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Engineering Research Center, Colorado State University

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9. ABSTRACT

A report of the annual accomplishments of this continuing project, using Pakistan as the study area. They are outlined as follows: 1) The development of knowledge and data on how best to conserve and use rainwater and the most efficient means of supplementing needed soil moisture. 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. 3) Development of surface and subsurface water removal systems to minimize hazards resulting from surface flooding, high water tables, and salt in the ground water. 4) Identification of important factors to be considered in land 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) Development and adaptation of water application methods suitable to and efficient for soils of varying physical properties (water-holding capacities, intake rates, etc.) with major crops. 6) Integration of these water use factors into productive cropping systems consistent with farm size and available farming practices. 7) Where water quality, soil salinity, and exchangeable Na are problems, studies included soil amendments, soil and water management procedures, and use of salt-tolerant crops. 8) Identification of institutional and policy factors (legal, social, economic, religious, manpower, credit, education, etc.) which influence efficient distribution, management, and utilization of water on the farm level.

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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 available resources, 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 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.

At the recent AID sponsored International Conference concerned with "On-Farm Water Management," water management specialists from developing countries, from the World Bank, FAO and AID concluded that the limiting factor in having large irrigation projects achieve their expected economic return was poor management of the water from when it leaves the canal till it enters the root zone. It was also emphasized that water management research was not complete until the "improved water management practices" are being used by the small farmer and are increasing his production and his profit.

B. Objectives of the Project

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 with appropriate consideration given to increasing employment in the rural sector and utilizing local resources.

1/ Council of U.S. Universities on Soil and Water development in Arid and Sub-Humid areas.

Specific Objectives are:

1. 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 amounts of irrigation water.

2. 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. Development of surface and subsurface water removal systems to minimize the hazards resulting from surface flooding, high water tables and salt in the groundwater.

4. Identification of important factors to be considered in land 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. 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. 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, means will be developed for increasing crop production by using amendments and management practices which will improve water and soil properties and by using 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, surveys in Pakistan and consultation with experienced water management personnel from USAID, FAO, the World Bank and several developing countries indicate that accomplishment of the original objectives will benefit the developing countries and contribute substantially to the fund of transferable water management technology. Survey of the resource positions of farmers in Pakistan, Vietnam and several other developing countries show that the average farmer is

unable to make a large capital investment 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 farmers. This will not necessitate change in our overall objectives, but will require our continuing attention to ensure that the technology which we help produce can be used to increase productive work opportunities, as well as produce more food.

Another new factor which bears consideration in development of technology packages for developing countries is the rapidly increasing price of hydrocarbon energy. In countries such as Pakistan and Vietnam, which have little hydrocarbon energy, the increasing cost of gasoline powered mechanization and nitrogen fertilizer production appear to be increasing the probability that animal power and legume production must be a permanent part of the crop production picture. Consequently our water management technology packages should have variants which are adapted to these low energy input situations.

A subject deserving major attention is assembly and development of information on seasonal water use and yields of all species and varieties of crops as a function of planting time (or season). This information would be used by local specialists for advising farmers on how to schedule their crops to make best use of fixed irrigation supplies. This subject can be treated to some extent under Objective #6, but probably deserves an objective of its own.

D. Accomplishments During the Reporting Year (Nov. 1, 1972 - Nov. 1, 1973)

These accomplishments are organized according to the specific objectives of the proposal, as stated in the last work plan. However, the last work plan covers the period from March 1, 1973 to March 1, 1974, and consequently this report covers the last five months of the previous work plan and the first seven months of the last work plan. Results from kharif crop studies planned and carried out during the past summer and fall are not yet available.

The following findings fall in two general categories: problem identification and problem solution. At first glance problem identification might appear to be the responsibility of the host country. However as our studies in these host countries progress we find that many "accepted facts" concerning water management in these developing countries are actually popular misconceptions originated by small amounts of questionable data and reinforced by repeated references. Consequently we've found it necessary to study delivery, application and crop use facets of water to determine where deficiencies lie and where improvement efforts will be most productive.

