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REPORT SUMMARY

A. Project Description

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Contract No: AID/csd-2162

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Contract Period: 28 June 1968 through 27 March 1973

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AID total funding to date:	$1,722,649
Total expenditures and obligations through 27 March 1972:	$1,241,649
Total expenditures and obligations for 28 March 1972 through 27 March 1973:	$ 481,000
Estimated expenditures for next year:	$ 481,000

B. Major accomplishments during this report period included:

Practical procedures were developed for analyzing various well designs, patterns of installation and pumping rates as these affect the salinity of water pumped from a fresh layer overlying saline groundwater. Considering these factors and the relative prices of materials and labor in Pakistan, shallow dug wells, pumped at 0.2 cu. ft./sec were found to be the least expensive facilities studied for retrieval of fresh water which is underlain by saline water.

It was found that irrigation beyond the consumptive use and leaching requirement (standard U.S. Salinity Lab calculation) did not increase yields of sorghum or berseem, even when salinity of the water was 2700 ppm. This information will provide guidelines which should help save large amounts of water which have previously been used in unnecessary leaching.

Based on flume studies, an empirical equation was developed which predicts sediment concentration of water passing through a turnout and establishes guidelines which will enable watercourse managers to distribute sediment where it will not interfere with water delivery to the farm.

An optimization model was constructed which indicates that irrigation water supply in Pakistan can be doubled and supplied on demand at relatively reasonable cost by enlarging the canal system to allow diversion of more summer river water, filling the underground storage and pumping this water when needed during the dry season.

Accomplishments during the life of this project:

In addition to those listed above, major accomplishments include development of an educational and training film on land leveling. This film is helping educate farmers, and congressmen to the benefits of land leveling and improved water management.

Reduction of corn seedling emergence by salinity has been partially overcome by application of phosphorous. This finding could help solve the chronic problem of low stands of corn, cotton and other summer crops in Pakistan.

Land leveling for more uniform water distribution and reasonably good cultural practices have increased yields of wheat, corn and cotton. These yield increases, if extrapolated over the whole irrigated area, could eliminate food deficits in Pakistan.

ANNUAL PROGRESS REPORT
FOR WATER MANAGEMENT RESEARCH PROJECT
FOR YEAR ENDING OCTOBER 31, 1972

Submitted to

The U. S. Agency for International Development
Contract AID/csd-2162

December 31, 1972

STATE UNIVERSITY COLORADO

Colorado State University
Fort Collins, Colorado

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ANNUAL RESEARCH REPORT

A. General Background

Inadequate water is the primary constraint on agricultural production in a large portion of the developing countries. The technology for using available water supplies most efficiently is either lacking, or not adapted to the resources available in many of these countries.

Recognizing that these water management problems were common to many countries, it was apparent that solutions gained in one country should be, to some degree, transferable to others. Consequently, it was decided that a coordinated effort should be made to build up a fund of transferable water management technology. A consortium of universities known as CUSUSWASH [1/] was formed to develop this fund of water management information and gain experience in the factors limiting or accelerating its adaptation in new countries. CSU was initially assigned the Near East - South Asia, with Pakistan selected as the study area in which on farm water management principles and concepts would be developed and adapted to resources similar to those available in many other developing countries.

Government of Pakistan and USAID/Mission spokesmen agree that the major bottleneck to improving irrigation efficiency on the 30,000,000 acres irrigated in Pakistan is at the on farm watercourse level. The overall water management problems of the farmers are:

1. Inadequate control of amount, timing and uniformity of distribution of water.

2. Inability of farmers to use modern efficient irrigation farming techniques due to a combination of technical, educational, economic and legal/institutional constraints.

3. Salinity of some tubewell waters.

[1/] Council of US Universities on Soil and Water development in Arid and Sub-Humid areas.

The following objectives indicate the general areas in which research is needed. The specific studies have been designed in cooperation with USAID and GOP scientists, to gain needed guidelines for better water management.

B. The General Objective of the Project is:

To increase food production in the arid and sub-humid lands of the less developed countries through the improvement of water management practices and the integration of these with other good management and cultural procedures.

Specific Objectives are:

1. The development of knowledge and data on how best to conserve and utilize water falling on the land as rain and the most efficient means of supplementing needed soil moisture by limited amount of irrigation water.

2. The development of knowledge and data that can be used for the economic design and construction of water conveyance and delivery systems including structures for control and measurement of irrigation water, especially on the farm.

3. The development of surface and subsurface water removal to eliminate the hazards resulting from surface flooding and high water tables, especially on the farm.

4. The identification of important factors to be considered in preparation and leveling of the various irrigated soils in the major climatic zones and the relationship of these factors to water management, erosion, water infiltration, and good land use and cropping practices.

5. The development and adaptation of methods of water application, including time and amounts, which are suitable and efficient for different soils of varying physical properties (water-holding capacities, intake rates, etc.) with major crops.

6. The integration of these water use factors into a productive cropping system consistent with farm size and available farming practices.

7. Where water quality, soil salinity and exchangeable sodium are problems, studies will include soil amendments, soil and water management procedures and use of salt-tolerant crops.

8. The identification of institutional and policy factors (legal, social, economic, religious, manpower, credit, education, etc.) which influence efficient distribution and management of water on the farm level.

C. Continued Relevance of the Objectives

Our research findings, preliminary surveys in Pakistan and consultation with USAID and GOP personnel indicate that accomplishment of the original objectives will benefit Pakistan and contribute to the fund of transferable water management technology. A survey of the resource position of the Pakistani farmer shows that the average farmer is unable to invest a large amount in technology. Consequently, variants of our water management technology package should be developed which will be labor intensive and within the means of the small farmer. This will not necessitate any change in our overall objectives, but will require our continuing consideration to ensure that the technology which we help produce can be used to increase productive work opportunities, as well as produce more food.

D. Accomplishments to Date

The report is organized according to departmental endeavors to correspond to last year's work plan. The field party chief and three additional scientists who arrived in Pakistan this year have initiated additional studies on Water Management as opportunities for effective cooperation developed with GOP agencies. These new studies have been interdisciplinary in nature and are reported in the last section.

1. Agricultural Engineering

a. Designs for Pumping Fresh Groundwater While Minimizing its Contamination by Saline Water from Lower Levels of the Aquifer (contributing to Objective #7)

The first step of the research plan for the report year was to investigate the validity of existing theories used for "skimming well" design. This was accomplished through the use of a physical model. The next step was to develop a mathematical model which eliminated the most restrictive assumptions and approximations in the existing theories. These first steps have been completed and are reported in detail in CSU Water Management Technical Report No. 18 (Sahni, B. M., Salt-Water Coning Beneath Fresh Water Wells).

The most important practical conclusions derived from the above study are that:

(1) The optimum penetration of skimming wells is the upper 10 to 20 percent of the original fresh water thickness. This is in contrast to the much greater penetrations recommended by other investigators who based their conclusions on a less realistic analysis.

(2) The salt-water cone becomes unstable if allowed to rise above a certain critical elevation. The range of critical cone heights for various degrees of penetration is between 50 and 70 percent of the distance between the original fresh-salt water interface and the bottom of the well.

The above findings constitute useful criteria for the design of skimming wells in Pakistan.

Technical report No. 20 (McWhorter, D. B., Steady and Unsteady Flow of Fresh Water in Saline Aquifers) was also completed during this reporting period. The major accomplishments outlined in this report are:

(1) The "State of the art" and the advantages and disadvantages of several theoretical approaches and results are summarized.

(2) Procedures for analyzing the effectiveness of horizontal tile drains and collector wells as skimming facilities were developed and it was found that depth of horizontal drains below the water table must not be more than about 5% of the thickness of the fresh water layer if tapping of the underlying salt waters is to be avoided. Changes in water-table elevation, cohesionless soils, installation expense, and land ownership in Pakistan reduce the potential of horizontal tile drains as practical skimming facilities.

(3) An approximate differential equation was derived which describes unsteady flow of fresh water in saline aquifers. Procedures for using this solution to analyze the rate of rise of the salt water cone, interference among wells, and the effect of operating schedules are outlined. These results are useful for ascertaining the relative merits of distributed pumping, large diameter wells, and different well patterns as skimming facilities.

The work contained in Report No. 20 was a necessary intermediate step toward the practical design of field installations because the mathematical model of Sahni can not be directly used to provide answers to the practical questions posed above.

A third document entitled, "Practical Skimming Well Design" was produced and will soon be published as a Water Management Technical Report (by F. A. Zuberi and D. B. McWhorter). The purpose of this work is to bridge the gap between the previous theoretical and laboratory studies and actual design of skimming facilities in Pakistan.

It was established that the approximate solution of McWhorter (Report #20) was sufficiently accurate to be useful for certain aspects of engineering design. This was accomplished by comparison with the experimental data collected from the physical model. The solution was then used to make comparative calculations for several well patterns. The depth of penetration and the maximum permissible cone height predicted by Sahni were adopted as design constraints throughout the work.

In addition to the comparison of the different well patterns and pumping schemes on a technical performance basis, the costs of alternatives were computed under Pakistan price structures (for details see appendix A). The most important conclusions are:

(1) A large diameter dug well penetrating the upper 10-15 percent of the fresh water layer and cased with brick is the most economical scheme for collecting fresh water, but the cost of skimming this fresh water is about 50% higher than the cost of indiscriminate pumping from the saline aquifer.

(2) Under "typical" conditions in Pakistan, a discharge of about 0.2 ft^3/sec (100 gpm) can be realized without salt water intrusion from such a well. The cost of the well and the pump is approximately 3200 rupees.

Comparison of design alternatives contained in the Zuberi-McWhorter report was based on several factors besides technical performance. Cost of materials and availability in Pakistan were considered in relation to the farmer's resources. Skills available in the village, foreign exchange, labor intensive vs. capital intensive designs and tradition were other factors given consideration. The dug well is apparently the best alternative because:

(1) Technical performance rates are high.

(2) The ratio of labor costs to capital costs is a maximum.

(3) Bricks used for well lining are commonly available.

(4) Skills required for construction of dug wells are commonly available and widespread.

(5) Total cost is comparable to other skimming systems studied.

The next step is to field test in Pakistan the guidelines developed for skimming well design. Plans have been prepared and a field installation is anticipated in 1973.

The findings that "skimming" to achieve water of the lowest salinity is best accomplished using inexpensive, small capacity wells has the following implications.

(1) Relatively small farmers may be able to construct such wells.

(2) There is a need for irrigation methods which will achieve good distribution of small flows (i. e. 0.2 cu ft/sec) of irrigation water.

There are two aspects of skimming well hydraulics which remain less than adequately understood. These are:

(1) The effect of low permeability in the vertical direction relative to that in the horizontal direction.

(2) The effect of a transition zone between the fresh water and the underlying saline water.

Both of these conditions are common in Pakistan and may have a significant effect on optimum design and pumping rates from wells. A numerical solution which accounts for the differences in vertical and horizontal permeability has been completed. Preliminary results show that optimum pumping rates may be 50 to 100 percent higher than calculated assuming isotropic permeability.

Studies of the effect of a transition zone have just begun. The major accomplishment to date has been the preparation of a literature review on miscible displacement; the phenomena which determines the effect of the transition zone.

b. Land Leveling Film

The development of a second training film depicting the process of land formation has been underway throughout this reporting period. Filming was accomplished, principally in Pakistan, under local conditions. The script for this training film was completed this past year and is presently out for review. Photography is about 80% complete.

c. Water Control and Land Preparation (contributing to Objective #4)

(1) Effect of tractor powered tillage on crop yields and soil characteristics important for improved irrigation water management

Some of the silty soils of Pakistan have low infiltration rates and the crops have shallow root systems. This study was designed to determine whether mold board plowing, deep tilling or amendments would allow deeper root penetration, which would give the crop a larger available water reservoir (reducing drought incidence) and reducing the amount of water which leaches past the root system without being used.

Treatments were subsoiling to 20", plowing (mold board), and cultivation with the standard tiller now in use. Plots were split to receive gypsum, gypsum plus manure, manure alone and a check plot. Wheat yields were measured in the spring of 1972. During the summer the experimental area was leveled and smoothed and wheat was planted again in the fall. Water contents of the soil were measured during the growing season, but analysis of the data has not been completed. The major difference noted in wheat yield was substantially lower yields on the deep tilled plots due to severe lodging.

(2) Comparison of Water Management Practices under Mechanized and bullock farming conditions

This work is carried out with the Machinery Demonstration Unit, Agricultural Engineering Directorate of Lyallpur. The objective is to compare water use effectiveness and yield of wheat under mechanized border irrigation and compare it with the traditional system of bullocks, bunds and basins. The demonstration covers about 16 acres. Water is measured into 30 foot borders that range from 600 to 900 feet in length. Data gathered includes soil moisture before and after irrigation, rates of water advance and rates of water recession on the borders and infiltration rates on all plots. This study was initiated in the fall of 1972

and preliminary results (advance and recession curves) indicate that border irrigation (with 0.8 Cu ft/sec flow) results in more uniform application of water than the common bullock associated system in which several basins are filled in succession (by allowing the first basin to fill, cutting the bund separating it from the second, allowing the second to fill, etc.).

2. Agronomy

a. Yield of Wheat, Sorghum Fodder and Berseem as Affected by Water Quality and Leaching Fraction (contributing to Objectives #5 and #7)

This experiment was initiated to study the effect of water quality and leaching fraction on the growth of rabi and kharif crops at the Punjab Agricultural Research Institute in cooperation with Hyatt Bhatti, Agricultural Chemist. There are four water qualities ranging from 175ppm soluble salts (canal water), to 2700ppm (tubewell water) with two mixes of 1000 and 2000ppm. Leaching fractions varied, depending on the water quality, from zero to 60% of the consumptive use.

The experiment was initiated first in the fall of 1970, but since the tubewell was not connected until 1971 the first results with water quality were not obtained until the 1971-72 wheat crop. This was followed with sorghum fodder for 1972 kharif and with berseem for the 1972-73 rabi crop.

Results for the 1971-72 wheat crop, the sorghum fodder and the first cutting of berseem are given in the attached table.

There was only a small effect of water quality on the yield of wheat (rabi 1971-2) since the tubewell water used to establish a water quality variable was not applied until the first irrigation for wheat in December, 1971. Water quality and leaching fraction were as planned throughout all subsequent irrigations, however. The yield differences among leaching fractions for each water quality appear to be field variation and not treatment effects.

The results for the fodder and berseem crops show, in general, that the water quality effect has quite a marked effect on crop yield and that the use of an increasing amount of leaching water above that calculated from the Salinity Lab equation (the lowest leaching fraction for each water quality) is of no additional benefit. In the case of the 2700ppm salinity water, additional leaching appears to reduce yields which could be due to nitrate leaching. Field variation, however, appears to prevent any firm conclusions on the effect of leaching fraction at this time.

Table 1. Yield of wheat, sorghum and berseem as affected by water quality and leaching fraction, PARI, 1971-72

Salinity of water ppm	Leaching Fraction (%) 0	10	15	20	30	45	60	Average
	- - - - - - - Yield of wheat - md/A - - - - - - - -							
175	46.1	45.0	(45.3)	45.6				45.6
1000		42.0	(44.0)	46.0	46.2			44.7
2000			46.6	(46.9)	47.7	49.2		47.8
2700					50.1	46.8	45.1	47.4
	- - - - - - - Yield of sorghum - md/A - - - - - - - -							
175	515	483	(480)	476				491
1000		402	(394)	386	451			413
2000			343	(348)	358	434		378
2700					400	370	329	366
	- - - - - - - Yield of berseem - lb/A (1st cutting) - -							
175	622	625	(648)	671				639
1000		620	(592)	555	674			616
2000			515	(445)	411	491		472
2700					380	294	356	343

( ) Calculated value by assuming linear response between leaching fractions.

b. Physical, Chemical and Mineralogical Characteristics of Punjab Soils (contributing to Objectives #4, 5, and 7)

Transference and generalization of crop yield data from one location to another requires that the soil and climatic conditions be characterized. Since adequate characterization was not available on most of the soils where we were establishing cooperative work, our cooperators and potential cooperators took samples in the 0 to 1, 1 to 2, 2 to 3, 3 to 4, and 4 to 5 ft. intervals at eleven locations in the Punjab. These samples were shipped to CSU and analyzed for mineralogy, texture, water holding capacity at 15, 0.33 and 0.0 bars tension, water soluble cations and anions, sodium adsorption ratio, exchangeable sodium percentage, pH, organic matter, lime, and available phosphorous, zinc, and iron.

Details of these analyses are given in Appendix B and have been supplied to our Pakistani cooperators. Some of the general conclusions are:

(1) Low N(O.M.) and P levels are common which indicates that crop yields will be limited by lack of these nutrients as water management is improved unless these nutrients are supplied in large amounts.

(2) Available water holding capacities of these soils (15 to 1/3 bar suction) ranges from about 0.11 to 0.21 inches of water per inch of soil. Since crop roots in these soils appear to be restricted largely to the top 30 inches of soil, these data indicate that irrigations in excess of 3.5 inches on the coarser textured soils and 6.3 inches on the finer textured soils will result in water loss and nitrate leaching to the groundwater.

(3) Clay mineral types are relatively uniform over the area sampled. Low-swelling type clays, mica and chlorite, are predominant. High swelling montmorillonite and/or vermiculite are found in lesser amounts. A metamorphic rock origin is indicated for

sand and silt minerals. The calcium-bearing mineral content is low, indicating that little calcium release, which would tend to improve water quality, can be expected through chemical weathering.

(4) These soils are high in silt (average 54%) and low in organic matter (average 0.6% in the surface soil). The surface soils are low in available nitrogen and phosphorous. Micronutrients generally are sufficient. The combination of the mineralogical suite, the high silt content, and the low organic matter explains the poor structural properties, low infiltration rates, and the difficulties encountered in seed-bed preparation for upland crop production. The same properties can also explain the excellent puddling properties for paddy rice.

(5) The mineralogy, texture, organic matter content and crusting, water table and salinity problems of these soils are similar to those of the Grand Valley in Colorado. Consequently much of the extensive technology developed for water and salinity management and associated production improving practices in the Grand Valley is physically compatible and should be adaptable in the Upper Indus Basin.

c. Effects of Salinity and Na on the Growth of Alfalfa and Barley at Various Levels of Available Phosphorous (contributing to Objective #7)

Most of the soil samples from Pakistan that were analyzed in the Colorado State University Soil Testing Laboratory were found low in available soil phosphorous. Phosphorous deficiency among crop plants in Pakistan probably is second only to nitrogen deficiency. A crop response to phosphorous would be expected on non-saline, non-sodic soils shown to be deficient in phosphorous by the soil test. However, there is a strong local belief in Pakistan that fertilizers are wasted when applied to lands irrigated with saline and sodic water. Since 16% of the irrigated land is supplied with water of 1000ppm or more salt (M. Hussain, 1970 NESA Conference, p 311), information is needed to determine if the results of the sodium bicarbonate soil test procedure for P, which is

highly successful for non-salt-affected soils, can be applied to the saline and sodic soils of Pakistan. Essentially, no published results are available that will provide this information. An unpublished Israeli report and some indirect observations in the literature constitute the extent of information.

The objective of this research was to determine the influence of soil salinity and exchangeable sodium (originating from irrigation water) on plant growth response to increasing levels of available soil phosphate. The first phases were planned as a greenhouse study with subsequent studies to be conducted in a field program in Pakistan if the results indicated need.

Details of this study are outlined in Appendix C. In general it was found that 20% exchangeable sodium on these sandy, physically stable soils, did not reduce barley or alfalfa yield and that P fertilization at 20% ESP gave yield increases comparable to P fertilization in non sodic soils. At ESP = 40, plant yields were reduced and added P gave relatively small increases in yield.

Salinity of the soil water of 4 mmho/cm (saturation extract) compared to 0.26 mmho/cm caused reductions of vegetative barley and alfalfa growth ranging from 0 to 35%, and averaging about 25%.

Extrapolation of the ESP conclusions to finer textured soils would not be wise since 20% ESP generally results in considerable dispersion, structural collapse and decreased permeability of fine textured soils. However, it is apparent from this study, that the deleterious effect of high Na levels (at least up to ESP = 20) on yields is not due to a direct negative effect on the nutrition (P or other nutrients) of the plants. Decreased growth observed in the field at ESP = 20 must be due to the effect of the Na on the structure, water permeability and possibly aeration of the soils. Low permeability and dispersion results in soil surfaces being sealed against air entry for long periods of time during and following irrigation. This condition could lead to decreased O_2 supply and possible denitrification of the NO_3 ($2NO_3 \rightarrow N_2 + 3O_2$) and other reductive processes which are deleterious to plant nutrition.

3. Civil Engineering

a. Sediment Conduction of Farm Turnout Structures

(Contributing to objective #2)

Sediment accumulating in watercourses reduces the carrying capacity of the watercourses, resulting in bank breakage, loss of water and eventually the necessity of cleaning the accumulated sediment from the watercourse. Data on the effect of turnouts on sediment conduction is scarce and such data is needed to provide guidelines for optimum sediment distribution in canals and watercourses.

A recirculating flume 100 feet long, 8 feet wide and 3 feet deep, capable of velocities up to 2.5 ft./sec. represented a section of a distributary and a turnout with a 4.5" square throat was constructed in the side wall to simulate the type of turnout used in Pakistan. The level of the turnout was made adjustable to represent the range of levels encountered in the field. Data on the amount of sediment passing into the turnout was collected for wide flow conditions, both in the flume and in the turnout. Data were also collected on sediment transport in the flume.

The data showed a large stochastic component of the sediment conduction through the turnouts related primarily to migration of bed forms past the turnouts. Elaborate regression analysis was required to arrive at predictive equations that will be of value to designers and operators of distribution systems.

The scope of the study provided good understanding of the phenomena controlling conduction of sediment by farm turnouts, but emphasis of the project on-farm water management has resulted in termination of this study before all the variables in the model were completely explored.

The study included over 130 runs including the following range of dependent and independent variables:

(1) Discharge of water per foot width in the flume: from 1.2 to 2.4 cubic feet/sec.

(2) Discharge of water in the turnout: from 0.25 to 1.7 cf/s

(3) Concentration of sediment in the flume: from 1 to 1050 ppm

(4) Concentration of sediment in the turnout: from 3 to 3860 ppm

The sediment used had a mean diameter of 0.19 mm and a gradation coefficient of 1.35 comparable to the bed material.

In all cases the average concentration of sediment in the turnout was larger than the average in the flume. This was found to result from turnouts drawing their water selectively from the lower strata of the flume flow where the sediment concentration is highest. A predictive equation obtained by regression analysis has the form

$$C_t = 26\ C_f^{0.86}\ Z^{2.1}\ F_n^{2.0}$$

and was applicable to the range of data obtained in this study. In this equation C_t is the sediment concentration of water passing through the turnout, C_f is the concentration in the flume, and Z and F_n are the Rouse and Froude numbers of the flow in the flume.

Details of these studies are outlined in the thesis titled, "Sediment Conduction in Farm Turnouts," by Allah Rakha and the thesis to be completed in February by Ata Nazar titled, "Sediment Withdrawal Characteristics of Farm Turnouts."

A surprising aspect of this study was that height of the turnout had relatively little effect on sediment conduct through the range of heights studied (0.2 to 0.5 ft. above the flume floor).

Realizing that low velocity turnouts at the water surface will draw off water with sediment concentration lower than the average concentration of the flume or canal, it is apparent that to a large extent sediment can be distributed where desired in a water delivery network by proper design and placement of turnouts.

b. Optimum Conjunctive Use of Canal and Well Water

(Contributing to objective #2)

Two primary characteristics of the canal water supply to Pakistani farms are: (a) its insufficiency, approximately 48 million acre

feet of water per year on 33 million acres of cultivatable land, and (b) its ephemeral nature. Most of the canal water is diverted directly from the river and there is little surface storage capacity in the system. These characteristics of the water supply are one of the main constraints on crop production in Pakistan.

