost, (Rupees/ha)	--	(183 + 12) = 195	(520 + 44) = 564
Field supply rate (litres/sec)	51.8	83.0	94.0
Area irrigated (hectares)	2.88	4.64	5.25
Gross returns, (Rupees)	2542 * 2.88 = 7321	2542 * 4.64 = 11795	2542 * 5.25 = 13346
Cost of production + lining (Rupees)	1635 * 2.88 = 4709	(1635 + 195)* 4.64 = 8491	(1635 + 564)* 5.25 = 21656
Net benefit (Rupees)	2612	3304	(1800)

Combined Improvement of the Conveyance and Application Systems

To realize the maximum potential, an analysis of the conjunctive improvement of the conveyance and application systems was also performed. The field supply under earthen improvement was found to be 83 lps. The area that could be irrigated under improved application system was 5.12 ha. With the increased supply of water at the farm, it was found that the area could be increased to 8.17 ha.

The area of the individual field units can be increased significantly under precision level conditions because of smaller differences in elevation. This removes most of the field channels that were present under the traditional level conditions. This reduces the total length of the canals significantly. Therefore, the cost of canal improvement now becomes Rs 38/ha and Rs 412/ha, respectively, for earthen improvement and canal lining.

The costs and benefits of different improvement alternatives are presented in Table 8. Obviously, canal lining without improving the application system is not beneficial to the farmer. In fact, the farmer incurs a heavy loss. Earthen improvement with optimal design of the application system with precision land leveling is more beneficial under the given situation. But, it must be emphasized that canal lining also would become beneficial as the potential returns per unit area increase.

Table 8. Comparison of benefits from different conveyance and application system improvements.

Characteristic Parameter	Earthen Improvement		Canal Lining	
	Traditional	Precision	Traditional	Precision
Canal length, (m)	27,423	5,559	27,423	5,559
Earthen, (m)	27,423	5,559	21,864	0.0
Lining, (m)	0.0	0.0	5,559	5,559
Annual cost of improvement, (Rs/ha)	183 + 12	38.33 + 12 + 423	520 + 44	412.22 + 44 + 423.00
Total cost of improvement, (Rs/ha)	195	473.33	564	879.22
Cost of production (Rs/ha)	1,635	1,635	1,635	1,635
Gross return (Rs/ha)	2,542	2,766	2,542	2,766
Area under cultivation, (ha)	4.62	8.17	5.25	9.24
Total benefit (Rs)	3,304	5,373	1,800	2,326

In Table 9, the performance of the different improvement combinations is compared with the performance of the traditional irrigation system. The added net benefits are RS 692, RS 1014, and RS 2761 under the improvement combinations of traditional application and improved conveyance, improved application and traditional conveyance, and improved application and conveyance, respectively. The benefit/cost ratios of these improvement alternatives were almost the same. Also, the area of cultivation is more than doubled under the combined improvement alternative since the benefit/cost ratios of all the improvement alternatives are the same, any improvement alternative may be chosen depending upon the circumstance whether money or land is the constraint.

Table 9. Comparison of benefits from 4-different combinations of improvements.

Performance Parameter	Traditional Application and Conveyance	Traditional Application and Improved Conveyance	Improved Application and Traditional Conveyance	Improved Application and Conveyance
Field supply rate (lps)	52	83	52	83
Area irrigated, (ha)	2.88	4.64	5.12	8.17
Yield (Kgs/ha	2542	2542	2766	2766
Total benefits (Rs)	7321	11795	14162	22598
Cost of production (Rs/ha)	1635	1635	1635	1635
Cost of improving conveyance system (Rs/ha)	--	183 + 12 = 195	--	38.33 + 12 = 50.33
Cost of improving application system (Rs/ha)	--	--	423	423
Cost of improvement (Rs/ha)	--	195	423	473.33
Total cost (Rs)	4709	8491	10537	17225
Total net benefit (Rs)	2612	3304	3625	5373
Total added benefits (Rs)	--	4474	6841	15277
Total added costs (Rs)	--	3782	5827	12516
Percent improvement	--	26	39	106
Benefit: cost	--	1.183	1.17	1.22
Total added net benefits (Rs)	--	692	1014	2761