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

a. Evapotranspiration and Crop Scheduling

Seasonal potential evapotranspiration was estimated and analyzed (e.g. Clyma, Appendix G) at several locations in Pakistan. It was found that while the growing season is essentially 12 months long, the potential evapotranspiration in December and January at Mona is 0.08 inches per day, while in May and June it is four times as high. Comparison with cropping patterns and schedules indicates that farmers by design or by chance tend to plant Kharif crops in late April or early May so the small plant size during May and June limits the amount of water used. However, this study points out a sizeable potential savings in water that could be achieved by planning crops so the surface is largely bare during the high potential evapotranspiration months. Short season crops to avoid these months, row planting to concentrate foliage (rather than broadcasting), means for reducing evaporation from the soil while there is little vegetative cover and methods of irrigating small plants without wetting the whole soil surface should all result in significant savings of water during these hot dry months.

Clyma's data and calculations also indicate that despite more rainfall during the Kharif (summer) season net irrigation water requirements for the Kharif crop were almost double those for a Rabi (winter) crop. Clyma's data also points out that even the tubewell augmented watercourses, serving about 150 acres per cusec, can deliver water to plants at only half the rate of maximum evapotranspiration if all fields are planted. This illustrates the need in Pakistan for avoiding cropping during heavy evapotranspiration periods, or having crops at the stages of growth where they are so small that they evaporate little water or where water stress does not markedly reduce final yield.

b. Wheat Yield and Irrigation Timing

A Mexipak variety of wheat irrigated at the inception of tillering made much better use of the water (bushels/acre inch of water) than wheat irrigated at other times during the irrigation season. This response, while previously observed on improved wheat varieties in other countries, serves to affirm the need for planting schedules (and possibly additional varieties) which would allow a farmer to have wheat fields reach tillering on his successive irrigation turns. Such scheduling to allow use of limited winter water supplies at the sensitive tillering stage would increase the portion of their acreage which many farmers can plant without appreciably decreasing yield/acre. These conclusions are based on the data of one year. The wheat yield vs. irrigation timing study is now in its second year.

Objective #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.

a. Watercourse Capacities and Their Relation to Actual and Potential Water Distribution

A study of flow (Clyma and Ali, Appendix B) in several watercourses in the tubewell augmented (SCARP) area showed that the watercourses were almost never large enough to carry the total flow of the tubewell and canal supply. Consequently farmers on the lower end of the watercourse do not receive their share. Observations by our field party and their cooperators have shown that sometimes the lower end farmer allows farmers on the upper to use part of the water during his turn (which is actually illegal) in return for either cash, commodities or help by the upper end farmers on plugging holes in the ditch bank. In other cases the farmer makes a valiant lone attempt to repair breaks in the banks, but still loses a significant part of his water via spills. Frequently farmers on the upper reaches of the canal simply steal some of the water because chances of being detected are small (thefts were found to be more frequent on longer canals) or because farmers on the lower reaches are so accustomed to taking what is left that they will not assert their rights.

This informal trading and selling of water offers more flexibility with regard to timing and amounts of water applied than the Pucca Warabundi which is a fixed schedule distribution of water in the watercourse. The fact that extensive trading and selling of water occurs, when it is illegal, suggests that these farmers recognize at least some of the advantages of flexibility of water supply and are probably ready to consider water user organizations which could legalize trading and otherwise improve matching of water supplies to crop needs and facilitate more sophisticated methods of irrigation. Such organizations and rules and structures which allowed splitting the water supply would allow the use of smaller watercourses than are needed under the Pucca Warabundi systems. Four improved watercourses which will demonstrate the advantages of adequate capacity have been designed and construction bids have been called for. Since the official distribution system on these watercourses is the Pucca Warabundi it was necessary to design these watercourses for the full capacity right to their lower ends. Because these enlarged lower sections are obviously not the most economical physical design, they are expected to be a factor in convincing farmers and relevant irrigation officials that changes in the Pucca Warabundi water distribution systems are needed.

Watercourse Losses and Potential for Water Savings

Flow rate measurements (Corey and Clyma, Appendix A) in watercourses in the Mona and Lyallpur area have shown that water losses from "seepage" range from 5 to 65% per mile of watercourse and average about 35%. While some of this loss could be due to small undetected leakages, this overall loss is much larger than reported in previous studies or estimates in the Indus basin irrigation system and points out the substantial savings in water that could be achieved from stopping or reducing seepage from these canals. Local brick and mortar and several other types of linings will be installed and tested on the improved watercourses discussed above.