Most of the irrigated area is underlain by a deep sandy aquifer. Tubewells in this aquifer presently retrieve about 10 million acre feet of water per year which is used alone, or mixed with canal water for irrigation. This water is available on demand, and since it is generally used near the well, there is little transmission loss or evaporation loss. A conjunctive use model has been constructed to determine the extent to which use of this aquifer as an "on farm" or "within watercourse" reservoir and subsequent pumping from this reservoir could meet the specific water needs of certain crop patterns. The model can be used to determine the economically optimum mixture of surface storage, aquifer storage, and canal enlargement to utilize the water most efficiently in meeting crop requirements. Details of the model and relation of this study to previous studies are outlined in the thesis by M. T. Chaudhry titled, "Conjunctive Use of Indus Basin Waters." Assumptions used in constructing the model and in making the calculations, which lead to the conclusions indicated below, are discussed in detail in this thesis. Based on these assumptions, the optimization model and associated calculations have shown that:

(1) Unless the value of electric power goes up beyond reason it is more economical to enlarge the canals and divert more of the summer water, increase the summer rice acreage, and recharge the aquifer than to build surface storage sites on the river for storing irrigation water. For instance, water from surface storage such as Tarbela reservoir costs $9 to $15/acre foot delivered to the farm, whereas groundwater can cost as little as $2 to $3.50 for farm water supply at the tubewell if the increased recharge can be achieved at negligible cost as a result of necessary canal enlargement and increased rice acreage on permeable soils.

(2) The freshwater aquifers of the Indus Basin have adequate storage capacity to provide water during the dry season to areas which lie above them, and to adjoining areas lying over saline aquifers. These calculations indicate the advisability and feasibility of concentrating recharge (rice and leaky watercourses) in nonsaline areas, lining watercourses in the saline areas, and transferring pumped water from nonsaline to saline areas during the dry season.

(3) The water supply to the irrigation fields in Pakistan can be more than doubled by effective conjunctive use, recycling of water through the aquifer media, and enlarging the canal system to allow diversion of more of the summer river water. The conjunctive use system can be operated as a "supply on demand" system rather than as the "use when available" system for which there is now no option.

Although the results of this conjunctive use study could markedly improve the on-farm water supply, the broad aspects to which this study has expanded are not confined to on-farm water management which is the objective of the Water Management Research Contract. Funds for continuance of the conjunctive use studies will be sought from other sources.

Comparison of the results to date on this study and the skimming well study indicates that recharge to nonsaline areas and transfer of pumped water to saline areas could be a less expensive method for retrieving fresh water stored in the aquifer than skimming fresh water layers from the top of saline aquifers. Better cost estimates of recharge resulting from rice flooding, canal enlargement will be necessary to determine which of these methods is best for retrieving water from the aquifer for use during the dry season on saline areas.

c. Predicting Groundwater Basin Response to Pumping and Recharge Operations Using Surrogate Parameters

(Contributing to objective #3)

As groundwater development for irrigation reaches advanced stages the interaction of different wells and recharge operations become strongly interrelated. This study was designed to develop models

which are compatible with available data and give the best possible estimates of the interactions between recharge sources and pumping.

A surrogate-parameter approach was used to develop a basin model. Various aspects of inhomogeneity, isotropism and unknown boundary conditions are incorporated into the lumped surrogate capacity ($\bar{S}$) and transmission ($\bar{K}$) parameters. The surrogate-parameters in finite areas associated with available data points are linked by only the mass conservation principle. The basic assumptions of this development are:

(1) The response of a particular well in a nonhomogeneous, nonisotropic aquifer, assuming (i) no interference from adjacent wells, and (ii) no interference from boundary effects, can be predicted with sufficient accuracy (for practical modeling problems) using the same basic flow equation (Equation 1), but replacing the highly variable, continuously distributed parameters $S(x, y)$, $K(x, y)$ with lumped surrogate-parameters $\bar{S}_i$, $\bar{K}_i$ associated with well i and the near-well properties of the porous media.

(2) In order to properly consider well interference, we assume that the response at well i due to pumping at well j is <u>primarily</u> dependent upon the near-well properties $\bar{S}_j$, $\bar{K}_j$ of well j, rather than those of well i.

(3) The total response at well i due to several sources can be determined through linear superposition.

The advantages of this model over the currently used simulation type approaches are:

(1) Conduciveness to modeling nonhomogeneous and nonisotropic basins.

(2) Less arbitrariness, since complex boundary conditions and natural recharge to the basin need not be guessed.

(3) Not requiring arbitrary division of a basin into homogeneous sections.

(4) Formalization of the parameter identification problem as a mathematical programming problem.

Computational experience indicates that the surrogate parameter approach is a valid alternative to the current heavy emphasis on simulation modelling. Details of the model, its potential, limitations and needs for continued development are available in a report by John Labadie titled, "Predicting Groundwater Basin Response to Pumping and Recharge Operations Using Surrogate Parameters," copies of which may be obtained from the CSU Water Management Research office.

Although this model could eventually provide the best guidelines for well and recharge area placement in watercourses, the scope of the study goes beyond "on-farm water management" and it will not be continued under the Water Management Research Project.

4. Economics

In response to suggestions by AID/Washington and USAID/Pakistan, the economics research was reoriented during the year with a major emphasis being placed on the role of water law in facilitating good water management. Considerable new research has also been initiated in Pakistan by Dr. Jerry Eckert, and is reported in the Pakistan interdisciplinary section.

a. Water Law Legislation and Water Use Organization (Contributing to objective #8)

George E. Radosevich, Attorney and Assistant Professor of Environmental Law and Economics, is conducting the legal research. The primary purpose of this research is to identify, analyze, and describe the legal and institutional aspects of water distribution and control in Pakistan in order to ascertain the role of water law on farm production and to identify inherent constraints that impeded effective water management or may prevent the implementation of a proposed physical or economic program. The results of this research will provide the framework within which the proposed water management program will be affected by legal and institutional factors. The study will identify:

(1) Constraints on effective water management

(2) Changes in the laws and organizational arrangements which would promote or facilitate irrigation and improved "on-farm" water management practices.

To achieve this objective the effort is divided into three phases:

(1) Identification Phase--all identified source material pertaining to Pakistan water laws and institutions are set forth in a published bibliography.

(2) Descriptive Phase--culminate in a report narrating the Pakistani water laws as they exist from legislated, customary and Islamic Law and the multitude of organizations administering the laws.

(3) Development Phase--designed to meet the approval of the host government and the requests of the USAID Mission in Pakistan as a prerequisite to the implementation of an improved water management program designed by the Mission and Project personnel. This phase will yield a report containing the array of farmer water user organizational arrangements and a portfolio of the laws under which such organizational arrangements can be created. Phase 1 was completed this year, the report of Phase 2 is in rough draft form and Phase 3 is underway and will be completed next year.

Throughout this study, concentration has been upon the functional aspects of Pakistani water law, including legislative provisions and customary practices insuring the law will be followed. Consideration is given to related environmental and ecological impacts emanating from existing legal provisions and the identification of void areas of the law. Efforts to date indicate a lack of formal national water policy, weakness in the enforcement provisions of existing water law, and the need for a basic framework of related legislation sufficient to establish necessary water user associations.

In conjunction with the explicit interest of USAID Mission in Pakistan to promote an improved water management program commensurate with the Nation's announced integrated rural development plan and recognition of water management problems, CSU has been advising the Mission on water laws, regulations and organizational alternatives which

may profoundly influence the successful implementation of the Mission program. Similar consulting assistance was provided the Missions in Afghanistan and Nigeria during 1972 (Vietnam also has expressed interest).

In addition to conferring with a multitude of Pakistani and USAID personnel in Pakistan, Professor Radosevich has consulted with a number of water law experts in various other countries to discuss their water law system and to gain insight and material on the unique characteristics of the water laws in those countries. In particular, numerous conferences have been held with Dr. Dante Caponera, Legislative Chief, FAO, Rome, regarding the materials on file in FAO and the extensive experience of Dr. Caponera and his staff in this specialized field. Dr. Radosevich has been invited to coauthor the revised edition of "Water Laws in Moslem Countries" authored by Dr. Caponera. The successful obtaining of materials and information in the water law study can be attributed to the cooperation and linkages developed with FAO, IUCN, International Union for Conservation of Nature and Natural Resources, Dr. Kulzenferber of Germany and other such contacts.

In October, 1972, Drs. Radosevich and Daines (Utah State University) collaborated to examine the unique substantive water law and organizational arrangements for local water management in Valencia, Spain. Through the efforts of Dr. Vincente Giner Boira, Attorney and Secretary of the Tribunal of Water, the two water law specialists were able to investigate the evolution and status of water control in the Turia and Bar Rivers and the influence of the Moslem culture upon the system. These insights are of extreme value to the Pakistan project and the U.S. project in South America. Drs. Radosevich and Daines have been able to maximize their capabilities in providing requesting countries with additional alternatives through cooperation and coordination of work efforts.

The need for comprehensive and integrated water resources legislation and administration to promote provincial development objectives has been identified and publicized by CSU and USAID. Government officials have responded by requests for consultation. A four day requested

visit with the Governor of the Province of Baluchistan by Dr. Radosevich resulted in a request to USAID/Pakistan to provide for a nine to ten month training program in legislation and administration of water in arid lands at Colorado State University under the direction of Dr. Radosevich. Special courses of study are being constructed involving training and research in this specific area of water law and legislative drafting as well as enrollment in related discipline courses in order to provide the trainee with an understanding and appreciation of the influencing factors and sectors of water planning. This program will commence in December, 1973.

b. Studies of Agricultural Credit

Credit availability to small farmers in Pakistan and other countries is a major constraint on their ability to adopt improved water management practices. Consequently adoption of improved practices is often restricted primarily to the larger farmers who can generate sufficient capital, or have the credit to afford the investment. Recent concern in AID that technology be designed which can aid the small as well as the large farmer focuses attention on this credit problem.

A review was made of small farmer development projects around the world to evaluate their experiences with agricultural credit, new technology and improved water management. This review indicates the need for developing some water management technology which is labor rather than capital intensive.

5. Political Science

Water Scheduling, Model Development and Pakistan Institutions

In the early stages of this project, the need was felt to develop comprehensive bibliographies and other collections of water management related publications which would both focus attention on the subject and facilitate the orientation of U.S. personnel to Pakistan institutions, resources and problems. From November 1971 through October 1972, the Political Science component of the Water Management Research team completed the following studies which have been published as CUSUSWASH Reports:

(1) The Problem of Water Scheduling in West Pakistan: Research Studies and Needs

(2) Monastery Model of Development: Towards a Strategy of Large Scale Planned Change

(3) Pakistan Government and Administration: A Comprehensive Bibliography, Volume Number Three

Upon request from AID/Washington, the NESA Index was completed and three thousand (3,000) copies printed on the CSU campus. Five hundred (500) copies were sent to AID/Washington.

A two volume encyclopedic/bibliographic publication titled: Informational Sources on Water Management for Agricultural Production in West Pakistan: With Special Reference to the Institutional and Human Factors, is now in typescript form and is being sent out for review of technical content and to determine needs for this material in Pakistan and AID.

Other publications outlined in the Work Plan have been drafted or published, but work on them was supported primarily by the 211(d) Grant.

6. Sociology

a. Water Management Decision Making on the Farm and Watercourse

A proposal was developed by sociological researchers at CSU and West Pakistan Agricultural University, in consultation with USAID, for determining the factors which lead to good or poor water management decisions on the farm and watercourse. This proposal was submitted to the newly formed Agricultural Research Council in 1971. The war and associated factors have slowed a decision on this project. It was considered at a meeting of the ARC this year, with some favorable comment, but was returned to WPAU with the suggestion that it be returned to ARC with a reduced budget request. A final decision on this proposal is expected early in 1973. Meanwhile, the following studies have been conducted which are of general value, and will facilitate the proposed WPAU-CSU study when it is initiated:

(1) Field Training Manual

The six members of the field research team at WPAU are highly qualified and have extensive experience in gathering tightly structured interview data. However, they are not experienced in the open-ended observational skills required for our water management research. Principles applicable to this type of research are scattered through the literature of the social and physical sciences and it would be impractical to purchase and ship over the large number of books and journals involved.

The needed principles for guidance of data gathering in field settings was gathered from 97 books and articles and condensed into a paper by Kenneth McDonald. This paper will provide the basis for a training manual which will be used by personnel engaged in the Water Management Research Project.

(2) Preparatory Study Relating to On-Farm Water Management Decision Making

Information concerning factors which influence watercourse and farm water management decisions is generally insufficient to provide guidelines which would facilitate better decisions. To help fill this need and prepare preliminary information to facilitate the larger study anticipated later next year Mr. Ashfaq Mirza has reviewed studies of South Asian villages and has prepared three field data gathering questionnaires for use with informants who are: (a) Irrigation Patwaris (revenue officers), Irrigation Officers, and Agricultural Extension Agents, (b) Irrigation time keepers, (c) Village farmers. The field portions of Mirza's study will be conducted during the first half of 1973.

7. Interdisciplinary Research in Pakistan

a. Field Party Strength and Developing Linkages

The field party was expanded during the year to include Dr. Wayne Clyma from the CSU Agricultural Engineering Department, Dr. Cornelis deMooy from the CSU Agronomy Department and Dr. Jerry Eckert from the CSU Economics Department, who are now working with Dr. Gilbert Corey, Chief of the CSU party. These additional scientists in Pakistan have accelerated linkage development with Pakistan scientists and institutions as indicated in the following new research and proposals.

The Agricultural Research Council (ARC) of the Government of Pakistan is beginning to play an important role in the development of a sound agricultural research program in Pakistan. It has established a position of "Director for Soils, Irrigation and Engineering" and when this position is filled the CSU team will logically work with him in their efforts to assist and cooperate in the national program of water management research. Meanwhile, the CSU team, in cooperation with the Director General of ARC, has planned and will conduct a water management research seminar. This program will be the first of an annual series in which water management researchers from all provinces are brought together to discuss research results and plan future coordinated programs. The concept of this seminar has been well received by the Central Government and the seminar will be held during the last week in January, 1973.

Expansion of the field party also provided the necessary field input to start assembling a technology package which is tailored to the resources of the Pakistani farmer, and can increase the benefits derived from water use in Pakistan.

b. Target Definition

An important factor influencing the assembly of this technology package was the evaluation by Dr. Eckert of the resource position of the Pakistani farmer with particular reference to water and its management. Among other significant factors, this evaluation showed that 50% of the farmers had farms five or less acres in size and over 90% had farms less than 25 acres in size, although 43% of the total area is in farms larger than 25 acres. The significance of this and other statistics on farm sizes, on amount and distribution of water resources and on labor and capital available to the farmers showed that the lot of most of the farmers will not be improved unless a variant of the "technology package" can be developed which is compatible with bullock power and is labor intensive rather than highly consumptive of capital and hydrocarbon energy. On the basis of this information we have proceeded to assemble information on "package" components which will be within economic reach of the subsistence farmer in addition to components which will yield optimum benefits, but will only be within economic reach of the large scale farmers.

c. Preliminary Watercourse and Water Use Evaluation

(1) A limited survey of watercourses indicates up to 35% of the water allotted to some farmers is used in filling the "below ground level" portion of the watercourse leading to his field. In these areas with little slope this water is lost as it stays in the ditch and seeps away after the flow is diverted to another leg of the watercourse. While these high percentage losses are only the case for fields less than 0.5 acres in size, at the end of rather long watercourse legs, which are not watered in sequence with other fields along that leg, several fields meeting these specifications were observed and illustrate the benefits that could be derived from watercourse improvement.

(2) A limited survey of water applications in the study area showed several instances where single irrigation applications were up to 8 or 9 acre inches of water per acre. Soil water retention

characteristics of these soils (see Appendix B) and observations of rooting depth indicate that only about 4 or 5 inches of this water is held by the soil within the root zone, indicating that some of the farmers are not using their water resource to the best advantage. The extent of this practice of over concentrating water will be determined. Since NO_3 is completely soluble and moves with the water, such over irrigations will generally result in leaching most of the nitrate out of the plant root zone, this leaching will be more complete when the basin method of irrigation is used as compared to furrow irrigation.

d. Water, Fertilizer and Plant Population

Wheat production response trials were designed and planted in cooperation with the Punjab Agricultural Research Institute and Sind Agricultural College to determine response functions for water, nitrogen, phosphorous and their interactions. The CSU Field Team in cooperation with PARI have established one set of trials under the management assumption that farmers cannot vary either the timing or quantity of water applied. Three replications were planted in the fall of 1972 at each of three locations selected to represent different rainfall regimes.

Another set of trials at the main PARI station relaxes the fixed delivery assumption and allows the irrigator to irrigate at the critical phases of plant growth and to apply optimum amounts of irrigation water. These studies will provide measures of the efficency gains which may be obtained from better water management in addition to the general response surfaces which can be used to prescribe variants of the "technology package" which will gain maximum benefits from the water and fertilizer that farmers in various resource positions can afford.

CSU is cooperating with the Agronomy Department at the Sind Agricultural College in a trial which has fertility and irrigation treatments similar to those at PARI, and introduces a plant population variable. A radial spacing design was used. Plant populations ranging

from 0.14 to 2.5 times normal are included under multiple replications of a 4 irrigation and 3 nutrient treatment matrix. Separate plots were planted to evaluate the effects of solar orientation on yields within such designs.

Data from these studies will be available in 1973. Further details of the research are outlined in the research plan.

8. Improvements Needed Based on Research Experience with our Pakistani Cooperators

Most of the cooperative research initiated to date in Pakistan involves studies in addition to their ongoing programs. The additional analyses required aggravates a chronic tendency for long delays before soil and plant analyses are completed. This data is essential to understanding many of the cause and effect relations between water management and crop yields. Steps planned to improve their analytical capabilities include a survey of their present methods, development of recommendations for improved methods, and supplying essential chemicals and equipment which are unavailable to them in Pakistan.

Water management research quality in Pakistan is limited by scarcity of dependable facilities and capabilities for measuring water flow and climatic factors which affect consumptive use of water. Improved flow and climate measuring devices will be installed at our cooperative studies and special training sessions will be held for our cooperators and others to train them in the proper use and maintenance of this equipment. Help will be requested from Utah State University on the climate measuring and consumptive use estimating aspects since they have extensive experience and expertise in such measurements.

E. Dissemination and Utilization of Research Results

1. Efforts to Disseminate Research Results

Water management research in Pakistan is spread throughout several agencies and institutions. Lack of communication between these agencies and minimal dissemination of the results is a major constraint on the utilization of results from our cooperative studies and from other water management research in Pakistan. To improve the dissemination of our results and the coordination of future research, a water management research seminar was organized by the CSU field party in cooperation with the Pakistan Agricultural Research Council. This seminar (to be held the last week in January 1973) is designed to be the first of an annual series in which scientists engaged in water management research report their work, identify important problems and coordinate their research efforts. While the field party members will lead most of the discussions this year, it is planned that our cooperators and other Pakistani's will take the lead in presenting our data in the succeeding years.

A bibliographic list, including abstracts, of papers and publications developed this year under the contract is attached as Appendix D. A list of statements identifying known areas of the materials provided by the project for seminars, translations conferences, etc., is attached as Appendix E.

2. New Avenues to Expand Use of Research Results

a. The Mona Project

Worthwhile research results are coming from some of our cooperative studies. However, most of our cooperators are not closely linked to extension agencies and considerable time would obviously elapse before most of our research results would be used to increase production. An opportunity to accelerate this process appears to be possible at the Mona Reclamation Center. They have an extension component which works closely with their research people, and could disseminate

research results to a broad area as soon as such results are verified. Mona and their parent agency (WAPDA) have asked for the cooperation of the CSU field party on water management research and means for adapting research to the needs of farmers, and actual field demonstration of the benefits of water course management. Mona personnel and our field party in consultation with USAID have drafted a proposal for a cooperative study. USAID has indicated potential support of this study to the extent of Rs 2,000,000 over a three-year period. This project has not yet cleared the Pakistani Government, but indications are that it will do so early in 1973. Additional details of this cooperation are outlined in the work plan.

b. The Shadab Project

The Punjab Department of Agriculture has requested that CSU assist them with the development of a land leveling water course improvement pilot project within one of the Integrated Rural Development areas of the Punjab. USAID has evaluated the potential of this project and has indicated support to the extent of one million Rupees, and the Punjab Department of Agriculture has agreed to redirect approximately Rs 150,000 to it.

The initial thrust of the project will involve land leveling of farmers fields and rehabilitation of their water courses. After these two basic needs are met on the watercourse area, other water management and agronomic practices will be introduced and their effects on crop yields will be determined under controlled optimized conditions and under the actual limitations experienced on a field scale by Pakistani farmers. This work would be done in close cooperation with Department of Agriculture Extension Agents. Promising practices would be spread rapidly to other Integrated Rural Development project areas of the Punjab. A project agreement has been written and is in process of being signed by the appropriate officials.

Both the Mona and Shadab projects involve an extension component which is beyond the CSU Water Management Research Project objectives. However, these opportunities to join forces with USAID and Pakistani agencies, which have extension and utilization objectives, would greatly increase the speed with which our results are utilized and the proportion of these findings which are applied.

3. Involvement of LDC Personnel and Institutions

During the early stages of this project when CSU personnel could not be stationed in Pakistan, Pakistani research assistants with considerable knowledge of Pakistan conditions were hired to help identify significant water management problems and conduct research on the CSU campus which would help solve these problems. As the emphasis on research has shifted to overseas studies, and these research assistants have completed their CSU based research, most of them are now returning to Pakistan as well trained Water Management Research scientists. As the research emphasis has shifted to cooperative work in Pakistan, the planning of research has involved Pakistani scientists at several institutions, as full fledged cooperators in the planning of the projects. The execution of the field work has been done primarily by the Pakistani cooperator and his field assistants, with members of our field party involved in the more technical aspects of measurement. These technical aspects of measurement and equipment maintenance are taught to the cooperators as rapidly as possible. Every effort is made to keep CSU field party members from displacing a Pakistani if he is able to do the job. Some supervision by CSU field party members of field work is occasionally essential because of the tendency by many Pakistani agencies to delegate field work to untrained workers who do not comprehend some of the essentials of field plot technique. Analysis and reporting of results on most of the studies is initiated by the Pakistani cooperator with the field party offering advice and direction for publication as warranted.

Cases in which findings of the research project are being used in Pakistan or the U.S. include the following.

The Agronomy Department at WPAU used the water retention data to help them design irrigation studies and to estimate water contents from tensiometer readings.

The Punjab Agricultural Research Institute, after reading the CSU report of deficiency levels of P and border line cases of Fe and Zn, have included more work on P in their research, and are considering studies on Fe and Zn sufficiency in areas which the CSU data indicates are near deficiency.

The analyses of the Ca content of the sand and silt fractions has destroyed the growing illusion that the Na/Ca ratio of water percolating through these soils might be increased by Ca dissolving from these coarse fractions, and has encouraged salinity guideline makers in Pakistan to stick by the old established guidelines.

The data on effects of salinity on crop growth is the only known systematic comparison data taken on a field plot size basis. While there is lysimeter data, the practical problems of tillage, surface roughness, uneven distribution of water, etc., are a part of the real world and consequently the field plot data taken at PARI should provide the best practical guidelines available to farmers in many parts of the world, including the U.S., for use of saline water for irrigating crops.

While the above instances indicate some use of the project findings, these uses are limited and in a preliminary stage due to the relatively short time since initiation of these studies and the fact that few of the studies (particularly the field research) have had time to mature.

F. Statement of Expenditures and [illegible] and Contractor Resources

	Personnel	Travel and Allowances	Other Direct Costs	Equipment (including Transp.)	Research Operations	Indirect Costs (Overhead)
Field Operations:						
1. Water Control and Land Preparation	$ 9,168	$ 6,976		$ 3,500		
2. Comparison of Water Management Practices	9,168	6,976		3,500		
3. Yield of Wheat, Sorghum and Bermuda	6,996	3,750	-0-	4,560	-0-	
4. Field Party Strength and Development Linkages	19,383	8,502				
5. Target Definition	4,855	6,262				
6. Preliminary Watercourse or Water Use Evaluation	3,272	6,032		3,500		
7. Water, Fertilizer, and Plant Population	19,385	8,502		3,500		
Agricultural Engineering:						
1. Designs for Pumping Fresh Water	$ 14,895	$ 2,134	-0-	$ 113	$ 2,150	-0-
2. Land Leveling Film	-0-	250	-0-			
Agronomy:						
1. Physical, Chemical, and Mineralogical Characteristics	$ 12,083		-0-	-0-	$ 1,600	-0-
2. Effects of Salinity	10,290	-0-	-0-	-0-	-0-	-0-
Civil Engineering:						
1. Sediment Conduction of Farm Turnout Structures	$ 18,792	-0-	-0-	-0-	$ 3,000	-0-
2. Optimum Conjunctive Use of Canal and Well Water	15,137	-0-	-0-	-0-	-0-	-0-
3. Predicting Groundwater Basin Response	2,910	-0-	-0-	-0-	-0-	-0-
Economics:						
*1. Water Law Legislation and Water Use	$ 11,114	$ 4,136	-0-	-0-	$ 200	-0-
2. Adoption of Improved Water Management Practices in Relation to Policies and Credit	10,140	-0-	-0-	-0-	200	-0-
Political Science:						
1. Water Scheduling, Model Development	$ 8,250	-0-	-0-	-0-	$ 900	-0-
Sociology:						
1. Water Management Decision Making	$ 10,391	-0-	-0-	-0-	$ 1,800	-0-
Administration: (Includes Consultants)	$ 47,189	$ 2,492	** $23,763		$ 8,042	$131,240
TOTAL	$233,420	$56,012	$23,763	$18,673	$17,892	$131,240

* This includes personnel time spent overseas on Water Law Legislation of approximately three (3) months or $5,000.