SUMMARY AND CONCLUSIONS

A farm of 3.24 ha in Pakistan was considered in the present analysis. The theory developed in Part 1 of this paper is applied to the irrigation system. The conveyance, application, and water use subsystem models were calibrated using data from the study area. By simulation the performance of the existing irrigation system was found to be poor: an application efficiency of 39 percent and a conveyance efficiency of 53 percent. Two alternatives were considered to improve the performance of the existing system: improvement of the conveyance system and the application system. The effect of optimal design with precision land leveling was analyzed. It was found that the area of cultivation could be almost doubled, with an application efficiency of 61 percent. Net benefits under precision land leveling without other things being at optimum were not great.

Similarly, earthen reconstruction and canal lining were considered in the improvement of the conveyance system. Analysis showed that canal lining was not at all economical to the farmer, even though the conveyance efficiency was 95 percent to the middle of the watercourse (777 m). Earthen improvement was found economical. Net benefits of Rs 3304 were obtained under earthen improvement as against Rs 2612 and -8310 under traditional system and canal lining, respectively.

A comparison of benefits under earthen improvement and optimal design of the application system with precision land leveling indicated that the total net benefits from precision land leveling with optimal design were more than earthen improvement but with a higher level of investment. The benefit/cost ratios of the two improvement alternatives were the same (1.18). The analysis revealed that combined improvement of the application and conveyance system was more beneficial and with same improvement benefit/cost ratio (1.22). The area under cultivation almost could be doubled with the combined improvement of the application and conveyance systems.

The conveyance, application, and water use subsystems must be combined into a single mathematical simulation model to evaluate and improve existing irrigation systems. Relationships must be established, by simulation, between the design variables and water requirement efficiency, and water requirement efficiency and crop yield. Mathematical programming techniques can be successfully applied to the optimal design of surface irrigation application systems.

The performance of the existing application and delivery systems was not very good. The performance can be significantly improved by a combined improvement of the application and delivery systems. The area under irrigation almost can be doubled. If total investment is a constraint, then either the conveyance system or the application system can be improved because there is no difference in the benefit/cost ratio of the two alternative improvements.

REFERENCES

Clyma, W., Pakistan irrigation frequency analysis, unpublished material, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Colorado, 1978.

Clyma, W. and A. Ali, Traditional and improved irrigation practices in Pakistan, Proc. Water Managt. Irri. Drain. Practice, ASCE, Reno, Navada, July 20-23, 201-216, 1977.

Clyma, W. and M. R. Chaudhary, Calibration and application of the Jensen-Haise evapotranspiration equation, Water Mgmt. Tech. Repo. 40, Colorado State University, Fort Collins, Colorado, 1975.

Clyma, W., W. D. Kemper and M. M. Ashraf, Reducing farm delivery losses in Pakistan, Paper 77-2571, Winter Meeting of the Amer. Soc. of Agri. Engrs., Chicago, December, 1977.

Early, A. C., M. K. Lowdermilk and D. M. Freeman, Farm irrigation constraints and farmer responses: comprehensive field survey in Pakistan, Water Mgmt. Tech. Repo. 48-C, Colorado State University, Fort Collins, Colorado, 1978.

Freeman, D. M., M. K. Lowdermilk and A. C. Early, Farm irrigation constraints and farmers responses: comprehensive field survey in Pakistan, Water Mgmt. Tech. Repo. 48-F, Colorado State University, Fort Collins, Colorado, 1978.

Garbrecht, G., "Increasing of Irrigation Efficiencies Under the Conditions of Developing Countries," Journ. Assoc. Engrs. and Archi. in Isreal, No. 10/11, 1979, pp. 47-67.

Haider, G., M. A. R. Farooqui and C. J. DeMooy, Estimation of consumptive use of water for wheat under optimum management conditions, Publication 39, Mona Recla. Exper. Proj., Bhalwal, Pakistan, 1975.

Johnson, S. H., Z. S. Khan and C. M. Hussain, The economics of precision land leveling: a case study from Pakistan, Agri. Water Managt., Vol. 1, No. 4, 1978, pp. 319-331.