Preliminary studies at CSU have shown that puddling of even loamy sand soil can reduce its infiltration rate to from 5 to less than 0.5 cm/hour which would generally reduce seepage losses to less than 10% per mile of watercourse. Puddling, combined when necessary with addition of fine sediments in the irrigation water (see next paragraph), appears to have potential for markedly reducing seepage losses with negligible materials cost.

c. Sediment and Its Management in Watercourses

A computer-simulated canal network, whose sediment carrying characteristics were based on the findings of hydraulic laboratory studies, was developed (Mahmood, Water Management Technical Report No. 26) and identified the following facts. Branching of a canal or watercourse system reduces its sediment carrying capacity and will frequently result in high rates of sediment buildup in the channels immediately downstream from the branch point. This factor has the potential for being particularly severe when a small branch, such as a watercourse of a few cusecs, is taken from a canal carrying a heavy sediment load. Turnouts (or moghas) from the canal to the watercourse can be designed (primarily on the basis of their level in the canal) to take from 30 to 300% as much sediment per unit of water as is being carried by the canal. While this offers a major tool for sediment routing, the sediment in the canals must go somewhere and the general destinations are in watercourses, from which it must be cleaned from one to several times per year, or on the land where it can necessitate recurrent leveling every 5 to 20 years. Turnouts near the surface of the water deliver a much finer sediment than turnouts placed near the base of the canal. Extraction of the proper sized sediment from the canal to be deposited in an initially oversized watercourse channel and puddled with the local soil to obtain desired decreases in seepage rates is apparently possible and should be evaluated under field conditions.

Mahmood (WMTR #26) outlines computations for the design of the various aspects of a watercourse system pertaining to sediment. These include design of stable alluvial channels; design of turnouts to bring more or less of the sediment bed load (coarse sediment) into the watercourse depending on whether the farmers wish to have extra coarse sediment on their fields to lighten its texture and on whether the slope and flow rate of the watercourse channel will carry this amount of sediment; and design of channels to deposit various portions of the sediment on the fields or in the watercourse.

d. Overirrigation and Means for its Reduction

Flow measurements in watercourses coupled with measurement of field sizes and clocking of application times have been made on several watercourses in the Mona-Lyallpur area. The measured irrigation application was commonly in the 6 to 9 inch range and generally exceeded the amount of water needed to fill the root zone of the soil to field capacity by factors of from 2 to 5. This degree of overirrigation, and the inseparable nitrate leaching from these soils, illustrates the need for permanent structures on watercourses where flow rate can be measured by trained irrigation advisers who can advise farmers on how long they should apply their stream of water to their respective fields.

Objective #3. Development of surface and subsurface water removal systems to minimize hazards resulting from surface flooding, high water tables and salt in the groundwater.

a. Skimming Well Performance and Anisotropic Permeability of the Aquifer

The horizontal permeability of the Indus Basin aquifer has been reported to be greater than the vertical permeability by factors ranging from 2 to 25 depending on location. This anisotropy is caused by layers of fine sediment interspersed with the dominant sand. Intuitively it is apparent that this anisotropy should reduce the coning phenomena which brings lower saline waters up to contaminate tubewells during pumping. A numerical solution for the anisotropic case was developed and tested for cases where the vertical permeability was down to 1/25 of the horizontal permeability. A report titled "Salt water coning in anisotropic aquifers" was prepared by Chandler and McWhorter and is available on request from the Project Office. A technical journal article will be prepared from this report. It was found that the maximum well discharge without salt water entrainment in an anisotropic media occurs with wells that penetrate 30 to 40% of the undisturbed fresh water zone when ratios of vertical to horizontal permeabilities ranged from 1/5 to 1/25, which are reported commonly in Pakistan. This is significantly greater allowable penetration than the 15 to 20% which is optimum for wells in isotropic media.

Maximum safe discharge from properly designed wells in the anisotropic aquifer (1/25) is only about 18% greater than for the isotropic case. This increase in safe discharge is less than was anticipated, which means that influence of anisotropy on practical well operations is to decrease the probability that small variations (increases) in the pumping rates, designed as optimums for isotropic media, will entrain salt water.

b. Field Testing of Skimming Well Theory and Performance

During the current reporting period Dr. McWhorter spent ten weeks in Pakistan making the necessary preparations for construction and field testing of skimming facilities. Existing salinity-depth data was surveyed and additional data was collected to identify suitable test sites. Discussions regarding the need for and utility of skimming wells were held with several agencies, and WAPDA was selected as the cooperating agency.