** This includes retirement contribution of approximately $12,000.

1. Changes in Project Management and Staffing Pattern

In response to recommendations of the Jensen, Heady, Anderson review team, a full time project director with background in on farm water management was hired for this project. Dr. W. D. Kemper arrived on staff on June 15, 1972. In response to the suggestion that a larger portion of the research effort be in the developing countries, opportunities for significant research in Pakistan and encouragement of USAID to expand the field party, Dr. J. E. Eckert, Dr. Wayne Clyma and Dr. C. J. deMooy from the CSU Economics, Agricultural Engineering and Agronomy Departments respectively have joined our field party chief, Dr. G. L. Corey in Pakistan.

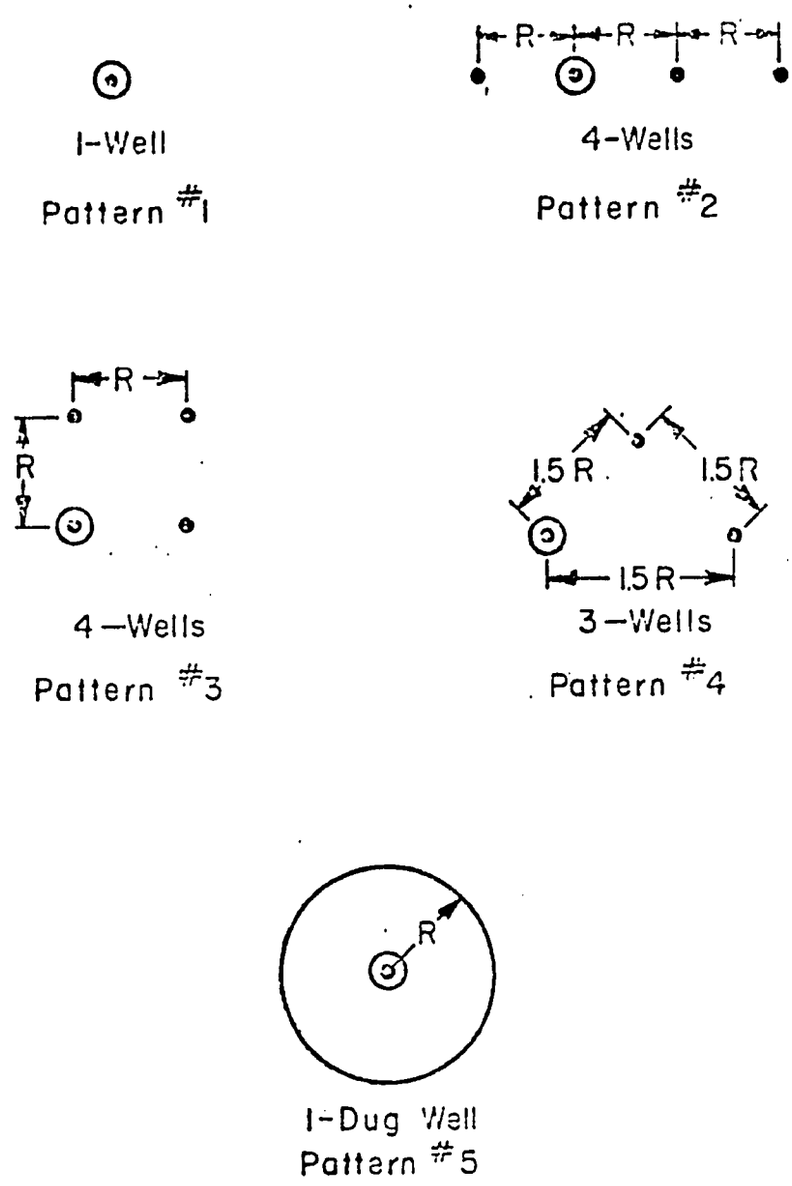
Early in the year consultations with USAID/Pakistan and AID/Washington revealed the importance of laws and regulations on the availability of water at the watercourse level. Dr. George Radosevich from the CSU Economics Department was assigned to evaluate the potential for improving laws and regulations which would result in more equitable and timely distribution of the water. Radosevich, Schmehl, Franklin and Kemper each worked on water management problems in Pakistan for extended TDY's at the invitation of USAID and our field party chief.

APPENDIX A

Comparative Cost Analysis of Tubewells, Electrically Powered Skimming Wells and Bullock Powered Skimming Wells - D. McWhorter and F. Zuberi

Based on the equations developed for predicting salt water coning, several well systems were designed which would draw fresh water from a saline aquifer topped by 100 ft. of fresh water. These skimming systems were designed to represent a range of utilization of resources available to the farmer in the village (generally labor intensive) as compared to materials and expertise which would have to be purchased outside the village. Cost estimates were made on each of these systems using Pakistani prices.

The material in this appendix is abstracted from the complete report by Zuberi and McWhorter which will soon be published as a CUSUSWASH technical report.



⊙ Point where maximum drawdown occurs.

Figure 4A.

TABLE 5A

COST OF A SKIMMING WELL - TYPE A

Pattern #1

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Boring 8"	rft.	30	5.00	150.00
2	Strainer, Coir String 6"	rft.	17.5	8.00	140.00
3	Casing Pipe, M.S. 6"	rft.	13	16.00	208.00
4	Pump, Motor (.75HP) & Control	No.	1	L.S.	1400.00
5	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
6	G.I. Pipe incl. bands 2"	rft.	20	3.00	60.00
7	Discharge Box	No.	1	L.S.	60.00
8	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				2218.00

TABLE 5B

COST OF A SET OF FOUR SKIMMING WELLS - TYPE B

Patterns #2 and 3

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Boring 8"	rft.	100	5.00	500.00
2	Strainer, Coir String 6"	rft.	50	8.00	400.00
3	Casing Pipe, M.S. 6"	rft.	52	16.00	832.00
4	Pump, Motor (1.25 HP) & Control	No.	1	L.S.	1300.00
5	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
6	G.I. Pipe incl. bands 1½"	rft.	70	2.00	140.00
	2"	rft.	10	3.00	30.00
7	Discharge Box	No.	1	L.S.	60.00
8	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				3962.00

TABLE 5D

COST OF A DUG WELL - 5 FT. INTERNAL DIAMETER

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Excavation - dry soil, up to 7.5' depth	1000 cft	0.31	60.00	18.60
2	Excavation - slush, incl. lift 7.5' to 25' depth	1000 cft	0.62	90.00	55.80
3	Brickwork (2nd. Class) in cement mortar	100 cft	0.53	200.00	1060.00
4	Curb	No.	1	L.S.	80.00
5	Pump, Motor (1.25 HP) & Conrtol	No.	1	L.S.	1600.00
6	Installation incl. wiring & fitting, etc.	No.	1	L.S.	100.00
7	G.I. Pipe incl. bands 2"	rft.	20	3.00	60.00
8	Discharge Box	No.	1	L.S.	60.00
9	Development of Well	No.	1	L.S.	100.00
	TOTAL COST (Pump house not included)				3134.40

TABLE 5E

COST OF A PERSIAN WHEEL - 8 FT. INTERNAL DIAMETER

Pattern #5A

S.No.	Item	Unit	Qty.	Rate(Rs)	Cost (Rs)
1	Excavation - dry soil, up to 7.5' depth	1000 cft	0.62	60.00	37.20
2	Excavation - slush, incl. lift 7.5' to 25' depth	1000 cft	1.24	90.00	111.60
3	Brickwork (2nd. Class) in cement mortar	100 cft	7.80	200.00	1560.00
4	Curb	No.	1	L.S.	125.00
5	Steel Chain with G.I. sheet buckets	rft.	40	60.00	2400.00
6	G.I. Water Collecting Pan	No.	1	L.S.	80.00
7	Steel Bucket Wheel, axle, gears, main wheel incl. dr. arm	No.	1	L.S.	1000.00
8	Main Beam (wooden) incl. supporting wheel	No.	1	L.S.	125.00
9	Discharge Box	No.	1	L.S.	100.00
10	Development of Well	No.	1	L.S.	150.00
11	Bullocks to Drive	No.	2	L.S.	2000.00
	TOTAL COST (cost of any shelter not incl.)				7631.00

TABLE 5F

COMPARISON OF COST OF VARIOUS SKIMMING FACILITIES

S.No.	Type of Well	Discharge (cfs)	Cost (Rs)	Cost/cfs (Rs)
1	WAPDA Tubewells[3]	4.0	45,000[1]	11,250
2	Private Tubewells[3]	1.0	6,850[2]	6,850
3	1 Tubewell (Pattern #1)	0.126	2,218	17,600
4	4 Tubewells (Pattern #2)	0.176	3,962	22,510
5	4 Tubewells (Pattern #3)	0.174	3,962	22,770
6	3 Tubewells (Pattern #4)	0.173	3,659	21,150
7	1 Dug Well (Pattern #5)	0.174	3,135	18,020
8	1 Persian Wheel (Pattern #5A)	0.186	7,689	41,338

1 From "Regional Plan for Northern - Indus Plain" by WAPDA and T & K Inc. (1967).

2 From "A Study of the Contribution of Private Tubewells in the Development of Water Potential in Pakistan" by University of Engineering and Technology, Lahore (June 1970).

3 These figures are presented only for comparison purposes and are not part of skimming facilities.

TABLE 5G

LIFE OF DIFFERENT COMPONENTS OF SKIMMING FACILITIES

	Component	Assumed Life
1	Tubewell	
	Well Construction	10 years
	Pump Motor, etc.	10 years
2	Dug Wells	
	Well Construction	30 years
	Pump Motor, etc.	10 years
3	Persian Wheel	
	Bullocks	10 years
	Well Construction	30 years
	Iron Chain, Wheel, etc.	30 years

TABLE 5H

ANNUAL OPERATION COST OF SKIMMING FACILITIES

S.No.	Item	Hours Operated Per Year	Operation Cost (Rs)
1	Tubewell	2130[1]	
	Cost of Power		1430[2]
2	Skimming Tubewell	2130	
	Cost of Power		180
3	Skimming Dug Well	2130	
	Cost of Power		250
4	Persian Wheel	2130	
	Bullock Feed @Rs.1'50/day/bullock		540
	Pay of one boy laborer @Rs.60'/month		360

1 It is assumed for the annual cost calculations that the well is operated for 50% of the time for six months.

2 Power cost has been taken from Table 6.5 of "A Study of the Contribution of Private Tubewells in the Development of Water Potential in Pakistan" conducted by W. P. University of Engineering and Technology, Lahore (June 1970).

TABLE 51

ANNUAL COST OF WATER

(All figures are in Rupees)

Item	Private Tubewell	Skimming Tubewell Pat. #1	Skimming Dug Well Pat. #5	Persian Wheel Pat. #5A
Operation Cost	1430	130	250	920
Replacement & Repairs	375	120	150	201
Amortization of Capital Cost	520	170	150	224
TOTAL ANNUAL COST	2325	470	550	1345
Capacity of Wells (cfs)	1.0	0.126	0.174	0.186
Annual Working Hours	2130	2130	2130	2130
Water Pumped Annually (AF)	176	22.2	30.6	32.7
Cost/Acre Foot	13.2	21.2	18.0	41.2

APPENDIX B

PHYSICAL AND CHEMICAL ANALYSES OF PUNJAB SOILS

W. Franklin and W. Schmehl

The on-campus research program was initiated at Colorado State University at the same time advisory relationships with various Pakistani agencies and workers were being established to undertake on-the-farm water management research in Pakistan. The general criterias used by the Agronomy Department in selecting specific research to be conducted on campus were:

1. To select areas where Pakistani researchers had little or no capability or were not properly equipped to conduct the research.
2. To select on-campus research from among several alternative areas as recommended by USAID Mission and by Pakistani agency staff; these alternative research areas were:
   a. The determination of additional soil mineralogy information as requested by the Pakistanis.
   b. The analysis of soils from sites selected as possible research areas in Pakistan (USAID request).
   c. Help in evaluating tubewell quality (Pakistan request).

The original research proposed was approved by both the AID Mission and Washington.

The soil samples which were collected for mineralogical analyses also represented potential sites for experimental water management studies and were analyzed for fertility, salinity, and physical analyses. The Land Reclamation Directorate and WASID (Lahore) both expressed interest in studies designed to help predict the effect of irrigation water salinity and SAR on hydraulic conductivity of soils in relation to texture and clay mineral species. Analytical results obtained on the CSU campus were given to both agencies. No program agreement was made with the LRD or WASID until very recently. The LRD is now largely concerned with getting large lysimeters into operation. WASID has expressed continuing interest in such a study by sending a large number of samples for mineralogical characterization (no further mineralogical studies are contemplated, however).

Results of on-campus research to characterize Pakistan soils are summarized in the following sections.

Soil and Clay Characterization

Basic soils data, for which no facilities and skills exist in Pakistan to obtain this information, are being compiled at CSU. These include physical and chemical properties including mineralogy and fertility. This data will facilitate the designing of pertinent and meaningful experiments in Pakistan. Compacted slowly permeable surface soils constitute a widespread problem for efficient irrigation and crop growth.

Fifty-eight soil samples representing 11 profiles from sites at Lahore, Lyallpur, and in SCARP I and II were obtained from Pakistan (Fig. 1). The objectives for obtaining the soil samples were:

1. To determine the sand, silt, and clay mineralogy of the Punjab soils.
2. To determine whether sufficient dissolution of Ca-bearing (and Mg-bearing) minerals takes place when irrigated with high SAR waters (<10) to favorably reduce the sodium hazard of the water.
3. To determine whether the type of clay minerals in the soils influence the proportion of exchangeable sodium adsorbed from waters containing various amounts of salts and varying proportions of Na, Ca, and Mg.
4. To characterize several chemical, physical, and fertility properties of the samples to facilitate judicious selection of experimental sites.

Mineralogy of Sands and Silts. The lime- and organic matter-free samples were fractioned into 5 sand, 3 silt, and 2 clay sizes. Light-heavy mineral separations were made on the sands and coarse silt with a magnetic separator, and total CaO, MgO, K_2O and Na_2O were determined on the sand and silt fractions. Petrographic identification and grain counts were made on the very fine sand fractions of 2 horizons from the 11 sites and the silt fractions were subjected to X-ray diffraction analysis. The results are summarized in Tables 1, 2, and 3.

The grains of the very fine sands examined are predominantly quartz and mica, together making up a total ranging between 60-83%. On the average,

the mica content is approximately equal to the quartz content. Plagioclase plus potash feldspars vary from 10-20%. Small percentages of chlorite, hornblende, pyroxene, garnet, magnetite, kyanite, zircon, and tourmaline were found. The proportion of chlorite increases in the silt fractions over that of the sands. The mineral suite indicates that the sediments were derived from a metamorphic proverance.

Calcium-bearing minerals appear to constitute only a small fraction of the mineral suite. Thus, it appears that soil lime and gypsum dissolution will be the only significant source of Ca which might alter the SAR of irrigation water after it has entered the soil. Dissolution of Mg-bearing minerals, such as chlorite, is more probable.

Clay Mineralogy. The mineral suites in the 2-.2μ and <.2μ clay fractions were identified by X-ray diffraction analyses of Mg- and K-saturated clays given ethylene glycol, glycerol, humidity, and heat treatments. The Punjab soils contain mica (illite), chlorite, smectite (montmorillinite), vermiculite, quartz, and feldspar.

A sodium pyrosulfate dissolution treatment was given to determine quartz-plus-feldspar contents of the clays. This treatment indicated less than 5% quarts + feldspar in the <.2μ fraction and 8-15% in the 2-.2μ fractions. Total K was determined as a quantitative estimation of mica (Table 4). Mica contents in the 2-.2μ fraction ranged from 35-44% and 20-38% in the <.2μ fraction. The mica average of the 2 clay-sized fractions was about 35% for all samples. Little variability was found to a depth of 5 feet. Cation exchange capacity determinations and surface area measurements were made for quantitative determination of the remaining suite (Table 4).

Salinity Analyses. Electrical conductivity of the saturated extract, water soluble cations (Ca, Mg, Na, K) and anions (CO_3 + HCO_3, Cl, SO_4) (Table 5), NH_4OAc soluble Na, cation exchange capacity, and exchangeable Na percentages (Table 6) were determined on each sample. Only 4 of the 11 profiles contained saline and sodic horizons. The anion and Ca-Mg ratios were examined for trends or unusual features. None was found. A correlation of the saturated paste extract SAR was made with exchangeable sodium

percentage because it has been noted that workers rely quite heavily on the SAR-ESP relationship developed by the U.S. Salinity Laboratory. The relation for the Punjab soils is shown in Fig. 2 and has a correlation coefficient of 0.96 for the linear SAR-ESP relation. The regression equation indicates a higher average Na adsorption at low SAR value but less Na adsorption at low SAR values compared with the U.S. Salinity Laboratory SAR-ESP relation.

Physical Analyses. One-third/ and 15-bar moisture retention and particle size distribution were determined for all samples (Tables 7 and 8). Because no standard pressure membrane apparatus has been seen in West Pakistan, empirical relations were sought with other soil physical properties which might give an estimate of 1/3 and 15-bar values. It would be expected that moisture retention would be closely related to texture. The relation between 15-bar moisture retention and the $< 5\mu$ particle percentage in the samples is shown in Fig. 3. This data shows a high correlation ($r = 0.97$). However, the $< 5\mu$ shows a poor relation ($r = 0.68$) with the 1/3-bar moisture retention (Fig. 4).

It was noted that the saturation point percentage was frequently used in Pakistan to estimate "field capacity" and "wilting point" using the thumb-rule of field capacity = 1/2 saturation percentage and wilting point = 1/4 saturation percentage. These "approximate" relations for these soils using the 1/3-bar and 15-bar values are given in Table 1 as the ratio of saturation percentage to 1/3-bar and 15-bar percentages. The decreasing ratios as the texture becomes finer probably represents the more reliable relationship.

Table 1. Saturation to 1/3 and 15-bar percentage ratios for Punjab soils.

No. Samples	Texture	Saturation 1/3-bar Range	Saturation 1/3-bar Avg.	Saturation 15-bar Range	Saturation 15-bar Avg.
1	LS	-	3.09	-	11.0
4	SL	1.62-1.83	1.69	3.5-6.3	4.3
17	L	1.43-1.67	1.55	3.0-4.8	3.3
31	S_1L	1.29-1.93	1.53	2.4-4.6	3.6
4	S_1CL	1.23-1.68	1.50	1.8-2.7	2.4
1	S_1C	-	1.65	-	2.6

Fertility Analyses

The fertility analyses are summarized in Table 9. The soils were all calcareous and the pH of some subsoils reached 9.7. The organic matter content of the surface soils ranged from 0.2 to 1.0% with an average of 0.6%. Available soil phosphorus was in the deficient range (< 50 lb. P_2O_5) in all of the 11 surface soils. Available potassium was adequate (250 lb. per A.) in 10 of the 11 surface soils. The soil tests showed that zinc deficiency would be expected for some crops in 5 of 11 soils (<1.0 ppm in surface soil), but iron availability is borderline in only one soil (LRD).

The data confirmed the low fertility status with respect to phosphorus and nitrogen that has been noted in Pakistan both by laboratory analyses and field testing. The zinc and iron analyses are new for Pakistan because of the extreme difficulty of determining these micronutrients by chemical procedures. There is no physical instrument (atomic absorption) in any Pakistan agricultural laboratory which does permit accurate and rapid determination of available iron and zinc.

Significance of the Analyses

The physical and chemical analyses provide the CSU field staff and Pakistan cooperators with both confirmatory and new basic soils information needed to explain current field observations and to aid in designing new experiments. The data emphasizes the importance of measuring and adjusting the nutrient status of the soil when conducting water-management experiments. It also points to possible causes of the poor soil structure and slow infiltration rates commonly noted in the Punjab. Because of the need to study the influence of cultural practices on soil physical properties and its effect on plant growth, Mr. Hyatt Bhatti has submitted a PL 480 proposal for funding in this area of study.

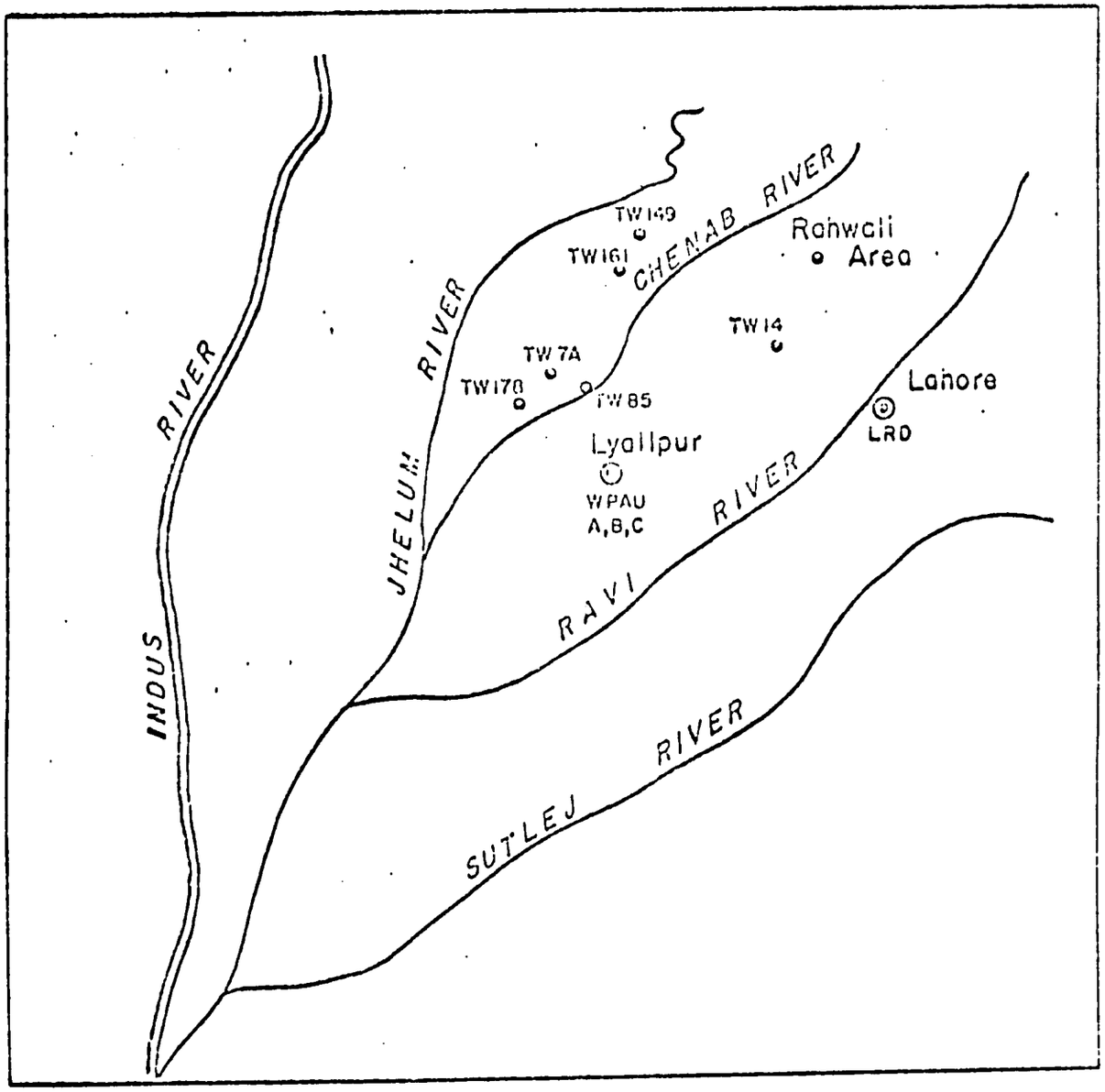


Figure 1. Location of the soil sample sites in the Punjab region of West Pakistan.