Kostiakov, A. N., On the dynamics of the coefficient of water percolation in soils and on the necessity for studying it from a dynamic point of view for purposes of amelioration, Trans., 6th Comm. Intern. Soc. of Soil Sci., Moscow, Russian part A, 1931, pp. 17-21.

Reddy, J. M. and W. Clyma, Optimal design of border irrigation systems, Journ. Irrig. and Drain. Div., ASCE. 1980, (submitted for publication).

Reddy, J. M. and W. Clyma, Irrigation system improvement by simulation and optimization, 1, theory, 1980a, (in preparation).

Reuss, J. O., M. Saeed, M. Abzal, H. U. Khan and W. Clyma, Irrigation advisory assistance, Annual Technical Report, Water Managt. Res. Proj., Colorado State University, Fort Collins, Colorado, 1976.

Soil Conservation Service, U.S., Border Irrigation, Chapt. 4, Sec. 15, USDA-SCS National Engineering Handbook, 1974.

Staff Paper #47

STATUS REPORT ON THE WATER MANAGEMENT ALTERNATIVES STUDY

Robert P. King

The Water Management Alternatives Study is concerned with the problem of determining how available resources can best be allocated for irrigation improvements at the farm and local delivery system levels. The primary objective of the study is to develop workable models for the evaluation of alternative irrigation system improvements at both these levels. In addition, the models developed will provide a logical analytical framework within which information from all the disciplines involved in the Egypt Water Use and Management Project can be integrated. As such they will help to identify data requirements and help to systematize the data collection process within the project, and they will provide a useful medium through which research results can be summarized and presented.

The overall structure of the modeling effort is described in an earlier report.[1/] Briefly, however, two major models are being developed: an aggregate delivery-drainage system model and a farm level model. These reflect the fact that at least two sets of decision makers have an important impact on the performance of the irrigation system: those who manage the delivery system and the farmers who make use of the water conveyed by it. These two models, though well coordinated with each other, are being developed as separate simulation models which can be run independently with the pattern of outputs from the other model being assumed or combined so that they actively interact with each other.

[1/] King, R. P. and E. N. Biggs, "Progress Report on Water Management Alternatives Study," mimeo.

In this report progress made to date on the models will be described, and future directions for the study will be discussed.

Farm Level Model

The farm level model is designed to identify optimal farmer-initiated investment-management strategies under realistic environmental conditions. The investment component of such a strategy directs changes in the farm level irrigation system such as land leveling and field restructuring, purchasing of improved lifting technology, digging a well, or installing an improved drainage system. The management component of such a strategy focuses primarily on the problem of irrigation scheduling but might also call for changes in levels of fertilization and/or cultural practices.

The farm level model has two major components: a water scheduling and application component and a crop production component. The water scheduling and application component models the implementation of the irrigation management strategy and so determines the timing and amount of water applied. Both the feasibility and the efficiency of any irrigation strategy considered is, of course, affected by investments in irrigation improvements. The crop production component simulates plant-soil-water relationships on a daily basis to determine crop yield. The impact of water table fluctuation is considered explicitly in the model. Outputs of the farm level model include: net return, crop yield, total water applied, total labor used for irrigation, water application efficiency, and water requirement efficiency.

A prototypical version of the model has been developed and tested on the HP9825 A computer. Several support programs for the model have also been developed. The total package of computer programs, which will be fully documented in a forthcoming EWUP staff paper, accomplishes the following tasks:

1. Calculation of reference crop evapotranspiration using the evaporation method described in Crop Water Requirements by Doorenbos and Pruitt.
2. Calculation of potential evapotranspiration for specific crops using procedures described in this same publication.
3. Simulation of soil-plant-water relationships under typical Egyptian conditions including a high, fluctuating water table.
4. Simulation of water application to a level border field given user-specified field size, flow rate, soil characteristics, and depth of irrigation.
5. Simulation of water application, consumptive use, and yield reduction due to moisture stress over an entire growing season for a particular crop grown under level-border irrigation. This program determines net return, overall water application, irrigation labor usage, application efficiency, and water requirement efficiency under user-specified irrigation strategies and system design characteristics.