A proposal for field testing skimming wells was prepared and submitted to USAID/PAK through CARE/PAK.

WAPDA officials asked Dr. McWhorter to do a study on salt water distribution in an area which has been particularly troublesome to groundwater users. Item H of the appendix is a brief report of this study. It describes and explains the distribution of salt with depth in the study area and makes recommendations relative to methods by which the fresh water can be recovered with minimum contamination.

Design details and construction specifications for the field tests were drawn up and are outlined in a 30-page document titled, "Field Experiments with Skimming Wells: Plans and Specifications," which is available from the Project Office on request.

c. Skimming Well Theory and Mathematical Models for Predicting Salt Concentrations of Pumped Water

Skimming well theory developed in the past has generally treated the saline and nonsaline waters as immiscible fluids of different densities with a sharp boundary. While the resulting theory has provided good estimates of coning height and other parameters helpful in designing and operating skimming wells, it cannot be used to make quantitative predictions of concentrations of water resulting from a given design and pumping rate in aquifers where salinity becomes progressively greater as depth increases. To provide this capability a new mathematical model has been developed in which the hydraulic flow equation and hydrodynamic dispersion equation are coupled. The mathematical model has been formulated and the computer coding is 75% complete. Production computer runs are anticipated early in 1974.

d. Conjunctive Use of Surface and Ground Water of Different Salinities in an Indus Basin Irrigation System

A mathematical model was developed to represent water and salt transfer in the Lower Jhelum canal system, the commanded irrigated area, the aquifer lying below that area and the pumps and wells required to bring the groundwater back to the surface. The model recognizes factors such as: the seasonal availability of river water; that this canal system can withdraw only its share of the additional available water from the river, based on its proportion of the mean historical withdrawal; that water pumped from zones with moderately saline aquifers must be mixed with canal water before use and that specially designed skimming wells must be used to retrieve surface fresh water accumulating on top of the saline aquifers; that saline water must be pumped from the saline aquifers and disposed of to maintain a salt balance; that the river supply and crop demand are seasonal and mismatched; that pumping costs vary as a function of water table depth and that the water table must be kept several feet below the soil surface. The variables considered as manipulatable were canal sizes, number and type of wells and pumps. The objective was to minimize the total cost of the system, including capital, operational and maintenance costs, for meeting the irrigation demand of 150% cropping intensity (i.e. an average of 1.5 crops/year which was considered a practical optimum in a study of crop water demands conducted by Tipton and Kalmbach). Recharge to the aquifer comes from seepage from canals and watercourses and deep percolation of temporary excesses of irrigation water and rainfall. Additional recharge of the aquifer in the nonsaline area was considered available by increasing paddy rice acreage without puddling the soil and overirrigating fallow lands as needed during the season of high river flow. The conclusions drawn from this model were:

1. There is sufficient water in the river system, even in low flow seasons to increase the cropping intensity to 150% or more in all the existing canal commanded areas and conjunctive use of surface and groundwater can provide an "on demand system" furnishing water to crops as needed.

2. Utilization of available river water to meet these crop demands requires enlargement of existing canal capacities in all three (nonsaline, intermediate and saline) of the groundwater quality areas.

3. During the season of low canal supplies the most economic overall means of meeting crop water requirements was to divert available canal supplies to the areas over saline aquifers and to utilize pumped groundwater to meet crop requirements in the areas over nonsaline aquifers, rather than transfer pumped water from the saline to the nonsaline areas. However, some export of water will be necessary to maintain a long term salt balance.

4. Due to the sensitivity of pumping costs and crop response to extreme fluctuations of the groundwater level when the aquifer is being used as the major storage reservoir, the aquifer storage coefficient (inches of water available for pumping/inch change in water table height) becomes a significant factor in designing the optimum system.

Maintenance of a long term salt balance in these areas requires export of saline water. It is probable that the most efficient way of removing this salt is with deep cased wells, from which water may be pumped to evaporation basins constructed on waste lands. Mineral composition of the saline waters should be studied in terms of the possibility of these waters being a source of potash, nitrate and other valuable minerals via systems of successive evaporation basins in which the various salts crystallize out of solution as is done at the Dead Sea Works in Israel.