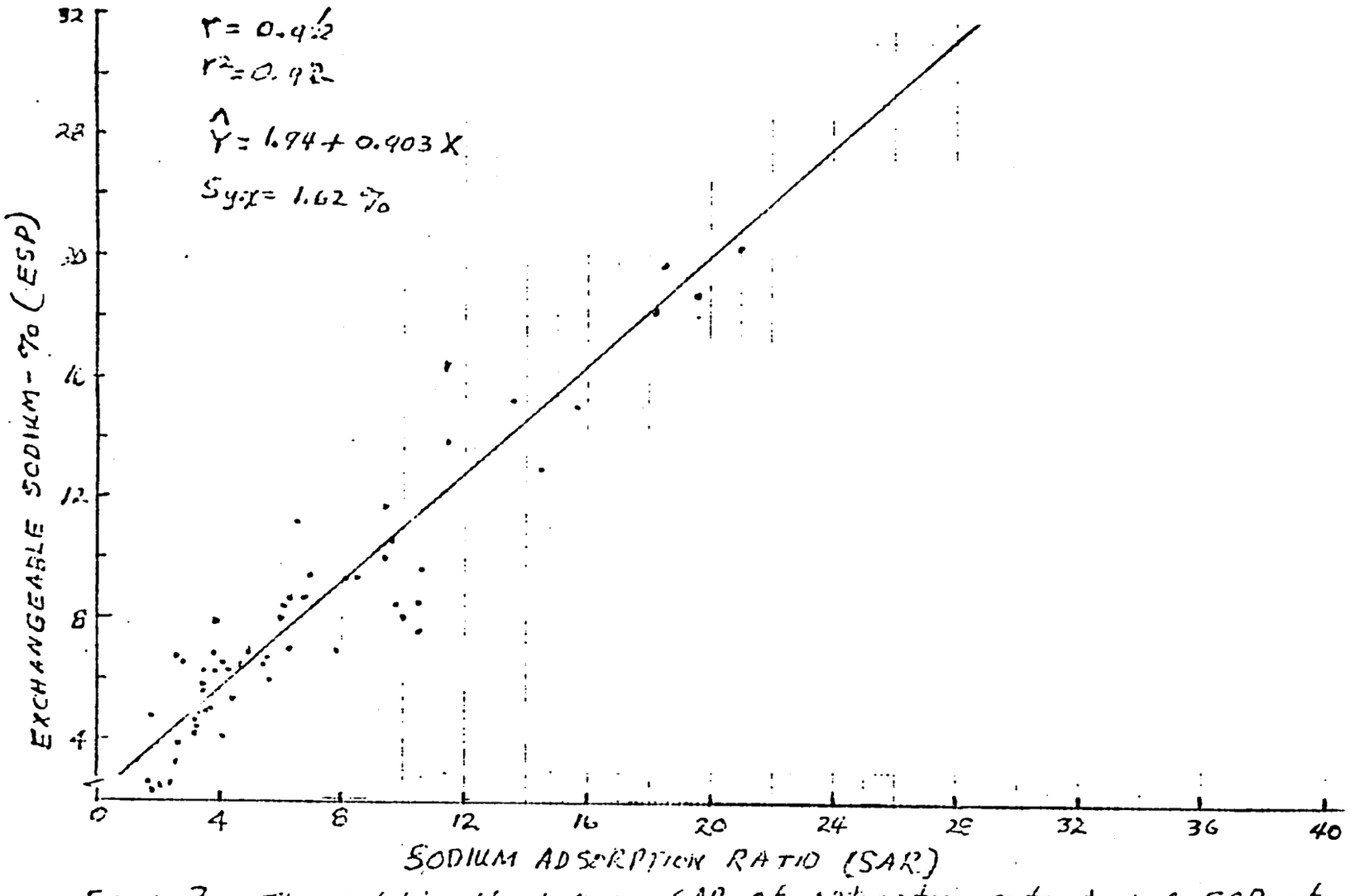


Figure 2. The relationship between SAR of saturation extract and ESP of Punjab soils.

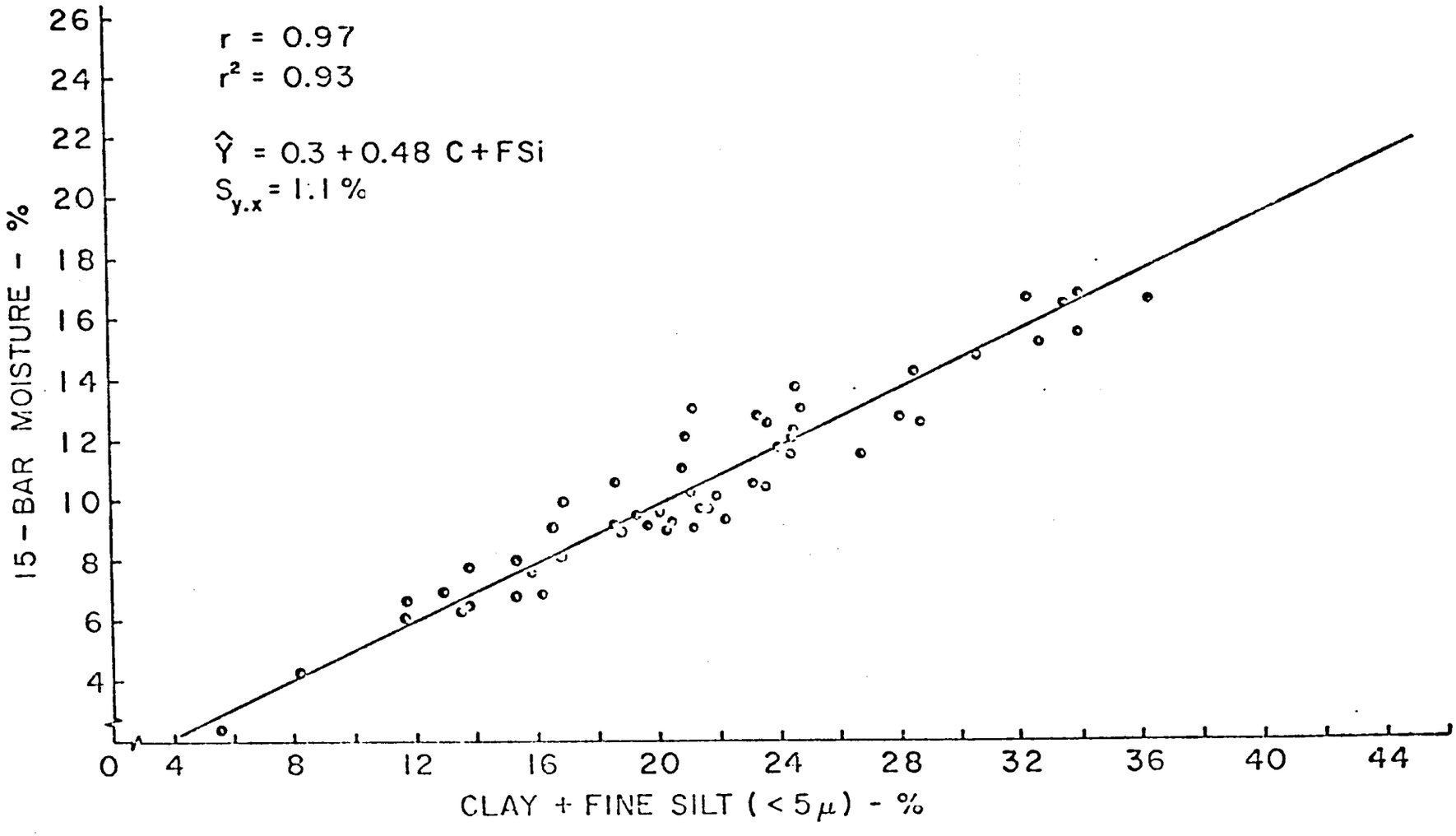


Figure 3. The relationship between the <5 μ particle size and 15-bar moisture of the soil samples.

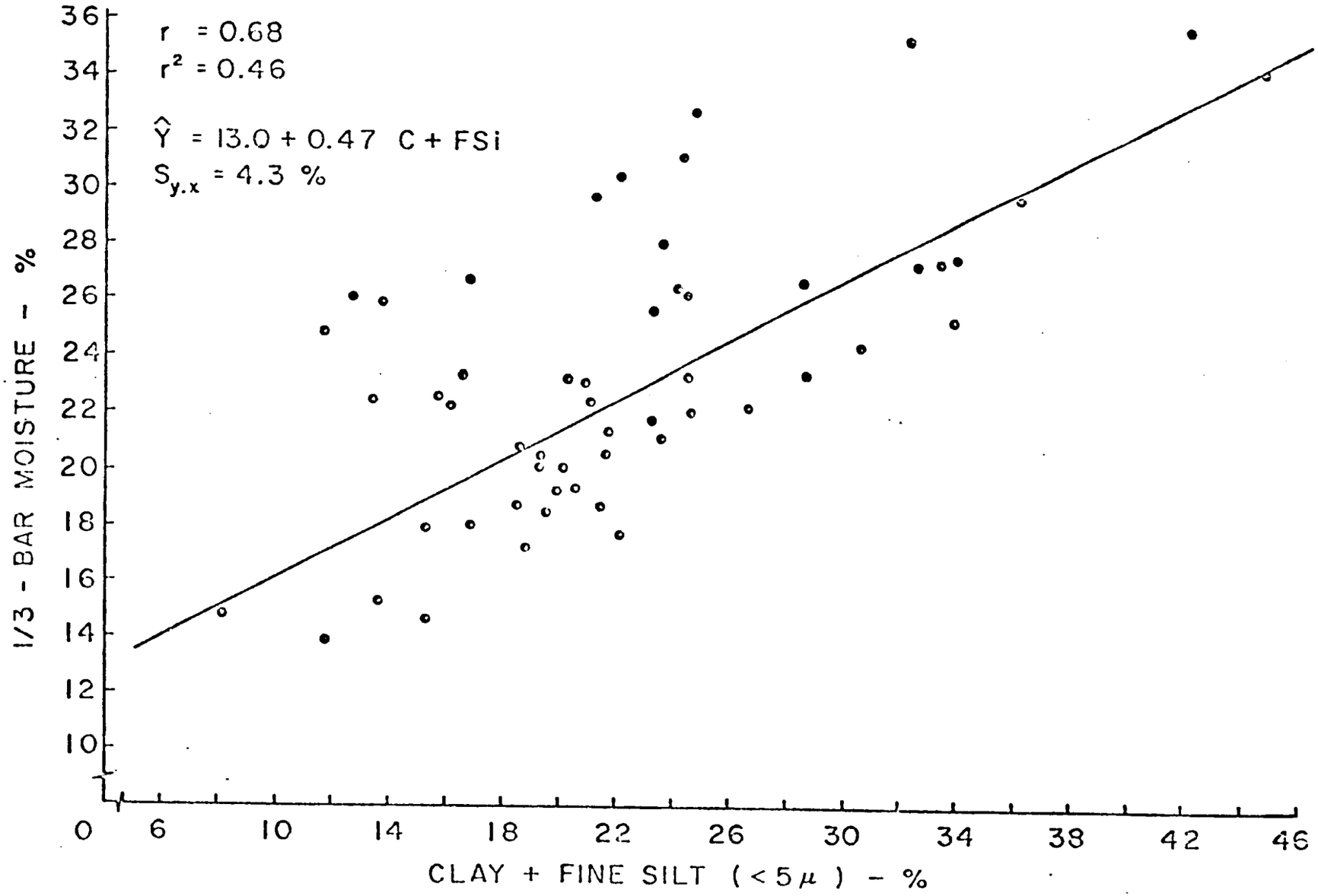


Figure 4. The relationship between the $<5\mu$ particle size and 1/3-bar moisture retention of the Punjab soil samples.

Table 1. Light-heavy* mineral percentages and mineralogic composition of West Pakistan soil samples.

Sample Number	Depth (ft.)	Heavy Mineral Percentages: Coarse Silt .05 - .02 mm (%)	Very Fine Sand .1 - .05 mm (%)	Fine Sand .25 - .1 mm (%)	Medium Sand .5 - .25 mm (%)
LRD 1/					
1.	0-1	26.0	31.3	15.2	-
2.	1-2	22.6	23.7	35.7	-
3.	2-3	22.4	31.4	34.4	-
4.	3-4	27.4	31.5	39.0	-
5.	4-5	19.6	27.8	37.5	-
WPAU 2/					
A 6.	0-1	23.0	24.3	21.2	23.3
7.	1-2	36.2	24.9	22.4	-
8.	2-3	35.8	39.7	25.5	-
9.	3-4	-	40.0	24.9	-
10.	4-5	29.9	35.6	29.0	-
11.	5-6	25.3	28.1	23.3	-
WPAU					
B 12.	0-1	23.6	19.7	23.2	-
13.	1-2	27.7	30.0	27.1	-
14.	2-3	16.7	23.9	23.6	24.3
15.	3-4	-	31.8	27.0	-
16.	4-5	31.8	28.3	27.8	-
17.	5-6	31.9	25.2	22.6	-
WPAU					
C 18.	0-1	14.4	19.5	23.8	27.5
19.	1-2	17.8	22.8	23.8	27.2
20.	2-3	19.4	22.9	23.9	-
21.	3-4	21.0	21.8	23.4	26.5
22.	4-5	16.9	24.2	22.8	27.2
23.	5-6	25.4	25.2	22.3	27.3
TW149 3/					
24.	0-1	-	26.4	37.4	-
25.	1-2	-	20.3	38.8	-
26.	2-3	-	26.8	39.8	-
27.	3-4	-	26.9	40.0	-
28.	4-5	-	29.3	38.9	-
TW161					
29.	0-1	-	28.2	36.6	-
30.	1-2	-	27.3	35.7	-
31.	2-3	-	33.9	38.2	-
32.	3-4	-	36.2	42.2	-
33.	4-5	-	33.3	41.3	-
TW14 FAO					
34.	0-1	-	23.9	22.7	-
35.	1-2	-	25.2	23.1	-
36.	2-3	-	32.7	24.3	-
37.	3-4	-	23.3	24.4	-
38.	4-5	-	20.7	-	-

*Separation by magnetic separator.
1/ LRD - Land Reclamation Directorate
2/ WPAU - West Pakistan Agricultural University
3/ TW - Tube Well

Table 2. Analyses of [illegible] in digests of Pre and [illegible] composite samples.

Sample	Depth cm	CaO %	MgO %	K_2O %	Na_2O %
LFD	0-1	[illegible]	1.12	1.83	1.68
	1-2	[illegible]	1.01	2.01	1.93
	2-3	0.69	1.57	2.02	2.03
	3-4	0.74	[illegible]	2.17	2.37
	4-5	1.12	[illegible]	[illegible]	2.51
WPAD A	0-.5	[illegible]	[illegible]	2.24	2.23
	.5-1	1.51	1.50	[illegible]	2.04
	1-2	0.97	[illegible]	2.51	2.23
	2-3	0.97	2.63	[illegible]	[illegible]
	3-4	1.22	2.05	2.77	2.24
	4-5	1.51	1.11	1.50	1.82
WPAD B	0-.5	1.15	1.04	2.22	2.16
	.5-1	2.17	2.31	3.17	1.92
	1-2	1.08	1.63	2.47	1.97
	2-3	1.20	2.60	[illegible]	[illegible]
	3-4	[illegible]	2.01	[illegible]	2.66
	4-5	2.02	1.16	1.76	3.33
WPAD C	0-.5	1.73	1.52	2.24	3.05
	.5-1	1.23	[illegible]	2.06	2.03
	1-2	1.13	1.16	2.15	2.03
	2-3	1.72	[illegible]	2.12	3.35
	3-4	1.15	1.15	1.22	2.01
	4-5	1.72	1.23	2.16	3.20
TW 145	0-1	0.95	1.32	2.22	1.65
	1-2	1.56	1.63	[illegible]	2.27
	2-3	0.78	1.45	[illegible]	[illegible]
	3-4	1.23	1.74	[illegible]	2.62
	4-5	1.14	1.36	2.23	2.82
TW 161	0-1	1.21	1.47	1.97	3.23
	1-2	1.16	1.13	1.76	1.60
	2-3	1.12	1.11	1.79	1.61
	3-4	1.71	1.55	2.01	3.75
	4-5	1.63	1.57	2.06	2.76
TW 14	0-1	0.98	0.79	2.50	1.81
	1-2	1.36	1.45	2.81	2.68
	2-3	0.92	0.89	3.39	2.03
	3-4	1.59	1.22	2.95	3.17
	4-5	1.03	1.01	2.82	1.97

Table 2 (Cont)

Soil	Depth ft	CaO %	MgO %	K_2O %	Na_2O %
TW 25	0-1	0.97	1.72	2.50	2.06
	1-2	0.83	1.85	2.81	2.02
	2-3	1.42	2.45	3.39	3.45
	3-4	1.40	2.09	2.95	3.11
	4-5	0.66	1.93	2.82	1.82
TW 7A	0-1	1.86	1.79	2.15	3.30
	1-2	1.39	1.54	2.03	1.95
	2-3	1.47	1.52	2.03	1.91
	3-4	1.47	1.71	2.09	1.99
	4-5	2.76	2.79	2.60	4.26
TW 17B	0-1	1.13	1.50	2.34	2.07
	1-2	0.53	1.92	2.96	2.08
	2-3	0.78	2.08	3.16	2.00
	3-4	0.79	2.16	3.17	1.84
	4-5	0.81	2.17	3.02	1.95
Rahwali Area	0-1	0.88	1.83	2.73	2.25
	1-2	1.06	0.96	2.06	2.02
	2-3	0.97	0.97	2.03	2.01
	3-4	0.91	1.32	2.31	2.02
	4-5	0.43	1.41	2.45	2.18

1/ LRD - Land Reclamation Division, [illegible] Department of Water Resources
TW - Tulare Well

Table 3. Mineral 1/ content of very fine sand grains of Pakistani soils.

Soil 2/	Depth	Grain Count - %												
		Qtz.	K-Fld.	Pl-Fld.	Mica	Chl.	Pyr.	Amph.	Gar.	Mag.	Tr.	Agg.	Alt.	Un.
	(ft.)													
LRD	0-1	40.0	6.9	10.1	34.0	2.6	0.4	0.4	0.2	0.6	1.2	1.0	2.4	0.2
	4-5	26.3	7.3	4.7	49.0	3.4	1.6	1.3	0.1	1.1	0.8	0.8	2.4	1.2
WPAU A	0-.5	38.6	4.7	7.9	40.0	2.4	0.6	0.8	0.8	1.0	1.0	0.4	1.8	-
	4-5	34.4	4.2	5.8	42.8	3.3	0.9	1.3	2.0	0.4	0.2	0.4	3.3	1.0
WPAU B	0-.5	36.7	4.2	8.4	39.2	2.8	0.4	0.2	0.4	1.0	0.7	1.8	2.8	1.2
	4-5	37.3	1.7	10.9	35.9	3.2	0.2	1.5	1.0	2.2	2.2	1.2	2.2	0.5
WPAU C	.5-1	34.7	8.9	9.1	38.8	1.0	0.8	1.4	1.0	1.4	0.4	1.0	1.2	0.3
TW 149	0-1	33.5	8.1	7.9	36.0	2.6	1.1	1.3	0.4	1.5	0.4	4.5	2.1	0.6
	4-5	35.5	5.3	8.5	37.2	3.4	0.5	0.7	0.2	0.5	0.2	3.9	3.4	0.7
TW 161	0-1	39.6	8.3	12.5	20.4	4.2	0.9	1.3	2.0	1.3	0.6	4.8	2.8	1.3
	4-5	35.8	7.0	7.5	29.3	3.3	1.9	0.9	1.4	2.3	1.3	6.0	2.3	1.0
TW 14 FAO	0-1	44.2	9.3	11.4	34.6	1.2	1.2	0.7	1.2	0.9	0.2	2.8	1.6	0.7
	4-5	45.6	8.6	12.5	24.2	0.8	0.8	1.6	1.0	1.0	0.7	2.4	0.6	0.2
TW 85	0-1	33.0	5.9	7.7	40.7	2.9	0.7	0.9	1.1	0.7	0.4	3.8	1.8	0.4
	4-5	39.3	8.5	8.2	36.4	1.5	-	0.4	0.4	0.2	0.3	2.6	2.0	0.2
TW 7A	0-1	35.6	5.9	8.3	33.2	4.4	1.5	1.8	1.3	0.7	1.0	2.2	3.7	0.4
	4-5	35.2	4.2	7.3	37.4	4.0	1.3	0.8	1.5	1.3	0.8	3.1	2.5	0.6
TW 178	0-1	36.7	5.9	4.2	44.9	2.7	0.4	0.4	0.4	0.8	0.9	1.0	1.3	0.4
	4-5	24.7	4.7	5.1	58.1	3.3	0.2	0.4	0.4	0.2	0.3	1.2	1.2	0.2
Rahwal	0-1	35.1	4.9	7.0	44.5	1.7	-	0.4	0.2	0.4	0.7	2.1	2.6	0.4
	4-5	27.1	2.7	9.8	50.6	3.7	-	0.5	0.2	0.7	0.5	2.0	2.2	-

1/ The key to mineral abbreviations is given in table 2b.
2/ LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well

Table 3a. Key to mineral abbreviations.

Qtz.	-	Quartz
K-Fld.	-	Orthoclase and microcline
Pl-Fld.	-	Plagioclase feldspar (mainly oligoclase but a range from albite to andesine is found)
Mica	-	Biotite and muscovite
Chl.	-	Chlorite
Pyr.	-	Hypersthene and clinopyroxene (probably diopside)
Amph.	-	Metamorphis blue-green hornblende
Gar.	-	Garnet
Mag.	-	Magnetite
Tr.	-	Trace mineral (tourmaline, calcite, zircon, kyanite, epidote (?)
Agg.	-	Aggregates of silt-sized minerals cemented by Fe-oxide and/or carbonates
Alt.	-	Highly altered feldspars apparently weathering to clay
Un.	-	Unidentified with petrographic microscope

Table 4. Analyses of Pakistani soil clays.

Soil[1/]	Depth	CEC 2-.2μ	CEC <.2μ	Total K_2O 2-.2μ	Total K_2O <.2μ	Surface Area 2-.2μ	Surface Area <.2μ	Quartz & Feldspar 2-.2μ
	(ft.)	(meq/100g)		(%)		(M^2/g)	(M^2/g)	(%)
LRD	0-1	22.9	73.5	4.1	2.6	69	288	10.4
	1-2	27.6	62.3	3.7	2.7	109	337	8.1
	2-3	26.0	60.6	3.9	2.8	82	339	
	3-4	28.8	60.0	3.7	2.8	103	307	
	4-5	24.9	59.9	4.1	2.7	117	336	11.1
WPAU A	0-.5	35.9	55.6	3.5	3.3	117	319	8.4
	.5-1	29.0	55.8	3.9	2.8	118	307	
	1-2	31.3	59.8	4.0	3.0	138	331	
	2-3	24.9	57.4	4.1	2.6	100	317	
	3-4	24.7	58.2	4.1	2.8	95	325	12.5
	4-5	24.9	57.5	3.9	3.0			
WPAU B	0-.5	28.5		3.6		133		9.7
	.5-1	27.9				102		
	1-2	28.5		4.1		119		
	2-3	24.9		3.8		108		
	3-4	24.9		3.8		112		12.6
	4-5	32.9		3.7				
WPAU C	0-.5	33.9	66.7	3.9		135	347	10.6
	.5-1	35.8	65.4	4.1	3.3	202	363	
	1-2	41.9	60.0	4.2	3.2	182	372	
	2-3	41.8	65.5	4.2	3.1	211	379	
	3-4	43.8	67.5	4.2	2.8	208	336	
	4-5	39.8	69.0	4.2	3.0	161	335	10.1
TW 149	0-1	42.4	69.3	4.2	3.1	169	346	7.9
	1-2	46.9	74.4	3.7	2.5	170	352	
	2-3	42.8	74.4	3.6	2.0	166	344	
	3-4	49.8	73.5	3.7	2.1	173	351	
	4-5	42.9	76.2	3.5	2.1	202	364	7.6
TW 161	0-1	29.9	77.7	3.7	2.4	154	343	11.0
	1-2	37.8		3.6	2.3	175	379	
	2-3		75.0		2.0		386	
	3-4	37.8	73.5	3.4	2.0	166	380	
	4-5	32.9	73.2	3.5	2.2	97	373	8.6
TW 14 FAO	0-1	30.2	66.1	4.2	2.7	152	371	9.0
	1-2	36.8	87.4	3.7	2.2	171	389	
	2-3	42.5	86.9	3.4	2.0	216	404	
	3-4	40.7	87.2	3.6	2.0	223	414	8.3
	4-5		70.4		2.6			
TW 85 Khadiv	0-1	31.8	57.5	3.7	3.1	177	316	10.6
	1-2	28.2	64.6	4.1	3.2	129	296	
	2-3	23.6	67.1	4.1	3.1	103	279	
	3-4	26.9	67.7	4.1	3.2	93	299	
	4-5	30.8	72.4	3.5	2.8	64	275	11.3

Table 4. Analyses of Pakistani soil clays.