The programs which accomplish the first three of these tasks, when used in conjunction with data from experiments designed to determine the effect of water stress in crop yield, provide the information needed to estimate the parameters of a yield response to water model of the general form suggested by Hanks:[1]

$$y_r = r_1^{\lambda 1} r_2^{\lambda} \cdots r_n^{\lambda} n,$$

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[1] Hanks, R. J., "Model for Predicting Plant Growth is Influenced by Evapotranspiration and Soil Water," Agronomy Journal, 66 (5): 660-665

where y_r = relative yield (actual yield divided by potential yield)

r_i = relative evapotranspiration in the i^{th} physiological growth stage (actual evapotranspiration for the period divided by potential evapotranspiration)

λ_i = a parameter to be estimated for the i^{th} growth stage.

This model provides a reasonably good fit, and its functional form allows the use of linear regression for parameter estimation.

Using Egyptian data, the parameters of this yield response model have been estimated for wheat. The details of the estimation procedure will be given in the staff paper currently being prepared. Allowances are made for water table fluctuations and their effect in root development and evapotranspiration. This is of particular importance for this data set, since water table levels were not controlled in the experiment which was the source of the data.

A coefficient of multiple determination of .70 was obtained in this initial test of the estimation procedure. This is an encouraging result, since the reliability of the parameter estimation process will likely be improved as programs to estimate actual and potential evapotranspiration and the effect of high water table levels are refined. It should be noted, however, that a sensitivity analysis indicated that the parameter estimates for the model are strongly affected by the accuracy of water holding capacity measurements for specified soil levels, which serve as inputs to the program which simulates soil-plant-water relationships. Since there was some question concerning the accuracy of these measurements for the experimental site, the results obtained to date must still be considered to be preliminary. This problem can be easily corrected in the future, however.

A matter of concern in the use of yield response models based in experiment station results is that they may not be reliable tools for the prediction of yield response under actual farm conditions. One of the advantages of this model is that the effects of at least some of the factors that cause such discrepancies--fluctuating water table levels for example--are endogenous to the model. Still another advantage is that the dependent variable is relative rather than absolute yield. The model can be adjusted for changes in agronomic practices, then, by simply specifying a higher or lower potential yield.

Using weather and soil data for the Kafr El-Sheikh area and the wheat yield response model, the program which accomplishes the fifth task identified above, which can be considered to be a prototype version of the farm level model, has been used to evaluate a range of irrigation strategies. In its current form the model can also be used to evaluate investments in improved lifting technologies. Results to date indicate that the model performs well.

In the near future work on the farm level model will focus on several extensions and improvements. First, efforts will be made to estimate yield response parameters for additional crops such as maize, cotton, berseem, and a vegetable such as tomatoes. Second, the capability to model level furrow and traditional small basin application systems will be added to the model. Third, linkages between patterns of water application and water table levels within the model will be strengthened so that the effects of changes in irrigation strategies and investments in improved drainage on water table levels can be more properly evaluated. Finally, the model will be incorporated into an optimization framework and used to evaluate the effects of alternative water delivery schedules on net returns, yields, and water use.

In the longer term output from the farm level model will be used to develop farm planning models that consider more then a single crop. These will be used to evaluate the effects of alternative investment management strategies on the performance of the overall farm system. In addition, the task of developing the linkage between the farm level model with the delivery drainage system model will be undertaken.

Delivery-Drainage System Model

The delivery-drainage system model simulates water flow through a canal network. Given input data on daily precipitation, daily patterns of irrigation, evapotranspiration levels, soil characteristics, groundwater movements, and canal characteristics it can be used to model spatial and temporal variations in the depth of water in the canal, fluctuation in the water table, canal losses, and the amount and location of return flows within the system. As such the model can be used to evaluate the feasibility of alternative strategies for the management of a local water delivery system. It can also be used to evaluate the effects of delivery-drainage system improvements such as canal lining in the installation of improved devices for the control of water flows.

At present a computer program designed to implement the model has been written but is not yet operational. The program's structure is quite general so that it can be used to model most irrigation systems with a minimum of modification. Once operational, it will be run with data collected at the Mansouria site and used to analyze several alternative system management-design strategies.