Details of this study are available in a Ph.D. dissertation by Mr. Fang-Hong Wu which is presently in draft form and is available on request from the Project Office. This study was initiated as a cooperative effort between the Water Management Research Project (for On-Farm Water Management) and the 211(d) Grant (for Developing Expertise in Water Delivery and Removal Systems). Mr. Wu's salary was paid by the Water Management Research project. Most of his advisers received salary and developed their relevant expertise under the 211(d) Grant.

However, certain aspects of this study were sensible and essential prerequisites for on-farm conjunctive use studies and recommendations. For instance, we could not recommend heavier drafts on groundwater to supply water on demand to expanded cropping acreage on farms unless we knew that adequate water supplies were available and could be transported for recharge of the whole area at reasonable cost.

Objective #4. Identification of important factors to be considered in land 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.

a. Training Film

A film designed to help train developing country engineers in the basic operations of surveying, computing optimum cuts and fills, grading and staking for land leveling was finished during this reporting period. The text of this film, narrated in English, has been completed. The Urdu translation is in progress and will be completed early in 1974. Copies of this film will be made available through AID, TA/AGR.

Infiltration Rates as Affected by Elevation in Basin Irrigated Plots

Inspection of the Agricultural Research Institute (ARI) plots irrigated by water of various salinities at Lyallpur indicated slight accumulations of salt on high areas which had developed following land leveling. Dr. deMooy and his cooperators measured infiltration rates on these high areas (1 to 3" above the low areas) as compared to adjacent lower areas with ring infiltrometers and found that infiltration rates of the high areas were approximately half those of adjacent lower areas. These findings are similar to those of Amemiya and Robinson on similar soils at Grand Junction, Colo., in 1956. Inadequate water to leach salts down and out of high spots results in an accumulation of salts (primarily Na salts) on the high area and when irrigation water is applied to these fields the higher Na percentages on the higher areas disperse the clay, reducing infiltration still further. Less time in contact with the free water, and lower infiltration rates reduce intake of water on high areas to a small fraction of that occurring on adjacent lower areas. These detailed infiltration measurements point out that precision leveling is particularly important in achieving uniform applications of water on fields when those waters contain 1000 or more ppm of dominantly Na salts.

c. Border Irrigation and "High Spots"

Uniformity of water application by border irrigation was found to be poor when elevation differences of 0.1 ft. existed in the cross slope, even though water eventually covered the high spots. It was concluded that precision grading is just as, or even more, essential on border irrigation systems than on flat basin systems. Details of this study are contained in the report "Evaluation of border irrigation with a 'High Spot,'" by Clyma and Hussain, which is available from the Project Office on request.

d. Elevation Variation in Irrigated Pakistani Fields and its Role in Water Distribution and Nitrate Leaching

A survey of farmers' fields before precision leveling indicated that approximately one fourth of the area was 2" below the average elevation of the field and one fourth of the area was 2" above the average level. Under these conditions minimum irrigation necessary to cover the highest spot in the basin is generally about 3". The studies discussed in b and c indicate that a 3" average irrigation applied to these fields will apply more than 5" of water to the lowest areas in the field and less than 1" of water to the highest areas. When the crop evapotranspiration needs are 3"/irrigation an excess of more than 2" per irrigation is being applied per irrigation to the low spots. Lysimeter data (see Appendix Item E for details) shows that when 8 to 12 inches of overirrigation is

applied by basin flooding, a large portion of the applied N has been leached below the root zone. Since farmers normally apply 6 or more irrigations to Kharif crops, it is apparent that lack of precision land leveling is exposing 25% of the applied N to loss by leaching.

Objective #5. Development and adaptation of methods of water application which are suitable and efficient for soils of varying physical properties (water-holding capacities, intake rates, etc.) with major crops

a. Evaluation of Border Irrigation Applications of Water

Uniformity of application was studied (Clyma, "Irrigation Practices with a Modern Border System," available on request) on high and low permeability soils on border irrigation plots at Mona and Lyallpur. The applications were reasonably uniform on the soil with a high infiltration rate, except for a few high spots where leveling was not complete. However the amount of water added to the soil was double the amount needed.