Soil[1/]	Depth	CEC 2-.2μ	CEC <.2μ	Total K_2O 2-.2μ	Total K_2O <.2μ	Surface Area 2-.2μ	Surface Area <.2μ	Quartz & Feldspar 2-.2μ
	(ft.)	(meq/100g)		(%)		(M^2/g)	M^2/g)	(%)
TW 7A Khadiv	0-1	35.6	68.1	3.5	2.4	160		9.1
	1-2	35.6	66.6	3.6	3.2	189	323	
	2-3	36.2	69.4	3.6	2.5	192	358	
	3-4	37.8	75.9		2.6	201	353	
	4-5	36.3	72.0	3.5	2.5	181		8.5
TW 178 Khadiv	0-1	29.4	69.3	3.9	2.9	138		12.5
	1-2	22.8	71.6	3.9	3.3	132	294	
	2-3	27.8	74.8	4.2	3.2	104	327	
	3-4	29.8	73.6		3.2	130	323	
	4-5	29.8	71.2	3.8	3.5	118	339	
Rahwal Mirja	0-1	23.9	67.4	4.2	3.7	96	297	15.4
	1-2	24.9	64.0	4.2	3.6	91	276	
	2-3	27.2	64.8	3.9	3.3	112	275	
	3-4	33.7	70.6	3.8	3.0	130	287	
	4-5	30.8	70.9	3.9	2.8	116	279	11.3

1/ LRD - Land Reclamation Directorate
WPAU - West Pakistan Agricultural University
TW - Tube Well

Table 5. Water soluble cations and anions of Punjab soils.

Soil[1/]	Depth	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
	ft.				me/l				
LRD	0-1	45.0	17.7	138.1	1.3		4.0	153.8	23.8
	1-2	2.9	1.3	10.0	0.1		5.7	4.2	6.8
	2-3	1.4	0.4	11.0	0.1	1.7	2.7	1.4	6.9
	3-4	2.1	0.8	22.0	0.1	0.7	4.0	7.5	13.1
	4-5	2.4	1.1	24.5	0.2	0.4	3.9	8.5	18.2
WPAU A	0-.5	34.3	9.3	155.0	2.0		4.5	64.8	130.0
	.5-1	4.1	2.7	38.5	0.6		4.7	8.5	37.6
	1-2	1.6	1.7	20.0	0.[illegible]		4.0	3.9	15.6
	2-3	0.9	1.2	9.0	0.2		3.7	2.3	4.8
	3-4	3.8	3.9	7.0	0.5		4.0	2.1	8.0
	4-5	5.0	4.5	4.0	0.6	0.7	3.3	3.4	8.5
WPAU B	0-.5	11.5	5.6	42.5	1.3		4.3	11.3	42.5
	.5-1	10.0	3.9	51.5	0.7		4.0	16.9	46.0
	1-2	13.7	8.2	45.0	0.5		3.0	14.1	50.0
	2-3	12.2	10.7	21.5	0.4		2.8	14.1	28.8
	3-4	6.9	4.5	7.0	0.4		4.3	11.3	9.5
	4-5	4.1	1.8	6.0	0.4		4.0	5.6	4.8
WPAU C	0-.5	7.9	1.8	12.5	1.2		3.9	9.0	9.0
	.5-1	11.9	2.4	7.0	0.6		3.5	6.8	9.8
	1-2	11.9	2.5	6.0	0.3		2.8	3.9	12.4
	2-3	11.9	2.2	4.5	0.2		3.1	2.8	12.0
	3-4	9.9	1.8	5.0	0.3		3.5	4.2	10.0
	4-5	8.0	1.1	4.0	0.3		3.8	4.2	6.5

(Continued)

Table 5. (Continued)

Soil[1/]	Depth	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
	ft.				me/l				
TW 149	0-1	3.3	0.8	8.1	0.2	0.2	3.5	4.7	4.2
	1-2	1.5	0.3	7.8	0.1		6.0	2.8	2.4
	2-3	2.7	0.7	7.0	0.1		4.7	3.7	4.4
	3-4	7.1	1.9	7.0	0.1		3.3	4.7	8.5
	4-5	12.5	3.4	7.6	0.2		2.0	9.5	11.6
TW 161	0-1	4.1	0.9	6.8	0.3	0.2	5.5	2.8	3.9
	1-2	4.5	0.9	5.3	0.2		3.8	4.0	3.6
	2-3	3.2	0.5	4.8	0.1		4.0	3.7	3.1
	3-4	3.3	0.5	5.0	0.1		3.8	3.3	2.2
	4-5	3.9	0.7	4.8	0.1		3.7	3.7	2.2
TW 14	0-1	2.0	1.8	11.0	0.4	1.0	4.5	4.3	5.1
	1-2	1.3	0.9	10.8	0.3		4.3	2.8	4.4
	2-3	1.2	0.7	9.1	0.1		4.9	2.8	4.4
	3-4	1.0	0.6	8.4	0.1	0.3	5.5	3.5	3.8
	4-5	0.8	0.6	9.6	0.1	0.5	5.0	2.8	3.8
TW 85	0-1	7.0	4.1	14.0	0.4		5.0	8.4	8.5
	1-2	4.4	2.7	8.8	0.4		4.0	5.7	6.0
	2-3	3.6	1.9	6.8	0.2		3.7	3.8	4.4
	3-4	3.6	1.7	6.6	0.2		3.4	4.3	4.0
	4-5	4.1	0.6	6.8	0.2		2.9	4.5	4.0
TW 7A	0-1	22.2	7.0	32.5	0.6	2.0	1.0	42.3	16.0
	1-2	51.5	10.3	52.5	1.1		3.0	83.2	32.3
	2-3	36.9	20.3	53.5	0.6		3.3	60.6	47.0
	3-4	28.4	17.5	30.0	0.5		4.0	33.8	47.5
	4-5	29.4	16.7	29.3	0.6	0.4	3.0	20.7	53.1

(Continued)

Table 5 . (Continued)

Soil[1/]	Depth	Ca	Mg	Na	K	CO_3	HCO_3		SO_4
	ft.				me/l				
TW 178	0-1	12.0	3.7	18.2	0.8		5.0	11.3	6.3
	1-2	5.5	1.6	8.4	0.4		3.7	5.6	5.0
	2-3	5.2	1.9	7.4	0.3		3.0	4.7	3.3
	3-4	4.7	1.4	6.8	0.3		3.0	3.7	3.3
	4-5	4.7	2.1	6.4	0.3		4.0	4.2	4.0
Rahwali Area	0-1	6.2	3.1	14.6	0.4		3.4	6.2	11.8
	1-2	3.5	1.3	7.0	0.3		2.4	2.8	4.4
	2-3	3.5	1.1	5.8	0.3		2.8	3.4	4.0
	3-4	2.9	0.9	6.8	0.2		3.2	2.8	3.5
	4-5	3.3	1.1	5.4	0.2		3.2	3.4	3.2

1/ LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well.

Table 6. Salt and exchangeable sodium, and cation exchange capacity analyses of Punjab soils.

Soil[1/]	Depth	$EC \times 10^3$	SAR	Exch. Na	CEC	ESP
	ft.	mmhos/cm		me/100 g.		
LRD	0-1	16.0	25.0	1.00	8.2	12.2
	1-2	1.6	7.0	0.70	7.4	9.5
	2-3	1.6	11.5	1.12	7.2	15.5
	3-4	2.3	18.2	1.30	7.2	18.1
	4-5	3.0	18.5	1.53	7.8	19.6
WPAU A	0-.5	14.7	33.2	2.57	8.6	30.0
	.5-1	4.3	21.0	1.90	9.4	20.2
	1-2	2.4	15.7	1.35	9.0	15.0
	2-3	1.2	9.8	0.70	8.2	8.5
	3-4	1.5	3.6	0.36	7.4	4.9
	4-5	1.5	1.8	0.29	4.8	6.0
WPAU B	0-.5	5.5	14.5	1.11	8.6	12.9
	.5-1	6.1	19.6	1.68	9.0	18.7
	1-2	5.8	13.6	1.46	9.6	15.2
	2-3	4.0	6.3	0.67	9.6	7.0
	3-4	1.9	2.9	0.37	5.0	7.4
	4-5	1.3	3.5	0.24	3.8	6.3
WPAU C	0-.5	2.2	5.7	0.63	10.4	6.0
	.5-1	2.0	2.6	0.32	10.0	3.2
	1-2	1.7	2.2	0.24	10.4	2.3
	2-3	1.7	1.7	0.30	11.4	2.6
	3-4	1.5	2.1	0.26	10.4	2.5
	4-5	1.3	1.9	0.24	10.4	2.3
TW 149	0-1	1.3	5.6	0.76	11.4	6.7
	1-2	1.1	8.1	1.35	14.6	9.3
	2-3	1.1	5.4	1.15	17.8	6.5
	3-4	1.7	3.3	0.74	16.8	4.4
	4-5	2.4	2.7	0.62	15.8	3.9
TW 161	0-1	1.3	4.3	0.39	6.2	6.3
	1-2	1.1	3.2	0.31	7.4	4.2
	2-3	0.9	3.5	0.47	9.6	4.9
	3-4	0.9	3.7	0.50	10.0	5.0
	4-5	1.0	3.2	0.42	9.0	4.7
TW 14	0-1	1.4	7.9	0.54	7.8	6.9
	1-2	1.1	10.5	1.05	14.0	7.5
	2-3	1.1	9.6	1.38	13.0	10.6
	3-4	1.2	9.4	1.28	11.0	11.7
	4-5	1.2	11.4	1.21	7.4	16.4

(Continued)

Table 6. (Continued)

Soil[1/]	Depth	$EC \times 10^3$	SAR	Exch. Na	CEC	ESP
	ft.	mmhos/cm		me/100 g.		
TW 85	0-1	2.5	6.0	0.62	7.8	8.0
	1-2	1.6	4.7	0.60	9.4	6.4
	2-3	1.3	4.1	0.95	14.6	6.5
	3-4	1.2	4.1	0.60	16.4	4.1
	4-5	1.3	4.4	0.50	9.4	5.3
TW 7A	0-1	5.1	8.5	1.07	11.4	9.4
	1-2	10.4	6.0	1.08	10.8	10.0
	2-3	9.9	10.0	0.94	11.8	8.0
	3-4	7.8	6.3	1.03	11.8	8.7
	4-5	7.3	6.1	0.91	10.8	8.4
TW 178	0-1	3.6	6.5	0.69	6.2	11.1
	1-2	1.7	4.5	0.49	7.4	6.6
	2-3	1.7	3.9	0.49	7.8	6.3
	3-4	1.4	3.9	0.52	6.6	7.9
	4-5	1.4	3.5	0.41	7.4	5.6
Rahwali Area	0-1	2.3	6.8	0.82	9.4	8.7
	1-2	1.3	4.5	0.72	11.4	6.3
	2-3	1.1	3.8	0.50	7.4	6.8
	3-4	1.3	5.0	0.44	6.4	6.9
	4-5	1.1	3.6	0.56	8.2	6.8

1/ LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well.

Table 7 . Moisture retention properties of Punjab soils.

Soil[1/]	Depth	Saturation	1/3-Bar	15-Bar
	ft.	%	%	%
LRD	0-1	34.6	22.5	7.5
	1-2	33.7	22.4	6.3
	2-3	32.5	24.8	6.1
	3-4	35.3	26.0	7.0
	4-5	35.4	25.8	7.8
WPAU A	0-.5	30.9	20.6	10.6
	.5-1	34.9	22.0	13.5
	1-2	38.4	25.6	12.7
	2-3	41.9	32.5	13.0
	3-4	39.4	26.7	9.8
	4-5	27.0	14.8	4.3
WPAU B	0-.5	31.2	21.3	10.0
	.5-1	33.4	23.5	12.3
	1-2	37.1	26.0	12.0
	2-3	43.2	31.0	11.5
	3-4	32.5	22.2	6.8
	4-5	26.5	8.6	2.4
WPAU C	0-.5	29.3	20.3	9.5
	.5-1	29.1	18.5	9.1
	1-2	30.4	17.7	9.3
	2-3	30.8	18.7	9.7
	3-4	31.0	19.1	9.8
	4-5	29.7	19.2	9.1
TW 149	0-1	35.3	22.2	11.5
	1-2	36.7	24.3	14.7
	2-3	42.0	25.0	15.4
	3-4	42.2	29.3	16.6
	4-5	45.1	27.2	16.5
TW 169	0-1	25.5	15.3	6.5
	1-2	23.9	14.6	6.7
	2-3	26.5	17.1	9.0
	3-4	28.7	20.0	9.4
	4-5	28.4	18.6	9.1
TW 14	0-1	24.0	13.9	6.6
	1-2	36.4	23.4	12.2
	2-3	34.2	21.2	10.4
	3-4	28.2	18.0	8.1
	4-5	29.0	17.9	8.0

(Continued)

Table 7. (Continued)

Soil[1/]	Depth	Saturation	1/3-Bar	15-Bar
	ft.	%	%	%
TW 85	0-1	38.2	23.1	12.1
	1-2	45.3	27.1	15.1
	2-3	42.0	34.2	23.8
	3-4	54.2	32.8	20.8
	4-5	48.2	26.5	14.2
TW 7A	0-1	36.7	23.2	9.0
	1-2	33.5	20.0	9.5
	2-3	34.7	20.5	9.8
	3-4	36.9	21.7	10.5
	4-5	37.1	22.3	10.3
TW 178	0-1	25.9	23.2	9.1
	1-2	41.9	29.7	13.0
	2-3	52.9	28.5	12.7
	3-4	52.4	35.2	16.7
	4-5	47.9	37.0	11.1
Rahwali Area	0-1	42.4	27.4	16.7
	1-2	56.5	35.6	23.2
	2-3	38.5	26.2	11.7
	3-4	41.4	30.3	9.0
	4-5	45.2	28.0	12.6

LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well.

Table 8. Organic matter-and-lime-free separates of Punjab soils.

Soil[1/] and Depth (ft.)	% Clay <.2μ	% Clay .2-2μ	% Silt 2-5μ	% Silt 5-20μ	% Silt 20-50μ	% Sand .05-.1 mm	% Sand .1-.25 mm	% Sand .25-.5 mm	% Sand .5-1 mm	% Sand 1-2 mm	Total Clay	Total Silt	Total Sand	Texture
LRD 0-1	4.9	6.5	4.4	28.2	34.0	16.3	4.3	0.6	0.6	0.2	11.4	66.6	22.0	SiL
1-2	4.8	5.4	3.3	27.4	34.8	18.2	4.0	0.5	0.9	0.7	10.2	65.5	24.3	SiL
2-3	4.5	5.3	1.9	29.9	35.1	18.3	2.6	0.7	1.0	0.7	9.8	66.9	23.3	SiL
3-4	5.1	5.7	2.1	33.2	35.1	14.4	2.3	0.5	1.0	0.6	10.8	70.4	18.8	SiL
4-5	5.1	6.3	2.4	26.9	36.6	19.4	2.1	0.3	0.5	0.4	11.4	65.9	22.7	SiL
WPAU A 0-.5	6.3	8.9	3.5	28.4	18.0	10.8	21.2	2.3	0.4	0.1	15.2	49.9	34.9	L
.5-1	7.9	11.9	4.9	38.4	14.0	7.5	13.6	1.5	0.3	0.0	19.8	57.3	22.9	SiL
1-2	7.3	11.0	5.1	45.5	16.8	5.2	7.9	0.9	0.2	0.1	18.3	67.4	14.3	SiL
2-3	8.2	10.3	6.3	40.2	26.9	3.2	4.5	0.3	0.1	0.0	18.5	73.4	8.1	SiL
3-4	6.0	6.8	4.1	34.5	26.6	9.0	11.9	0.5	0.5	0.1	12.8	65.2	22.0	SiL
4-5	3.3	3.3	1.6	14.3	14.0	15.3	47.6	0.5	0.1	0.0	6.6	29.9	63.5	SL
WPAU B 0-.5	8.1	9.3	4.5	24.6	17.5	10.7	22.7	2.3	0.3	0.0	17.4	46.6	36.0	L
.5-1	8.0	13.3	7.5	40.6	13.8	5.6	9.7	1.3	0.2	0.0	21.3	61.9	16.8	SiL
1-2	8.4	10.8	5.3	28.6	12.9	9.3	22.1	2.3	0.3	0.0	19.2	46.8	34.0	L
2-3	8.0	10.8	5.7	43.3	18.5	5.6	7.4	0.6	0.1	0.0	18.8	67.5	13.7	SiL
3-4	5.3	6.1	4.8	29.8	14.7	10.7	25.3	2.6	0.6	0.1	11.4	49.3	39.3	L
4-5	2.2	1.9	1.5	7.6	8.0	15.3	63.0	0.4	0.1	0.0	4.1	17.1	78.8	LS
WPAU C 0-.5	5.8	9.3	4.2	18.6	23.3	15.2	21.2	2.1	0.3	0.0	15.1	46.1	38.8	L
.5-1	6.0	9.5	4.1	17.2	20.4	15.6	24.3	2.6	0.3	0.0	15.5	41.5	43.0	L
1-2	7.4	10.6	4.2	17.6	20.5	16.5	21.0	1.8	0.4	0.0	18.0	42.3	39.7	L
2-3	7.3	10.4	3.8	13.4	18.0	16.5	28.1	2.3	0.2	0.0	17.7	35.2	47.1	L
3-4	7.1	9.3	3.5	14.6	18.4	16.6	27.5	2.7	0.3	0.0	16.4	36.5	47.1	L
4-5	7.2	10.1	3.2	13.7	18.5	16.0	28.1	2.9	0.3	0.0	17.3	35.4	47.3	L

(Continued)

Table 8. Continued.

Soil[1/] and Depth (ft.)	% Clay <.2μ	% Clay .2-2μ	% Silt 2-5μ	% Silt 5-20μ	% Silt 20-50μ	% Sand .05-.1 mm	% Sand .1-.25 mm	% Sand .25-.5 mm	% Sand .5-1 mm	% Sand 1-2 mm	Total Clay	Total Silt	Total Sand	Texture
TW 149 0-1	8.5	10.8	7.5	29.8	25.3	7.4	6.7	3.3	0.[illegible]	0.0	19.3	62.6	18.1	SiL
1-2	10.8	14.2	5.6	32.6	23.0	6.4	4.7	2.3	0.4	0.0	25.0	61.2	13.8	SiL
2-3	13.3	14.9	5.8	34.7	21.0	4.8	3.7	1.5	0.3	0.0	28.2	61.5	10.3	SiCL
3-4	13.7	16.3	6.3	32.2	22.1	5.6	2.6	1.0	0.2	0.0	30.0	60.6	9.4	SiCL
4-5	10.7	17.3	5.6	36.1	21.7	5.5	2.2	0.7	0.2	0.0	28.0	63.4	8.6	SiCL
TW 161 0-1	4.1	7.1	2.5	15.1	20.4	15.3	21.9	12.0	1.6	0.0	11.2	38.0	50.8	L
1-2	5.8	7.0	2.5	16.7	15.4	8.4	26.1	15.7	2.4	0.0	12.8	34.6	52.6	L
2-3	6.5	9.3	3.0	14.3	17.5	8.6	22.4	15.8	2.3	0.3	15.8	34.8	49.4	L
3-4	7.3	8.5	3.1	19.3	17.9	6.8	19.6	14.7	2.4	0.0	16.2	40.3	43.5	L
4-5	6.7	8.6	3.3	19.5	18.2	7.9	19.1	14.4	2.3	0.0	15.3	41.0	43.7	L
TW 14 0-1	3.2	5.9	2.7	13.7	15.0	9.4	37.9	10.8	1.4	0.0	9.1	31.4	59.5	SL
1-2	4.9	11.3	4.8	27.2	14.5	7.6	19.5	7.3	1.2	1.7	16.2	46.5	37.3	L
2-3	8.9	10.4	4.3	17.6	13.7	8.3	26.2	9.3	1.3	0.0	19.3	35.6	45.1	L
3-4	6.7	7.5	2.7	13.0	13.6	11.1	32.9	11.1	1.4	0.0	14.2	29.3	56.5	SL
4-5	6.6	6.8	2.1	13.6	14.3	10.3	33.5	11.3	1.5	0.0	13.2	30.0	56.6	SL
TW 85 0-1	6.3	12.0	6.2	28.4	26.2	14.2	6.1	0.5	0.1	0.0	18.3	60.8	20.9	SiL
1-2	8.1	16.1	8.5	38.1	19.9	5.9	3.1	0.3	0.0	0.0	24.2	66.5	9.3	SiL
2-3	6.6	24.0	14.3	37.0	13.0	3.3	1.3	0.2	0.1	0.0	30.6	64.4	5.0	SiCL
3-4	6.5	34.4	6.7	21.2	22.4	5.0	3.2	0.4	0.2	0.0	40.9	50.3	8.8	SiC
4-5	7.3	13.5	7.8	36.3	19.8	11.1	3.6	0.3	0.1	0.2	20.8	63.9	15.3	SiL
TW 7A 0-1	5.7	9.3	5.3	26.6	26.4	12.2	13.3	1.1	0.1	0.0	15.0	58.3	26.7	SiL
1-2	5.7	10.8	3.6	22.2	25.5	17.4	13.7	1.0	0.1	0.0	16.5	51.3	32.2	SiL
2-3	6.7	11.2	3.8	22.0	25.7	16.0	13.8	0.8	0.0	0.0	17.9	51.5	30.6	SiL
3-4	7.4	12.3	3.5	25.8	22.8	16.5	10.9	0.8	0.0	0.0	19.7	52.1	28.2	SiL
4-5	7.1	10.8	3.2	28.8	28.0	12.2	8.2	0.5	0.2	1.0	17.9	60.0	22.1	SiL

(Continued)

Table 8. Continued.

Soil[1/] and Depth (ft.)	% Clay <.2μ	% Clay .2-2μ	% Silt 2-5μ	% Silt 5-20μ	% Silt 20-50μ	% Sand .05-.1 mm	% Sand .1-.25 mm	% Sand .25-.5 mm	% Sand .5-1 mm	% Sand 1.2 mm	Total Clay	Total Silt	Total Sand	Texture
Tw 178 0-1	4.1	8.6	3.9	23.7	27.6	22.8	8.5	0.7	0.1	0.0	12.7	55.2	32.1	SiL
1-2	3.7	16.1	1.4	32.3	31.3	8.1	6.3	0.6	0.1	0.1	19.8	65.1	15.1	SiL
2-3	6.0	14.9	7.1	45.4	22.8	2.4	1.2	0.1	0.0	0.1	20.9	75.3	3.8	SiL
3-4	7.3	15.2	9.8	42.5	19.6	3.0	2.3	0.3	0.0	0.0	22.5	71.9	5.6	SiL
4-5	5.0	10.3	5.6	43.3	31.2	3.1	1.4	0.1	0.0	0.0	15.3	80.1	4.6	SiL
Rahwali Area 0-1	7.2	17.5	9.3	30.6	23.3	8.2	3.8	0.1	0.0	0.0	24.7	63.2	12.1	SiL
1-2	3.2	23.3	15.8	36.6	14.9	2.6	3.1	0.3	0.2	0.0	26.5	67.3	6.2	SiL
2-3	6.2	8.1	9.9	23.0	32.1	10.3	9.4	0.7	0.3	0.1	14.2	65.0	20.8	SiL
3-4	4.8	11.2	5.2	32.7	35.4	7.6	2.5	0.6	0.0	0.0	16.0	73.3	10.7	SiL
4-5	6.4	8.7	8.6	31.7	30.9	6.9	6.2	0.5	0.1	0.0	15.1	71.2	13.7	SiL

1/ LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well.