Most of the water, applied in the borders with low permeability, ponded at the lower ends of the fields resulting in much more water application at the lower ends than at the upper ends. On the basis of these studies it was recommended that when borders are used to irrigate soils with the low infiltration rates common in the Lyallpur-Mona area, these borders should be level.

b. Application Efficiencies

Efficiency was calculated as the ratio of the water needed to fill the root zone (to field capacity) to the amount of water applied to the field in over 25 trials on the small fields in SCARP areas. These efficiencies varied from 10 to 50% with the majority of them being less than 25%. These low efficiencies are generally due to overirrigation associated with the fact that the farmer fills his bunded field till the highest spot is covered before turning the water to his next field. Again the solution appears to be land leveling, expanded crop acreage and crop scheduling to make best use of the fixed water supply.

c. Irrigation Method, Pore Size and Modulus of Rupture

The method by which a soil is irrigated following cultivation was found (Kemper, Olsen and Hodgdon, Appendix Item C) to be the major determinant of the amount of large size pores which persist in a soil. This is particularly true of weakly structures soils, as occur in the Indus Basin and Mekong Delta. Slow capillary wetting as occurs in ridges adjacent to furrows increases the proportion of the large aggregates and pores which persist as the soils become wet. Slow wetting reduces the gradient in swelling induced displacements which are a primary factor

causing disintegration of aggregates. Flood irrigation of freshly cultivated soil causes rapid wetting, disintegration of aggregates and drastically reduces the amount of large size pores, particularly in the top inch or two of weakly structured soils.

Strength of a poorly structured soil, dried following wetting, remained at levels which allowed seedling emergence if the freshly cultivated soil was wet by capillarity. Saturation of the soil, even when this occurred after capillary wetting, markedly increased the subsequent dry modulus of rupture. This increase is due to greater slump and disintegration of the aggregates as air-water interfaces and surface tension holding the aggregates intact are eliminated as the pores fill with water. The resulting structureless mass is compressed by surface tension forces during drying into a dense strong crust.

Texture, mineral content and organic matter content of a soil all influence its aggregate stability, persistence of large size pores and crusting strength. However, data from this study show that adequate large size pores and sufficiently low crusting strength for 100% seedling emergence can be maintained in a weakly structured soil if the soil in the ridge surrounding the seed is wet slowly by capillarity from furrows. Flood irrigation of the same soil reduced seedling emergence by 50%.

d. Irrigation Method, Fertilizer Placement and Nitrate Leaching

Irrigation in furrows and placement of fertilizer in bands in ridges was evaluated as a means for allowing overirrigation to bypass nitrate and reduce leaching losses (Kemper, Olsen and Hodgdon, Appendix Item E). In a loamy sand, placement of band 0 to 5 cm higher than the surface of water in the furrow allowed over 120 cm of overirrigation before the salt began to leave the root zone. In the clay loam a similar delay of nitrate removal was not achieved until the band was 10 cm higher than the water surface. This difference appeared to be associated with a perched water table that developed in the "cultivated" layer of the clay loam soil due to higher hydraulic conductivity in cultivated than in the lower soil. Overirrigation of 30 cm, applied as basin flooding, leached a major part of broadcast "fertilizer" out of the root zone.

Downward movement of relatively concentrated salt solution near the band, due to its greater density, was a factor that allowed fertilizer bands at lower levels to enter the mainstream of the leaching water.

Leaching of nitrate from a soil can be delayed by placing it in ridges and irrigating in furrows rather than broadcasting fertilizer followed by flood irrigation. Some of this nitrate may become trapped in the dry layer at the top of the ridge, but will be made available again if light showers occur. The practical significance of nitrate staying in the root zone longer as a function of such water and fertilizer management should be tested in the field in terms of crop yields and N recovery.

Objective #6. Integration of these water use factors into productive cropping systems consistent with farm size and available farming practices.

a. Background

Field party members have worked with our cooperators to develop technological packages for increasing crop production which include improved water management, adequate fertilization, etc. Some of these technological packages have produced dramatic increases in crop production on Pakistan research stations. Practical problems, such as lack of information, lack of equipment, suspicion of benefits claimed and general mismatching of the technology requirements with farmers resources, have prevented farmers from adopting these technology packages.