Table 9. Fertility analyses of Punjab soils.

Soil[1/]	Depth (ft.)	Texture	pH (1:5)	O.M. (%)	Lime (%)	P_2O_5 (Lbs/A)	K_2O (Lbs/A)	Zn (ppm)	Fe (ppm)
LRD	0-1	SiL	8.4	0.6	7.1	111	245	1.55	4.2
	1-2	SiL	8.9	0.2	7.8	21	100	0.54	3.9
	2-3	SiL	9.1	0.1	8.6	16	100	0.48	4.0
	3-4	SiL	9.2	0.2	9.5	11	100	0.42	4.1
	4-5	SiL	9.2	0.1	12.2	7	140	0.52	4.6
WPAU	0-.5	L	8.5	0.5	9.8	41	540	10.00+	5.1
	.5-1	SiL	9.3	0.2	15.5	9	340	3.66	4.1
A	1-2	SiL	9.3	0.2	14.2	7	200	2.40	3.6
	2-3	SiL	9.1	0.2	12.6	17	200	6.30	3.8
	3-4	SiL	9.7	0.1	9.2	4	195	5.30	4.1
	4-5	SL	8.8	0.2	6.2	5	125	5.80	5.8
WPAU	0-.5	L	8.8	0.5	8.2	17	475	10.00+	4.6
	.5-1	SiL	9.0	0.2	15.0	5	370	10.00+	3.4
B	1-2	L	8.8	0.1	12.8	3	210	3.30	3.4
	2-3	SiL	8.6	0.1	13.8	3	165	.55	3.5
	3-4	L	8.7	0.2	8.6	8	120	6.10	4.7
	4-5	LS	8.8	0.1	5.6	5	65	6.00	7.3
WPAU	0-.5	L	8.6	0.8	2.0	27	725	6.00	6.4
	.5-2	L	8.4	0.3	1.0	33	455	1.47	6.1
C	1-2	L	8.3	0.4	0.8	19	300	0.64	6.9
	2-3	L	8.3	0.1	0.7	31	290	6.90	8.8
	3-4	L	8.3	0.1	0.5	37	300	2.16	8.7
	4-5	L	8.4	0.2	0.5	30	310	4.40	8.3
TW 149	0-1	SiL	8.7	1.0	0.9	5	330	1.06	7.7
	1-2	SiL	8.8	0.5	0.7	4	320	0.52	8.0
	2-3	SiCL	8.7	0.7	1.3	6	300	0.59	8.5
	3-4	SiCL	8.4	0.6	2.1	9	290	0.42	8.0
	4-5	SiCL	8.3	0.5	2.0	18	290	0.58	7.4
TW 161	0-1	L	8.7	0.4	3.7	5	200	0.92	6.7
	1-2	L	8.6	0.4	2.1	4	140	0.47	5.5
	2-3	L	8.6	0.4	3.1	4	135	0.51	5.3
	3-4	L	8.6	0.4	4.4	4	140	0.52	5.9
	4-5	L	8.6	0.1	6.7	5	120	0.54	5.3
TW 14	0-1	SL	9.0	0.6	1.3	5	275	0.65	12.7
	1-2	L	9.1	0.1	5.9	3	350	0.39	4.6
	2-3	L	9.3	0.1	3.7	3	275	0.48	6.2
	3-4	SL	9.3	0.1	2.0	6	265	0.50	5.5
	4-5	SL	9.4	0.1	2.0	8	230	0.53	4.9

(continued)

Table 9. Continued.

Soil[1/]	Depth	Texture	pH (1:5)	O.M.	Lime (%)	P_2O_5 (Lbs/A)	K_2O (Lbs/A)	Zn (ppm)	Fe (ppm)
TW 85	0-1	SiL	8.7	0.5	7.6	5	370	0.65	9.6
	1-2	SiL	8.7	0.5	0.4	4	370	0.60	8.0
	2-3	SiCL	8.5	0.5	2.0	10	495	0.78	15.7
	3-4	SiC	8.5	0.1	2.0	3	425	0.55	14.7
	4-5	SiL	8.6	0.4	6.4	5	240	0.44	5.2
TW 7A	0-1	SiL	8.3	0.2	6.9	4	275	0.55	5.6
	1-2	SiL	8.5	0.2	6.0	4	340	0.56	3.4
	2-3	SiL	8.4	0.2	5.2	5	320	0.46	3.2
	3-4	SiL	8.5	0.1	8.3	10	370	0.54	3.0
	4-5	SiL	8.5	0.1	13.8	10	300	0.55	3.2
TW 178	0-1	SiL	8.6	0.3	5.0	5	290	0.68	5.6
	1-2	SiL	8.6	0.5	5.8	4	300	0.60	7.0
	2-3	SiL	8.5	0.2	7.6	2	230	0.51	6.8
	3-4	SiL	8.6	0.2	6.8	3	300	0.41	7.2
	4-5	SiL	8.6	0.1	5.4	1	180	0.51	7.4
Rahwali Area	0-1	SiL	8.7	0.6	4.4	12	405	0.54	28.8
	1-2	SiL	8.6	0.4	1.3	5	445	0.50	10.6
	2-3	SiL	8.7	0.1	3.8	3	240	0.48	4.9
	3-4	SiL	8.7	0.1	5.8	2	165	0.53	3.6
	4-5	SiL	8.7	0.3	6.9	2	240	0.59	4.2

1/ LRD - Land Reclamation Directorate, WPAU - West Pakistan Agricultural University, TW - Tube Well.

APPENDIX C

EFFECT OF EXCHANGEABLE SODIUM PERCENTAGE, SOIL SALINITY, AND AVAILABLE PHOSPHOROUS LEVEL ON THE GROWTH OF ALFALFA AND BARLEY IN GREENHOUSE EXPERIMENTS

W. R. Schmehl

Most of the soil samples from Pakistan that were analyzed in the Colorado State University Soil Testing Laboratory were found low in available soil phosphorous. Phosphorous deficiency among crop plants in Pakistan probably is second only to nitrogen deficiency. A crop response to phosphorous would be expected on non-saline, non-sodic soils shown to be deficient in phosphorous by the soil test. However, there is a strong local belief in Pakistan that fertilizers are wasted when applied to lands irrigated with saline and sodic water. Since 16% of the irrigated land is supplied with water of 1000 ppm or more salt (M. Hussain, 1970 NESA Conference, p 311), information is needed to determine if the results of the sodium bicarbonate soil test procedure for P, which is highly successful for non-salt-affected soils, can be applied to the saline and sodic soils of Pakistan. Essentially, no published results are available that will provide this information. An unpublished Israeli report and some indirect observations in the literature constitute the extent of information.

The objective of this research was to determine the influence of soil salinity and exchangeable sodium (originating from irrigation water) on plant growth response to increasing levels of available soil phosphate. The first phases were planned as a greenhouse study with subsequent studies to be conducted in a field program in Pakistan if the results indicated need.

This is a preliminary report, and as such, both descriptive material and results are incomplete. Dr. M. B. Malik is preparing a full report for publication.

Experimental Procedures

A sandy loam soil from the San Luis Valley of Colorado was selected for the study because it was low in available phosphorus (2 ppm) and because the sandy soil would reduce the physical effect of exchangeable sodium on plant growth. Soluble salts were removed by leaching with low conductivity tap water, then monocalcium phosphate was added at rates to give three levels of available phosphorus (approximately 2, 8, and 24 ppm P). Soil at each of the available phosphorus levels was then divided into three equal portions and sodium bicarbonate was mixed with the soil and aged at saturation capacity moisture to give ESP (exchangeable sodium percentage) levels of approximately 1, 20, and 40. Krilium (0.01%) was mixed with the soils representing nine treatments (3ESP x 3P) and each treatment was placed in six icecream cartons. Alfalfa and barley were planted March 3 and water was added to bring the soil to field capacity. Two salinity levels were established at this time by adding either tap water to three pots per treatment or salt solutions (composition varied with ESP) to the other three pots. This gave two soil salinity levels of 0.26 and 4 mmhos cm^{-1}. With barley there were 18 treatments and three

replications to give a total of 54 cartons. Because of a limited soil supply, the alfalfa experiment had the same treatments but with only two replications.

Results

Barley

The barley crop was harvested after 39 days and the dry matter yields are summarized in Tables 1, 2, and 3 with the analysis of variance in Table 4. The main effects of ESP, P level, and salinity level and the P-level x ESP and P-level x salinity interactions were highly significant.

The main effects show that the barley responded markedly to available phosphorus. The largest response was to the first level of P (8 ppm) with a much smaller, but significant, response to the next level (24 ppm). Increasing the ESP to 20 had little effect on the yield of barley but a further increase to 40 reduced yields about 45%. Increasing the soil salinity from 0.26 mmhos to 4 mmhos decreased barley yields about 12%. This is surprising in view of the expected tolerance of barley to low or even moderate levels of soil salinity.

The P level x salinity interaction was of particular significance. The results show (Figure 1) that the barley crop responded only to 8 ppm available P at the low salinity level but responded to 24 ppm P at the 4 mmhc level of salinity. Most crop plants do not respond beyond about 10 or 11 ppm available P when grown in non-saline soils. The results suggest that possibly higher levels of available phosphorus will be required for crops grown in saline soils.

The P-level x ESP interaction also is interesting (Figure 2). The yield of barley continued to increase to the highest available P level so long as the ESP was 20 or below, but when the ESP was 40, there was no benefit from an available P level of more than 8 ppm.

The total phosphorus content (% P) of the dry plant material also was determined. The results (Table 5) show that increasing salinity decreased the P content of the plant whereas an increase in ESP to 20 significantly increased the P content. There was no further effect of higher ESP (40) on % P. The results suggest that the higher salinity reduced the physiological availability of P since an analysis of the soil revealed that increasing salinity did not reduce the available soil phosphorus. Conversely, increasing ESP had no detrimental effect on available P as indicated by either soil test or plant analysis.

Alfalfa

The dry-matter yields and the analysis of variance for the first cutting are summarized in Tables 6 through 9. There were highly significant effect both for the main treatments and for the three first order interactions.

There was a response to the second level of available P (8 ppm) but not to a higher level (Table 6). This is consistent with current field recommendations. There was no significant difference in yield between the control (ESP = 1) and an ESP of 20, but the yield on the 40 ESP treatment was greatly reduced. The 4 mmho salinity treatment reduced alfalfa yields below the control (0.26 mmhos).

The two interactions of particular interest, P-level x salinity and P-level x ESP, are shown in Figures 3 and 4. The yield response to the second level of available P (8 ppm) was greater on the low salinity soil and, in contrast to the barley experiment, there was no additional benefit from the higher available P level on the saline soil. Figure 4 shows that the response to increasing available phosphorus was the same for ESP levels of 1 and 20 but that there was little benefit from increasing available P with ESP 40.

Total P was determined on the plant material. Increasing available soil P increased the P concentration (% P) in the plant tissue as expected. Increasing the ESP increased % P (0.01 level of significance) and increasing the salinity decreased % P (0.10) level. The two significant interactions (P-level x salinity and P-level x ESP) are shown in Figures 5 and 6. Increasing available soil P did not increase % P as effectively at the higher salinity (4 mmhos) as with the control (0.26 mmhos salinity), indicating again, as with barley, that higher available soil P may be required as soil salinity increases. The ESP level of 20 or below had no appreciable effect on % P in the plant, but with ESP 40, % P in the plant was significantly higher. Since yields were greatly reduced for ESP 40, the high % P could have resulted because of reduced growth. It does not appear, however, that phosphorus availability to the plant is limited by the high ESP.

Summary

Two experiments were conducted to determine the response of barley and alfalfa to increasing available soil P at three levels of exchangeable Na (1, 20, 40%) and two levels of salinity (0.26 and 4 mmhos conductivity of the saturation extract).

For both crops an ESP of 20 had no detrimental effect on growth response to increasing levels of available soil phosphorus, nor was % P affected adversely. When ESP was increased to 40, however, growth was greatly reduced and % P increased. Thus, it appears that an ESP to 20 can be tolerated by these crops when grown in a light textured soil, but that ESP of 40 will not maintain good plant growth. With no intermediate data point the highest ESP for satisfactory plant growth can't be determined.

The results confirmed the usual observation that alfalfa is more sensitive to even low levels of salinity than is barley. Of particular significance to the Pakistan project were the observations that: 1) increasing salinity decreases the plant availability of soil phosphorus

although available soil phosphorus by the soil test was unaffected; and 2) higher rates of phosphorus fertilizer are required for saline soils than for non-saline soils, other conditions being the same (i.e. available soil phosphorus level, soil texture, crop to be grown, etc.).

The results suggest that field research should be conducted to study the phosphate requirements of crops grown under saline-sodic soils situations in Pakistan.

Barley Experiment

Table 1. Effects of Phosphorus and salinity on the dry matter yield of barley--1.

(grams/pot)

P Level 1/	Salinity Level S_1	S_2	Mean for P
P_1	2.218	1.424	1.821
P_2	6.593	5.024	5.809
P_3	6.397	6.940	6.668
Mean	5.069	4.463	

1/ P_1 = Check = 2 ppm avail. soil P; P_2 = 8 and P_3 = 24 ppm available soil P; S_1 = check, and S_2 = 4 mmhos/cm.

Table 2. The effects of E.S.P. and phosphorus on the dry matter yield of barley--1.

E.S.P. Level 1/	Phosphorus Level P_1	P_2	P_3	Mean for E.S.P.
Na_1	1.942	6.858	8.318	5.706
Na_2	2.083	6.532	7.940	5.518
Na_3	1.638	4.037	3.747	3.074
Mean	1.821	5.809	6.668	

1/ Na_1 = Check = 1 E.S.P.; Na_2 = 20 E.S.P.; and Na_3 = 40 E.S.P.

Table 3. The effects of E.S.P. and salinity on the dry matter yield of barley--1.

E.S.P. Level 1/	Salinity Level S_1	S_2	Mean for E.S.P.
Na_1	5.882	5.530	5.706
Na_2	5.759	5.278	5.518
Na_3	3.567	2.581	3.074
Mean	5.069	4.463	

1/ See footnotes on Tables 1 and 2

Table 4. Analysis of variance for dry matter yield of barley--1.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	Significance	L.S.D. .05	L.S.D. .01
R	2	2.07954	1.03977	3.48			
T	17	366.74109	21.57301	72.22	.01	.908	1.219
Na	2	77.63498	38.81749	129.94	.01	.370	.493
P	2	240.81948	120.40974	403.07	.01	.370	.493
S	1	4.96254	4.96254	16.61	.01	.303	.405
Na x P	4	29.58561	7.39640	24.76	.01	.642	.862
Na x S	2	1.00828	.50414	1.69		.524	.704
P x S	2	10.27447	5.13724	17.20	.01	.524	.704
Na x P x S	4	2.45573	.61393	2.06			
Error	34	10.15685	.29873				
Total	53	378.97748					

Table 5. The effects of E.S.P. and salinity on percent phosphorus of barley--1.

E.S.P. Level 1/	Salinity Level S_1	Salinity Level S_2	Mean for E.S.P.
Na_1	.154	.147	.151
Na_2	.209	.174	.192
Na_3	.194	.176	.185
Mean	.186	.166	

1/ See footnotes on Tables 1 and 2.

Table 6. The effects of phosphorus and salinity on the dry matter yield of alfalfa

Phosphorus Level (ppm avail. soil P)1/	Salinity Level S_1	S_2	Mean Yield for P
P_1	1.503	0.983	1.243
P_2	4.106	3.190	3.648
P_3	4.335	3.120	3.727
Mean	3.315	2.431	

1/ P_1 = Check = 2 ppm avail. soil P; P_2 = 8 and P_3 = 24 ppm available soil P; S_1 = check, and S_2 = 4 mmhos/cm

Table 7. The effects of E.S.P. and phosphorus on the dry matter yield of alfalfa.

E.S.P. Level1/	Phosphorus Level P_1	P_2	P_3	Mean Yield for Na
Na_1	1.547	4.517	5.127	3.730
Na_2	1.630	4.885	4.927	3.814
Na_3	0.552	1.542	1.127	1.074
Mean Yield for P	1.243	3.648	3.727	

1/ Na_1 = Check = 1 E.S.P.; Na_2 = 20 E.S.P.; and Na_3 = 40 E.S.P.

Table 8. The effects of E.S.P. and salinity on dry matter yield of alfalfa.

E.S.P. Level 1/	Salinity Level S_1	S_2	Mean Yield for Na
Na_1	4.090	3.371	3.730
Na_2	4.526	3.101	3.814
Na_3	1.328	0.820	1.074
Mean	3.315	2.431	

1/ See footnotes on Tables 1 and 2.

Table 9. Analysis of variance for dry matter yield of alfalfa.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	Significance	L.S.D. .05	L.S.D. .01
R	1	0.00562	0.00562	0.10			
T	17	127.55062	7.50298	132.08	.01	.503	.691
Na	2	58.28969	29.14485	513.05	.01	.205	.282
P	2	47.84551	23.92276	421.12	.01	.205	.282
S	1	7.03134	7.03134	123.78	.01	.168	.230
Na x P	4	12.10474	3.02619	53.27	.01	.356	.498
Na x S	2	1.38376	0.69188	12.18	.01	.290	.399
P x S	2	0.72937	0.36469	6.42	.01	.290	.399
Na x P x S	4	0.16621	0.04155	0.73	N.S.		
Error	17	0.96572	0.05681				
Total	35	128.52196					

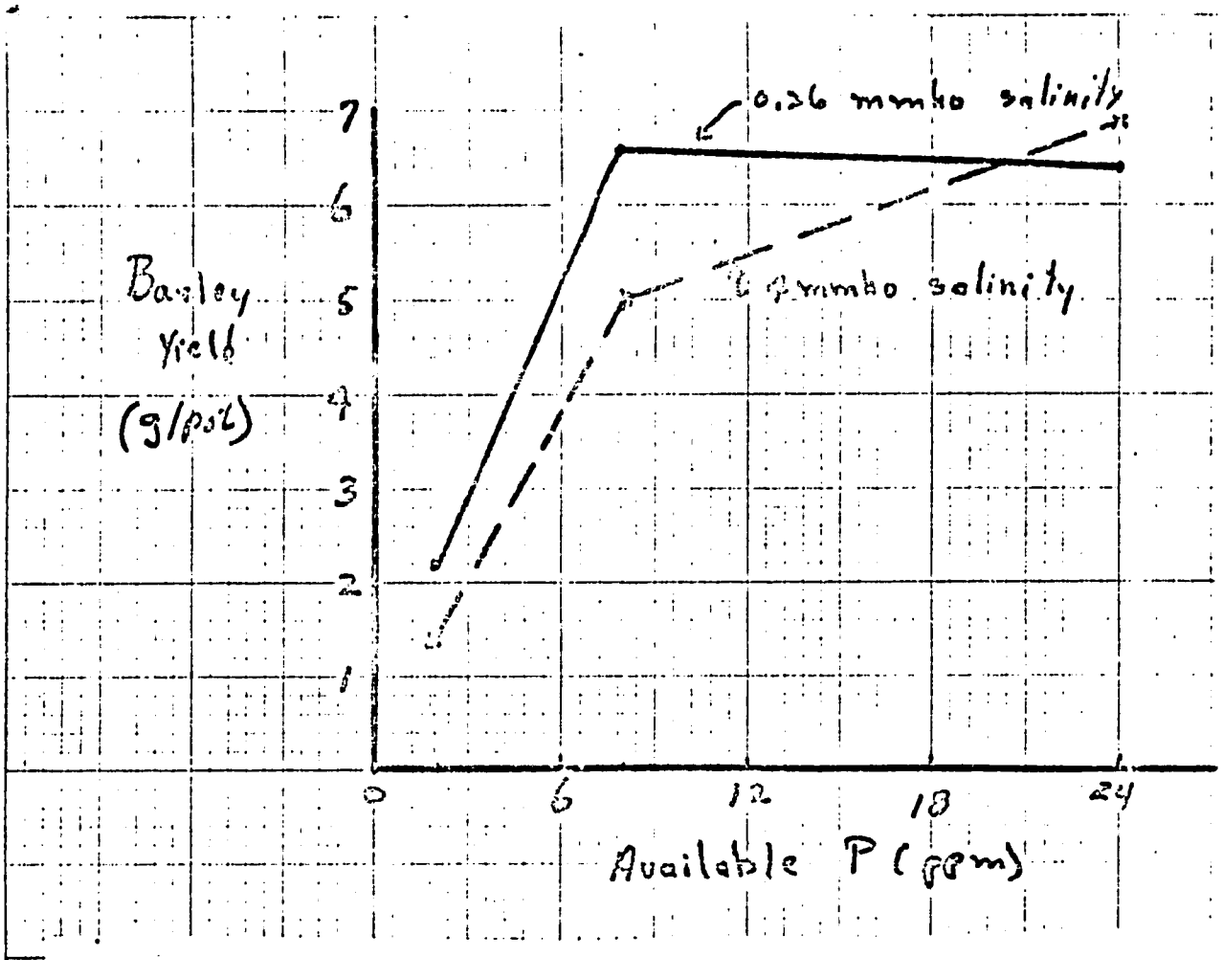


Fig. 1. Effect of available soil P and soil salinity on yield of barley.

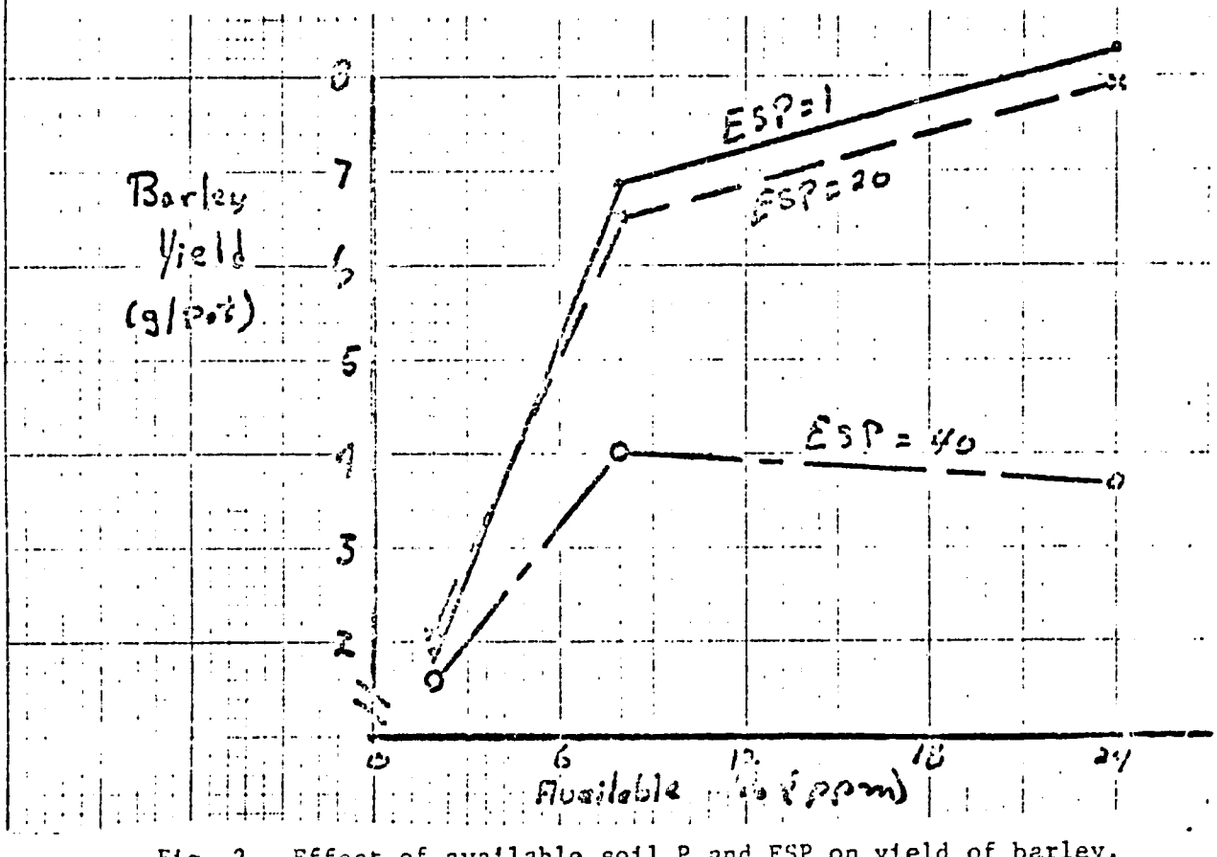


Fig. 2. Effect of available soil P and ESP on yield of barley.

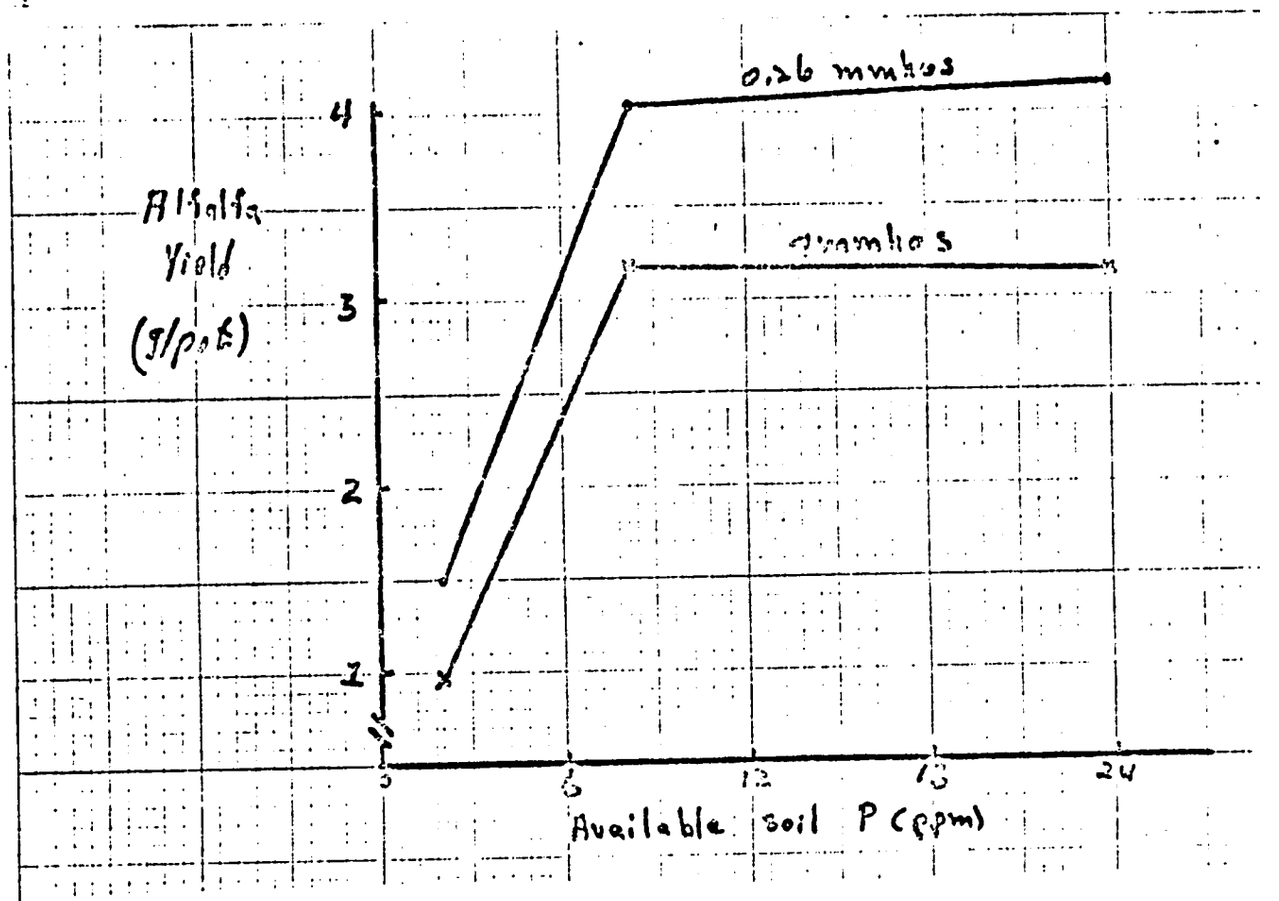


Fig. 3. Effect of available soil P and salinity on yield of alfalfa.

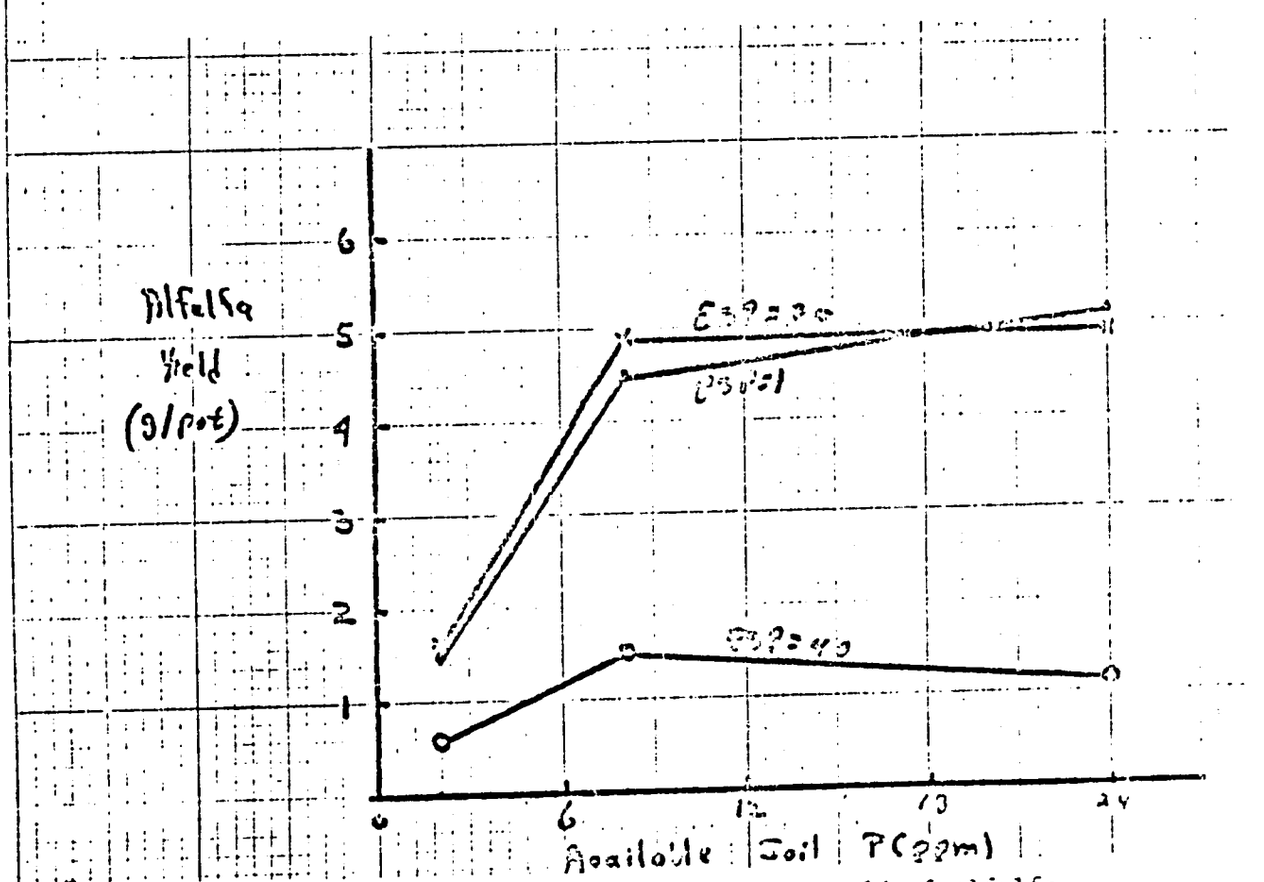


Fig. 4. Effect of available soil P and ESP on yield of alfalfa.

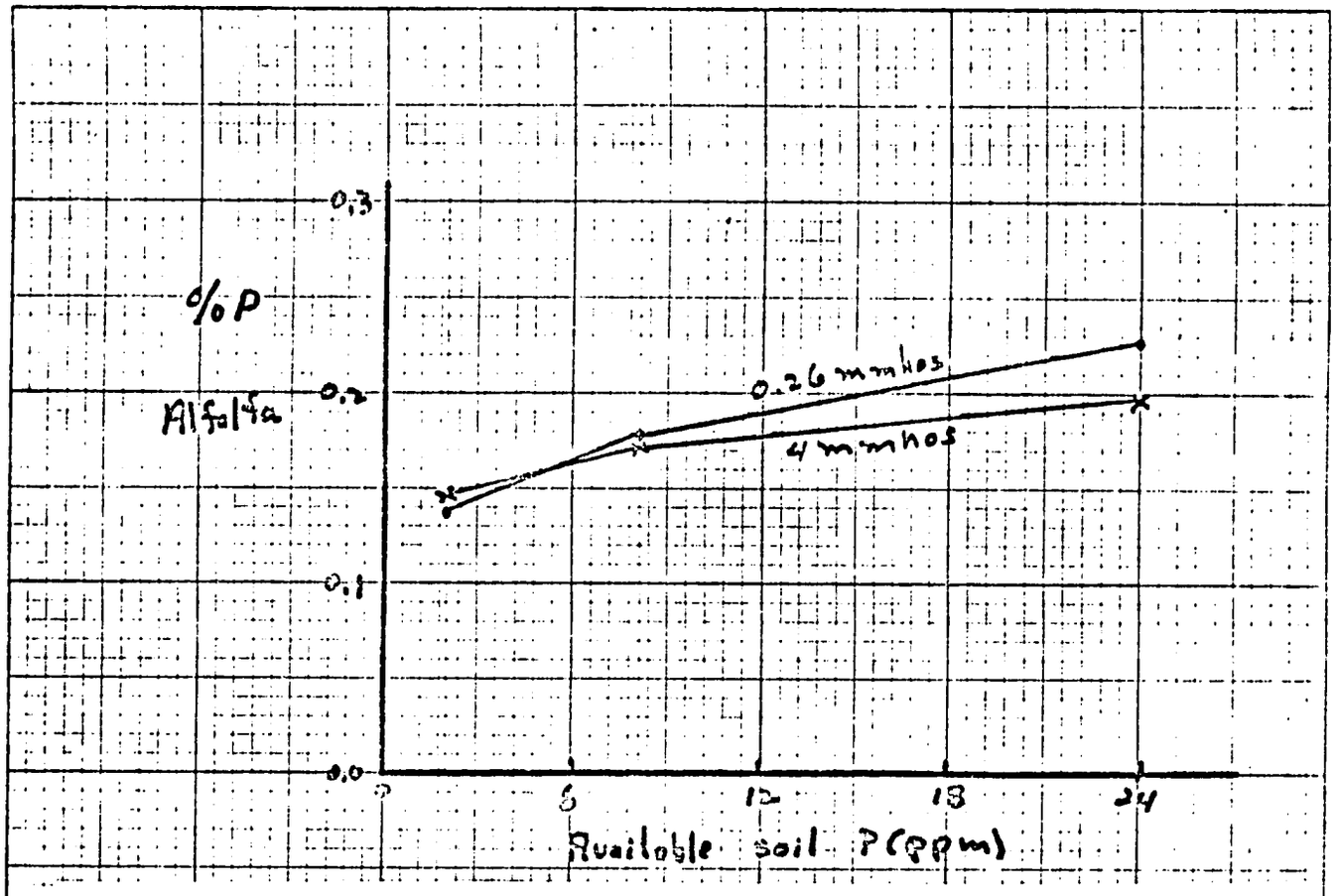


Fig. 5. Effect of available soil P (ppm) and soil salinity on % P in alfalfa.

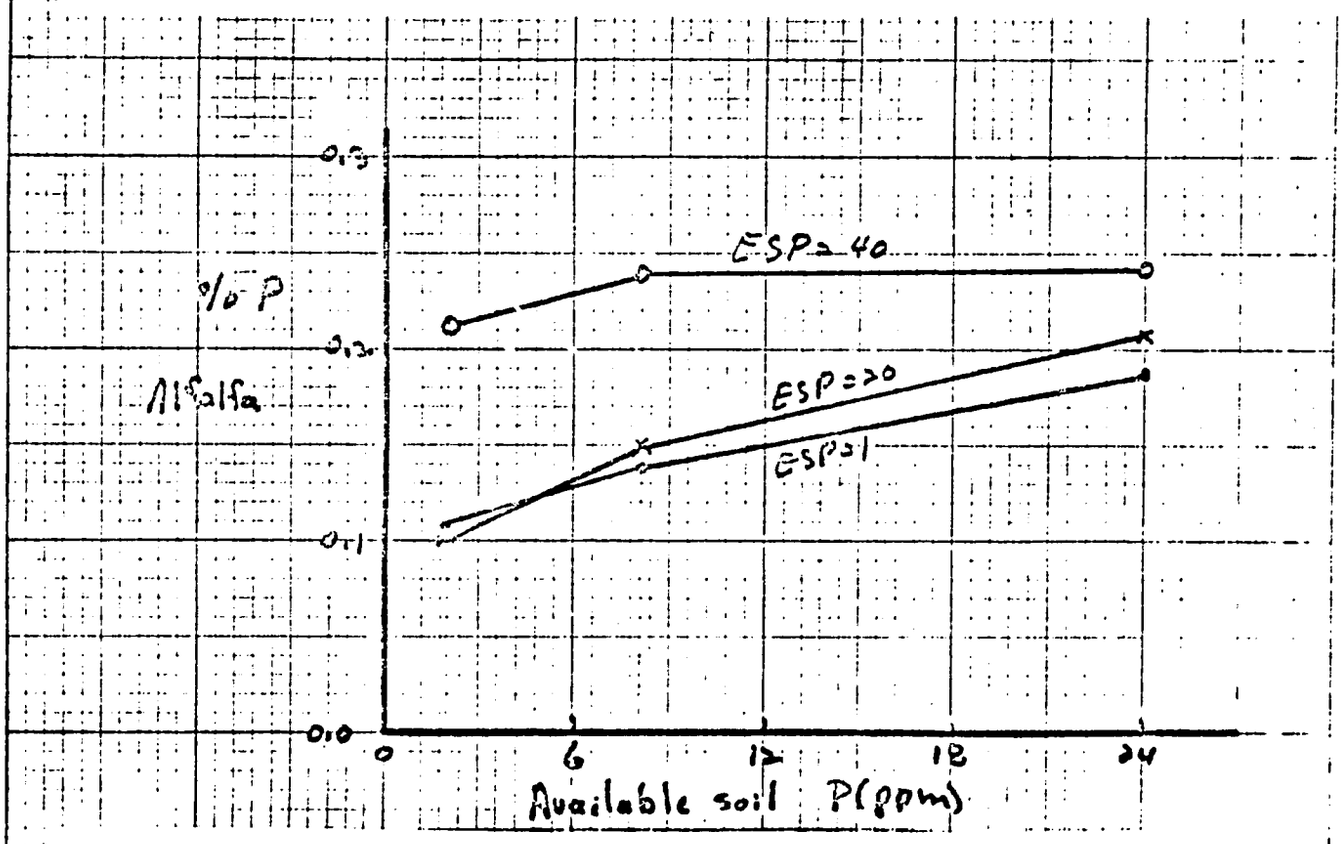


Fig. 6. Effect of available soil P (ppm) and ESP on % P in alfalfa.

APPENDIX D

Jones, Garth N. The problem of water scheduling in West Pakistan: Research studies and needs. November 1971. Water Management Technical Report No. 13.

The capacity to build and maintain the irrigation system has exceeded the capacity to manage the allocation of water for maximum agricultural production. The irrigation system was not designed to supply total crop water needs plus leaching requirements, but rather to provide sufficient water during the growing season to avoid complete crop failure and famine. In recent years the irrigation system has been substantially modified by increasing its storage capacity and by tubewells which utilize the storage capacity of the vast Indus aquifer. The irrigation system, in at least part of the Punjab, now has capacity to vary its water deliverance. Consequently, it is now possible to consider the development of irrigation scheduling based upon crop and soil needs. Reorganization of the irrigation system to achieve optimum delivery scheduling appears to be a formidable and long-term but worthwhile effort involving major changes in the social and physical structures. His relatively rapid acceptance of new seed, installations of private tubeweels etc., indicate that the Pakistan farmer is receptive to new technology. Consequently, the most rapid "water management" payoff will probably result from providing farmers who have access to controllable water with the technology which can help that control achieve maximum yields.

Jones, Garth N. Monastery model of development: Towards a strategy of large scale planned change. November 1971. Water Management Technical Report No. 14.

The primary purpose of this study is to advance a model which provides a realistic organizational approach in utilizing scarce resources in the development process. In essence the monastery model substitutes strong organization and efficient use of labor resources for capital in achieving development. An essential of the successful monastic models has been that the individuals were converted to a "new way of life" and were in some degree isolated from forces which could degrade their behavior to the previous norm.

Although the forces of change may be largely external, the desire to undertake change must emanate internally within a given organizational system. For instance, improved water management practices on all the farms on a watercourse may be suggested by an outside change agent, but the individual farmers must gain faith that the changes are for their benefit, before their efforts can be united strongly toward accomplishing that change. Uniting their efforts will require the presence (or development) of a village or watercourse level organization which has recognized status and authority, and has leaders or consultants who can provide mechanisms for attainment of the desired goals.

The monastery model can cause development assistance to be directly channelled to the poor rural people where it is most needed in the developing countries.

Mahmood, Khalid. Sediment routing in irrigation canal systems. January 1973. Meeting Preprint 1905 for ASCE National Water Resources Engineering Meeting, January 29 - February 2, 1973 in Washington, D. C.

The routing of bed material load through a branching irrigation canal system in such a way as to insure sediment discharge equilibrium is considered. All the sediment entering the system is disposed of with the water. It is shown that the system equilibrium can be more easily achieved if smaller sediment load concentrations are allocated to irrigation diversions from smaller channels. Also, approximate numerical model for predicting the bed material load from farm turnouts is presented.

McWhorter, D. B. Steady and unsteady flow of fresh water in saline aquifers. June 1972. Water Management Technical Report No. 20.

Problems of flow involving fresh water overlying saline water in aquifers and methods for their analysis are reviewed. Equations amenable to mathematical solution generally involve the idealization of treating the fresh water as a distinct zone separated from the underlying saline water by a sharp interface. The criterion for interface stability is derived in this study and its practical significance is described.

A new solution describing up-coning of saline water below horizontal tile drains is derived and used to calculate approximate optimum depth of drain placement. A procedure for estimating performance of collecting wells is outlined.

A procedure proposed in the literature for handling unsteady free surface problems was used to derive a differential equation which approximately describes the behavior of the unsteady interface. Practical applications of this equation are discussed and example calculations are given.

Sahni, Brij Mohan. Salt water coning beneath fresh water wells. April 1972. Water Management Technical Report No. 18.

The purpose of this research is to investigate the phenomenon of salt water coning below a discharge well partially penetrating an aquifer in which fresh water is underlain by saline water. The first portion of this report is concerned with the evaluation of techniques presently available for analyzing the performance of such wells. Both theoretical considerations as well as experimental results have shown that some of the assumptions used in the analytical techniques available are not valid while others are acceptable only under limited conditions.

The study also presents a mathematical model which is developed for evaluating the performance of a skimming well under a wide range of field situations. The practical utility of the results in deciding the optimum discharge from a skimming well is discussed. It is shown that for given aquifer conditions and well geometry the maximum steady-state production of uncontaminated fresh water is obtained at shallower well penetrations and closer well spacings than that predicted by the theory previously available.

APPENDIX E

List of Statements Identifying Known Uses of Materials Produced by the Project During the Report Year

The following seminars based on Water Management Project studies were presented at the International Interdisciplinary Seminar in Water Resources Management conducted at CSU and attended by nationals of at least a dozen foreign countries.

1. A sociological view of technology in development by D. M. Freeman.

2. A program for water and soil management in irrigated regions by Wayne Clyma.

3. Effects of varying levels of water availability on crop response by H. M. Neghassi.

4. An improved model for optimal timing of irrigation by H. M. Neghassi.

5. Pakistan's agricultural growth - its lessons and some unanswered questions by J. E. Eckert.

Other seminars, meeting presentations and writings during this period which were based primarily on the WMR studies included:

1. Effects of salinity and sodium in irrigation water on P and other nutrients in soils, by W. R. Schmehl and given at the Punjab Agricultural Research Institute at Lyallpur, July 1972.

2. Effects of sodium and salinity in irrigation water on the availability of P and crop growth by W. R. Schmehl, given at the Atomic Energy Commission Agricultural Section in Tandojam, June 1972.

3. Relations of salinity to drainage and pumping by Gil Corey at the Peshawar Agricultural Institute, October 1972.

4. Research designs for determining effects of plant population and crop stands on yield by Jerry Eckert, October 1972.

5. Legal problems and solutions to surface and groundwater management by George Radosevich presented at the Annual Symposium on Arid Zone Research held at Fort Collins, July 1972.

6. Water right changes to implement water management by George Radosevich, presented at the National Conference on Managing Irrigation Agriculture held at Grand Junction in May 1972.

7. Findings of Radosevich's studies were also used in preparing the chapter titled, "Pakistani Water Law" which is in press as part of the revised book titled, "Muslin Water Laws" to be published by FAO.

THE RESOURCE POSITION OF THE PAKISTANI FARMER

with particular reference to water and its management.

The purpose of this brief note is to describe the Pakistani farmer in terms of his productive resources and the types of constraints that influence his effective management of those resources. This paper is not a final statement, it is intended only to open discussion. Only through such an articulation can target strata or groups within the farm sector be identified and the research efforts of the water management research contract be oriented toward finding answers and techniques of specific relevance to the chosen clientele.

Any description of the type presented here runs the risks of overgeneralization. There will be variation around each of the characterizations discussed. The farmer under discussion relys to some extent on irrigation and as such is more typical of the Punjab or the irrigated portions of Sind Province. Farming under rainfed conditions is a wholly different environment governed by differing constraints, a different resource mix and managed within a different relative value set of the farm managers. No implications for the rainfed areas are intended from the following.

"Management" is defined as those decisions or actions taken to influence the quantities, qualities, timing or techniques with which resources are combined in a productive enterprise. The phrase "on-farm water management" is taken to delineate that subset of all water management decisions or actions which can be in some way affected by the farm operator.

It seems that in this context the general goal of the research program can be usefully disaggregated into three dimensions:

1. To enable the farmer to obtain more of the resources traditionally used.
2. To enable the farmer to use his traditional resources more productively.
3. To enable the farmer to utilize some of the more productive non-traditional inputs.

THE PAKISTANI FARMER

Land

Median farm size in Pakistan is 5.1 acres, which is, on the average, broken into 3.4 non-contiguous parcels.[1] An inegalitarian land distribution results in a much higher average, some 10 acres per farm. "Family farm" units have been variously approximated as either 8 or 12.5 acres, sizes that are felt to reflect the maximum acreage that one family with a limited number of dependents and a single pair of bullocks can operate effectively. The following cumulative percentages illustrate the differences between the distribution patterns of farm numbers and cultivated area.

Farms of:	Percent of Total Farms	Percent of Total Area
less than 5 acres	49.5	9.4
less than 7.5 acres	61.4	16.6
less than 12.5 acres	77.0	31.6
less than 25 acres	92.0	57.2

1 Most of the data in this exposition are from the 1960 Census of Agriculture, Vol. II, West Pakistan, Government of Pakistan, Karachi 1964

The implications of these data are obvious but warrant explicit specification. Humanitarian considerations suggest research towards techniques that will be relevant to the largest number of farm families. More than three-quarters of all farms are less than 12.5 acres in size. This group is characterized by the traditional resource mix and the traditional techniques of combining those resources such as discussed here in. Technologically, this group, or any less extensive group on the small end of the spectrum of farm size will be fairly homogeneous. Improved techniques of water use or control that are applicable to these small farms should be relevant to great numbers of individual farm units. Any grouping of similar size, beginning with large farmers, must reach down to such small farms that considerable heterogeniety would necessarily be included. Just to include half of the farm units would necessitate grouping all farms down to and including five acres in size.

To summarize this point I feel we must define farm groups based on technological homogeniety in order to establish identifiable resource environments within which to seek better techniques of water use. If we then wish to direct our efforts towards the largest of these groups, we will, per force, be working with small farmers.

On the other hand 43 percent of the cultivated area is in farms of 25 acres or larger. These farms are of a size where tractor mechanization, tubewells and other advanced techniques become realistic possibilities. If one assumes a slightly inequitable distribution of the water resource because these large farmers through the use of their influence and position might command slightly more water proportionally than they have land, then one concludes that approximately half of the irrigation water is used by farmers of 25 acres or more. If we

wish to maximize the average productivity of irrigation water without regard to the number of individuals involved, then we should point our efforts toward the more flexible technological environment that characterizes the large farmers.

Fortunately, we are not yet faced with a "one or the other" decision and we should be able to serve both groups of clients in the course of coming years. Emerging concepts of development which stress the human factor will not, however, let us ignore the smaller farmer.

Nor in a country where a people's government has just been established, can we ignore the bulk of their rural constituency; the small farmer.

Labor

The Punjabi land owning household includes an average 6.85 members disaggregated as shown below. Tenant farmers have slightly larger households, and those of landless agricultural laborers are smaller.[1]

Household Composition

	Adult Males (over 15)	Sub-Adult Males (10-15)	Adult Females	Unmarried Females (all ages)	Male Children (< 10)	TOTAL
Large Farmers	2.9	0.6	1.8	2.8	1.5	9.6
Small Farmers	2.1	0.5	1.5	1.5	1.0	6.6
Land Owners*	2.17	0.51	1.53	1.61	1.04	6.85
Tenant Farmers	2.7	0.5	1.5	1.9	1.2	7.8
Agricultural Labor	1.8	0.4	1.2	1.0	0.9	5.3

* Weighted average of small and large farmers.

Household size can be converted to the number of full income earners expressed in "adult male labor equivalents" by assigning an arbitrary factor to each type of person that reflects their effectiveness in generating new income for the

1 Jerry B. Eckert, Rural Labor in Punjab, forthcoming mimeographed report The Ford Foundation, Islamabad.

household. Applying such a conversion one obtains the following estimate of the amount of family labor available to the household head.

	Adult Male Labor Equivalents
Large Farmers	3.5
Small Farmers	2.6
Land Owners	2.7
Tenant Farmers	3.2
Landless Laborers	2.2

This amount of labor is under complete and direct control of the household head and to the extent that he is also the farm manager he can allocate this labor resource as he sees fit. Approximately half a man year within each of the above totals is derived from females and subadult males, whose roles are limited by tradition and training to a limited number of productive activities. In addition, education ranks high among village aspirations and often preempts a considerable amount of the time of male dependents.

In addition to labor services from the immediate family, it is common to share labor with one's more distant relatives. This frequently occurs for the operations of plowing, planting, and wheat threshing, operations which are traditionally performed by family rather than hired labor and for which extra men or pairs of bullocks are expeditious. An informal but careful accounting is maintained so that each day of man or bullock services is repaid. While there is some gain from being able to complete some operations on one field in a single day instead of longer, the primary benefits of this system seems to be social. Substantial benefits are possible, however, when different cropping patterns are employed by members of the same family.

In summary, the typical farmer has at his disposal only the labor of his immediate family. After adjusting for schooling and the limitations of females,

he probably has one man year of assistance in addition to his own available each year. He can periodically augment his supply of labor services, either human or bullock, by sharing but in doing so he forfeits some of his own time at a later date.

Some harvest operations are done almost exclusively by temporarily hired labor for which they are compensated in kind. These same men are available for day labor at other times throughout the year but are not often so employed by the small median farmer. The number of permanently hired farm laborers seems to be related to farm size. The straight-line relationship intersects points associating one permanent employee with farms of 20 acres, two with 35 acres and three with 50 acres. Thereafter, the labor : land ratio declines as capital is substituted for labor on larger, mechanizable farms.

Tools and Implements

The tools of production may be usefully disaggregated into those with no moving parts, those with moving parts and those using mechanical power sources. The term "modern", as distinct from "traditional", usually means the latter category which actually forms an important subset of the tools with moving parts.

Farmers with as much as 10-12 acres of land are normally quite traditional with respect to tools as well as production techniques. Their complement of tools will include a traditional plow, yoke, planker, pitch forks, sickles, hoes and shovels. All of these are obtained primarily in the village. Most of them are provided by village artisans, particularly the blacksmith and carpenter under seyp.

The seyp relationship is essentially that of patron-artisan where the artisan provides his services throughout the year in return for payment in kind at each harvest and other minor considerations received periodically. For centuries, seyp has provided security of employment to the artisan classes and a reliable supply of equipment inputs to farmers. The relationship has served as the primary integrator of various village occupational groupings.

The tool position can be summarized as follows. Any tools made entirely of wood are always obtained locally as part of seyp. Tools which have no working parts, are usually obtained in the village either for cash or seyp, with seyp predominating. Since payment rates are fixed by tradition,so also are the types of tools the artisans will provide under seyp. And since tradition and custom prescribe which families of artisans serve which farmers, the element of competition that would induce product innovations is missing. Hence the very elements of stability that contributed to income security in the past make the seyp system insufficiently flexible to meet the equipment needs of modern farming. Farmers are turning increasingly to the towns and market centers where they purchase a wider variety of materials with cash. Finally if a tool has moving parts, is largely metal or requires welding in its manufacture, it is probably only available from urban suppliers.

Evaluating the above generalizations for effective control, farmers have only limited flexibility within which to vary their tool mix if they rely on seyp. They will also have no opportunity to acquire modern or powered implements under this system. When they turn to non-village sources of supply their constraints become distance to market and cash resources. Within these constraints however, they are able to obtain a wider range of tools and to search out suitable combinations of quality and price.

Capital

The author's recent survey estimated the gross value of major crops produced by small farmers at 231 Rs. per acre.[1] Major crops including food and cash crops have been shown to compose 54 percent of the total value of agricultural production.[2] Adjusting the per acre figure above accordingly, the value of all types of agricultural produce per acre should approximate Rs. 420 annually. The median farmer with 5.1 acres produces products with an approximate value of Rs. 2140 per year. Savings ratios have been variously estimated between 10 and 20 percent. Consequently even if a median farmer were able to save 20 percent and convert all of his saved income to cash, he would still only have approximately Rs. 425 annually to reinvest.

The equivalent figure for a 12.5 acre "family farm" would be only Rs. 1050 annually. Converted to dollars at Rs. 11.00: $1.00 and viewed in an American context, this investment potential appears inconsequential. But in the Pakistan context, and again assuming a 20 percent savings ratio which is high for a subsistance farmer, annual savings from a 12.5 acre farm would permit purchase of a bullock drawn four row seed drill, or a moldboard plow, or a centrifugal pump or a small gasoline motor for the pump, or a sugar cane crusher.

Farms of this size thus have an investment capability that is important within their scale of operations. It is apparent, however, that there are definite limits to annual investment which could make the accumulation of a package of technology embodying several pieces of equipment a very extended

1 ibid Jerry Eckert, Chapter VII.
2 Text of the "Pre-Budget Review", a speech by Dr. Mubashir Hasan, Central Minister of Finance, "Pakistan Times", June 17, 1972, pp. 3-4.

process for a 12.5 acre farmer. A median (5.1 acre) farmer would obviously have a much more limited investment potential particularly if one accepts that the savings ratio drops markedly as the household/firm approaches subsistance. It has been the author's observation that many of these farms are only just able to cover depreciation of the most minimal complement of traditional tools.

Institutionalized credit proceedures do not alleviate the paucity of investment capital among small farmers. Commercial banks tend to minimize risk in their rural lending operations with the result that little of their credit resources are made available to small farmers. The Agricultural Development Bank requires minimum acreages as collateral for tubewell or tractor loans. In early 1971 twenty-five acres were necessary to qualify for the 10-12,000 Rupee loan for a 1/2 cusec tubewell loan.

One of the functions of the extended family is in expanding the geographical and occupational dimensions from which capital resources can be brought to bear on a perceived need. This source is occasionally use for investments in tractors, threshers or tubewells or for the construction of improved buildings by farmers whose own sources are inadequate. Members of the immediate family who have emigrated from the village to take employment elsewhere form another source of capital. As long as farm resources are inadequate for either consumption or investment, the out imigrant is expected to contribute to the extent of his ability. Fifteen percent of the households farming less than 25 acres claim to have an outmigrant among their immediate family. Half of these individuals were engaged in civil service, the remaining half equally distributed among skilled and unskilled labor and military service.

Twice as many (30%) of the households farming 25 acres or more reported outmigrants, reflecting the better education of this group which increases their off-farm access to employment. Consequently not only does the large farm have a much larger per capita land base from which to generate investment capital but much more extensive connections exist to extended and immediate family with access to urban capital sources. Investment potential and hence resource and technological flexibility increases faster than does farm size as one begins to examine farms larger than 12.5 acres.

To summarize, Pakistani farmers experience resource constraints with respect to most resource categories. The median farmer is particularly locked into traditional production methods by the inflexibilities of his resource position, by his limited earning and savings capacity and by the overriding necessity of generating at least subsistence volumes of food. Resource flexibility increases more than proportionally as one examines farms of larger sizes.

The package of resources over which the farmer has fairly complete control includes his land, his own and his family's labor, his seed, cropping pattern and purchased, divisible inputs. Recent increases in competition within the agricultural supply industry, have brought several types of fertilizer and pesticide within easy access at attractive prices for most farmers in the irrigated regions. To the extent the farmer is aware of advanced techniques involving only the above resources, he will consider adoption if he feels that the risks to his families subsistance are outweighed by the probable gains.

THE WATER RESOURCE

An early British traveler described what is now part of irrigated Punjab as "uninhabitable desert, glistening with salt".[1] In many districts of Punjab the mean expected monthly rainfall in winter during the wheat season is zero. The difference between the uninhabitable desert observed in the early 19th Century and the densely populated, highly fertile Punjab of today has been brought about by irrigation. Beginning with the first inundation canals in the 1880's, systematic development of the water resources of the Indus and its five tributaries has developed an irrigation network of nearly 30 million acres. Much of it was colonized from uninhabited land as canals brought water to each new area. The mix of economic activity and the societal structures that arose, especially in areas settled from scratch, were critically dependent on irrigation water. Water remains today the most valuable and closely guarded of farmers' resources; in much of Punjab it is the limiting factor in agricultural production.

The table below shows the sources of irrigation water in the provinces of Pakistan in 1967-68. Since then there has been only a small change in the canal irrigated acreage. The implementation of the Indus Waters Treaty in 1970 cut off completely the waters from the Beas and Sutlej rivers and forced Pakistan to rely on Mangla Dam instead. While the command area remained essentially the same, the inter-seasonal distribution as well as total quantities available were undoubtedly affected.

The one change of significance is the steady growth in tubewell numbers. Annual installation rates peaked at 9-10,000 per year in 1968-69. Since then,

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1 Reported in Malcolm Darling, The Punjab Peasant in Prosperity and Debt, Oxford University Press, Oxford, 1929.

installations have fallen off to about half of this number. Two reasons have been hypothetically advanced: first is the series of disturbances and uncertainty that has affected business activity and the investment climate, and second is the saturation of high payoff areas for tubewell investments. At one time national planners invisioned approximately 100,000 tubewells as adequate to exploit available ground water resources. Total numbers have continued to grow from 50,000 in 1967-68 to more than approximately 75,000 in 1970-71. A concurrent expansion of acreage served by tubewells would be expected, however, most of the recent installations have been to supplement land already irrigated by canals.

General Statement of the Problem

"Management" of a resource was defined at the outset as decisions or actions taken to influence quantity, quality, timing or techniques of application. It was recognized that input timing is merely a subset within the overall category of application techniques; it was mentioned explicitly because of the importance of these questions in Pakistan. A variant expression of the above may better serve to focus efforts on solutions to farmer's water problems. Simply stated the Pakistani farmer lacks some degree of control in each of three different dimensions of his water supply.

1. He has limited control over the quantity received either at one irrigation or during the season
2. He has only limited control over the conditions of receipt including quality, time of day and frequency throughout the season
3. Within the constraints imposed by 1 and 2, he is largely unable to use modern irrigated techniques because he is not aware of them or if he is aware, other technical, social and resource constraints interfere.

As shown below each of these three dimensions involves many individual, related and researchable questions. A national strategy to enhance the productivity of water resources will necessarily have to deal with questions at all three levels.

The water resource is discussed below in three parts representing the three different levels and types of controlling mechanisms. The official distribution system includes the rivers, storage reservoirs, link and distribution canals down to the level of the mogha where water enters the local water course. These portions are controlled by the Water and Power Distribution Authority (WAPDA) and the provincial Irrigation Departments. The farmer's control is limited by his ability to influence these agencies. Within the water course the farmers control is a function of the type of social organizations that exist within the village(s) and his ability to interact effectively with those organizations. Finally one has the set of management questions that are solved within the geographic limits of the farmer's own land. Social, economic and technical externalities exist even at this level which circumscribe the manager's actions to a certain extent.

The Official Distribution System

The entire irrigation system is constructed on the assumption of water scarcity. No water course has provision for closing the mogha[1] when water is not needed. The assumption is that there is always unsatisfied demand and that if there is water in the canal it should be diverted in predetermined proportions

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1 A mogha is a brick and mortar turn-out structure containing a narrow vertical slit extending the depth of the canal bank.

through all of the open mogha structures into the recipient water courses. Allowing minimal lags for changes in flow to spread along the canal, the system maintains an equilibrium in which partial flows are reflected equally in all water courses.

The determinants of the quanitity of water delivered into the water courses may be summarized as follows:

1. River flow: This is, in substantial measure, influenced by the operation of the link canals where water is diverted from more westerly rivers to augment the flows of eastern rivers (from the Jhelum to the Chenab and from the Chenab to the Ravi). A secondary variable would be the losses during inter-river transfers, either from seepage, evaporation or irrigation use. Primary authority for these decisions is WAPDA.

2. Diversions at canal heads: These diversions are controlled primarily by the provincial Irrigation Department and include the regulation of diversion barrages on the rivers as well as the further distribution of the water among primary and secondary canals. The Irrigation Department trys to balance river withdrawals among their many canals according to some criteria. It is unknown how flexible these criteria are to reflect change cropping patterns or how responsive these criteria are to the expressions of need by farmers.

3. Losses in the canal system: These are primarily the function of seepage, siltation and inefficient layout of canals. This latter factor is more of a problem within the water courses than with respect to canals since most of the canals were laid out before settlement when optimum design was more nearly possible. Since the canals were designed to be self scouring, some specialists have questioned whether sedimentation is a factor. The question must be left open here,

however, since in several locations villages have complained en masse to the author about their inability to get the Irrigation Department to clean out their canal and restore normal flow.

4. Size of moghas: As pointed out, there are permanent structures with fixed orifices. It is believed that the size of the outlet is an exclusive function of the acreage commanded by the water course and does not reflect the cropping pattern not the availability of supplemental water from other sources.

If any procedure exists for obtaining an official evaluation of mogha size in light of dynamic changes the needs of farmers, it is cumbersome and almost never used. And unauthorized alterations of the mogha are serious offenses, heavily punished.

5. Canal flow rotations: During periods of water shortage, which occur during most of the winter season, the Irrigation Department opens their canals at near capacity in rotation rather than operate them all constantly with a considerably reduced volume. Substantial water savings probably result and the efficiency of the distribution system is increased through this technique. But the farmer is faced with prospects of periodic, usually unannounced, canal closures. He has no means of timing the incidence of these closures to occur when his crop's water requirements are minimal. It seems probable that the conflict of interest between maximizing quantities delivered by the irrigation system and maximizing the productivity of water applied has never been quantified because the crop response functions have been unknown.

The determinants of the quality of water reaching the mogha include:

1. The source river
2. The proportion of the water that comes out of a storage reservoir

3. The number of tubewells pumping into a canal and the quality of water they provide.

No further discussion is necessary on the subject of quality variation within the irrigation network. First, this water is considered good to excellent for most purposes and second, there is almost no way an individual farmer can influence the variables determining quality as it arrives at the mogha.

It is evident from the above that farmers, either individually or as groups, have little influence over the decisions that allocate water among the rivers, or among the canals in the distribution network. Furthermore, the size and design of mogha construction fixes the relative discharges into each water course and once fixed this proportionality is basically unalterable as far as the farmer is concerned. Despite peculiarities of cropping pattern, soil type or availability of subsurface water, the amount of water discharged at each mogha and the schedule on which it is discharged are beyond the control of farmers.

The British, taking in view the social, administrative and agricultural milieu at the time, laid out a self regulating system to eliminate the necessity of referring these questions to farmers at regular intervals. The necessary allocative decisions were few and centralized in the responsibilities of senior government administrators several echelons removed from direct interaction with farmers.

In order to fully explore all means of enhancing the farmer's control over his resources two questions must be raised. First, do review and evaluation procedures exist and are they used with sufficient frequency so that the proportional distributions between different canals and different moghas vary in response to the needs of a dynamic agriculture? Second, is a participatory allocation system compatible with Pakistani conditions today through which

farmers could more nearly approach the ideal of water on demand? The answers, particularly to the second question, must be the preogative of Pakistanis. However, it is within the role of the CSU team to raise these issues and to assist in objective analysis of them if asked to do so.

THE WATER COURSES

The term water course refers to the distribution system between the mogha and the farmers fields or his personal irrigation ditches. Scarce water is allocated on a rotation system known as warabundi.[1] The system has two manifestations, the pucca warabundi or sanctioned rotation schedule and the katcha warabundi or informal rotation. With pucca warabundi the Irrigation Department participates in defining the rotation in terms of the duration and interval of turns as well as the days of the month on which each farmer's turn falls. This schedule is then registered with the Irrigation Department and becomes to all intents law. In the case of this formally sanctioned system the farmer's turn elapses on schedule whether there is water in the water course or not. In the informal variation, the rotation stops when the flow stops at the mogha for any reason and begins with the next farmer in turn whenever flow is restored.

Both rotations are enforced by a trusted villager, quite often the religious leader, who receives some small compensation for this service. He keeps the standard clock and signals the beginning and end of turns. There is some loaning of turns but very little sales.

The determinants of the proportion of the mogha off take that reaches the farmer are as follows:

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1 Warabundi is a composite of two words, wara meaning turn and bundi meaning a tying or closing.

1. Losses in the water course: This should be a function of distance the water must travel, soil characteristics, the rapidity of flow, the cross section, layout and maintenance of the ditches, and evaporation. Farmers have more control over the physical dimensions and maintenance of ditches than any other factors from this group. Individual or collective actions are feasible means of cleaning and reforming these channels. The Irrigation Department has the right to enforce proper maintenance although it is seldom exercised.

2. Distance from previous farmer in rotation: This becomes an important factor when there is an excessive number of feet of water course that must be wet and filled once the next man's turn begins and before the water reaches his field.

3. Farm fractionation: The necessity of irrigating noncontiguous plots seriously impedes the efficiency with which the water from an irrigation "turn" can be utilized. From the water course view point, substantial losses are incurred due to the additional footage of ditch that must be filled, from which infiltration occurs and in which water is left standing.

4. Rotation turn length: These are normally established in proportion to the acreage farmed. No flexibility currently exists that would allow the rotation to reflect varying water requirements of different crops or differing leaching requirements or infiltration rates.

No quality variation of importance is introduced between the *mogha* and the *naka*[1] unless tubewell supplementation is practiced and then only if there are

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1 The point at which water is turned from the ditch into the field.

qualitative differences between sources. Where subsurface water is more saline, the increased salinity that occurs when the two sources are mixed is a cost which must be balanced against the increased head, the reduction of the seepage loss fraction and the larger water quantities available for irrigation.

The two levels of control are possible with respect to this source of quality variation. If the tubewell is privately owned and if water testing and evaluation services are available, the farm manager can effect complete control over his water quality. Where information on water quality is missing, control of the tubewell does not lead to control of water quality. A second level of control occurs when the tubewell is publicly installed. Farmers may interact as a group and with the Irrigation Department to determine the location and size of the well and any additional water channels. Subsequently, however, the operation of the well is the Irrigation Department's or WAPDA's responsibility and the proportions in which canal and tubewell water are combined are beyond the farmer's control.

Water Management on Farm

(This is the section on which I need most help, first because it is the area in which most of our work should concentrate and second it is a technical area in which I have little training.)

The two sections immediately above have discussed the canal and water course systems, their sources of variation in quality and quantity of water and points of leverage at which these variables might be influenced. The ultimate point for measuring whatever variations might exist or be created in these two systems is the water received by the farmer during his irrigation turn.

The following section discusses the dimensions of water use on the farmer's own land in which variations can be important to obtaining maximum efficiency in the use of this resource.

Farmers are concerned with combining various types of inputs with plants in order to optimally attain one or more goals. Conceptually this means they can approach their desired combinations by varying the inputs to fit the needs of the plant or varying the plant to fit input rigidities. The latter is often overlooked yet is potentially important in Pakistan.

For example, he can either provide adequate moisture in the soil's upper three inches to permit emergence of the short coleoptile of dwarf wheat or he can plant a native wheat variety with a longer coleptile at depths of six to seven inches. He can either provide an irrigation in the third week after planting dwarf wheat or he can adjust his planting date to a point three weeks in advance of when his irrigation turn is scheduled.

Several of the specific dimensions of water control on farms are concerned with the speed with which water is handled, conducted from point to point, spread over a field, etc. This emphasis on time is derived from two facts; first the irrigation turn under warabundi is temporally limited and second the longer water is in transit, the greater is the proportion lost to seepage and surface evaporation.

Among specific items farmers can control are the following:

1. Rate of flow from point to point in the conduit ditch which is a function of the ditch's cross section, slope and layout as well as the absence of impedimentia, and the amount of water being carried. In general this rate should be maximized.

2. Rate at which water can be spread over a field which is a function of slope, infiltration rate, pre-irrigation moisture content, plant cover, presence of water conducting surface forms. The rate should not necessarily be maximized but should be adjusted in combination with infiltration rate and moisture holding capacity so that water is dispersed throughout the root zone and no more.

3. Infiltration rate which is a function of soil type, soil structure soil chemistry, height of water table and crop cover. Roughly speaking, with most crops it is useful to develop a rapid infiltration rate, however, with rice as little infiltration as possible is desired. The wheat-rice-wheat rotation found in parts of Punjab requires that the soil be converted from an anaerobic soil with almost no infiltration that is achieved by destroying soil structure through puddling to an aerobic soil with sufficient structure to permit relatively rapid infiltration. The speed of this conversion determines the amount of acreage that can be completed before it is too late to plant.

Farmers are not presently able to vary the quantity and timing of water applications to coincide with water requirements of the various growth phases of the plants. In part this derives from the rigidities of supply already mentioned and in part from the farmer's lack of understanding of his crops' water needs. Once flexibility and knowledge are achieved the farmer has a choice of strategies; either to maximize production with a given amount of water or, in the case of a subsistance orientation, minimize the amount of water used to produce a predetermined amount of the crop.

Most farmers have no reservoir or mechanism that would store water from one season to the next except insofar as water may be carried from one time to another in the root zone of the soil. There are, however, several means by which

farmers can enhance this carryover, most of them related to infiltration rate and water holding capacity of the soil as well as surface structures to prevent runoff in some areas.

Previous research and field observations has shown that there are obvious interactions between water and nutrient applications yet the functional relationships remain unspecified. If this information were available, farmer's could better adjust their nutrient and water applications to achieve maximum complimentarity between these two input classifications. Sources of variation within the farmer's control are largely in the area of timing of irrigation and technique of fertilization.

Finally, and most important, is the range of variation made possible by tubewells. The contribution of tubewells is best considered under two classifications increased water quantity and increased resource flexibility. Tubewells permit farmers to very closely approximate a situation of water-on-demand. Farmers must evaluate the benefits from each dimension and balance them against the cost of poorer water quality if such is the case. He must also assess the alternative costs of tapping ground water resources, a question with many more possibilities than are usually considered. Finally, the externalities of tubewell installation are incompletely understood and sometimes subtle. Since little attention has been given to this aspect of water use and control, the framework of law, rules and precedents has not been developed.