The Mona and Shadab projects were conceived as means for assuring that the practical problems of implementation were evaluated and solved.

b. Mona Project

This project was signed on Feb. 5, 1973, and involves a two million rupee USAID grant to the Mona Reclamation Center. The project involves continuation and expansion of research on water management and related crop production technology and a program of lining and managing watercourses so that the benefits of "water on demand" and other improved water management technology can be evaluated on a practical field scale basis. During the report year the areas served by three watercourses have been studied to evaluate present practices and production. These watercourses are being improved so that by June, 1974, an adequate system for fairly distributing water to all farmers on a watercourse will be operative. Brick lined systems for two major watercourse sections have been designed, specifications written and bids called for.

Several studies involving water management and practices essential to optimizing crop yields have been initiated on these test watercourses.

Shadab Project

This project was signed by the Government of Pakistan on April 2, 1973, and involves a one million rupee grant to the Punjab Department of Agriculture. The project involves: a study of procedures required for watercourse improvement and land leveling, studies to improve irrigation methods, field scale studies to improve water utilization and crop production and economic analyses of improved water management. A watercourse system including 53 farmers on 262 acres was selected. Fifteen acres were leveled before wheat planting time and several farmers await harvest of fodder in December to begin

leveling operations on their farms. A major portion of the 53 farms will be leveled during the next Kharif (summer) season since a large portion of the area is fallowed at that time.

This project is especially important as a companion program to the USAID sponsored SCS precision land leveling training program being initiated with the Governments of the Punjab and Sind. Farmer cooperation and enthusiasm for this project has been excellent. The Project Agreement provides for subsidization of the land leveling program, but farmers are already willing to pay the tractor costs if the project will furnish the required engineering. An experiment involving three water management and crop production technology packages for growing wheat was initiated about November 1, by Dr. deMooy on one of the leveled farms. Within two days of starting the experiment over 200 farmers had visited the site.

d. Factors Which May Limit Yield as Water Management Improves

Analyses of 58 soil samples from the Punjab (Franklin and Schmehl, Water Management Technical Report #28) showed that phosphorus is generally low and will become a limiting factor in crop production when water and nitrogen are supplied in adequate amounts. While zinc was adequate in most of the soils tested, about 1/3 of the samples had zinc levels sufficiently low that sensitive crops, such as maize, sorghum, potatoes, beans and paddy rice, may show increased yields from Zn fertilization.

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

a. Effects of Water Quality on Plant Growth and Infiltration Rates

Berseem was grown on the Agricultural Research Institute plots at Lyallpur during the Rabi season and cotton was grown during the Kharif season with salinity of irrigation water at 300, 1200, 2100 and 3000 ppm. The Berseem yields were reported in last year's annual report and the cotton yields have not yet been analyzed. The infiltration rates on these plots were measured by deMooy, Bhatti and Cheema (Appendix Item I). Irrigation with the water from 1200 to 3000 ppm, had reduced infiltration rates from over 0.5 inches/hour down to around 0.1 inches/hour. This means that the plots irrigated with the saline waters are innundated for about a day during a 3 inch irrigation and sometimes for 2 or more days on plots where larger amounts of water for leaching are applied.

Infiltration rate on plots irrigated with 3000 ppm water was as high as the rates on plots irrigated with 1200 or 2100 ppm water.

Consequently higher average infiltration rates would be achieved if the canal (300 ppm) and tubewell (3000 ppm) waters were not mixed. Plotting yield data from these plots as a function of irrigation water salinity does not show higher average yields for mixed vs. unmixed water. If the waters were not mixed and were used to irrigate separate areas, salt tolerant crops could be grown on the tubewell waters and higher yielding salt nontolerant crops on the canal waters. Consequently, the data to date using mixtures of this highly sodic (SAR=16) tubewell water indicate that using the tubewell water separately from the canal water on different fields rather than mixing the water would allow higher average production and infiltration rates.

b. Assessing the Sodium and Salinity Hazards of Marginal Quality Waters

A computer program was developed to calculate equilibrium solution compositions in calcareous and gypsiferous (Rai and Franklin, Water Management Technical Report #29) systems. The calculations in the program are based upon published solubility products of calcite and gypsum and take into account ion-pair formation and the solubility enhancement of calcite resulting from the presence of Mg^{++} and $SO_4^{=}$ in the solution. For a given pre-equilibrium solution, the program predicts equilibrium ionic strength, ionic activity coefficients, dissociated (free) ions, ion-pairs, and total concentration of solute species, amount of $CaCO_3$ precipitated or dissolved at a specified partial CO_2 pressure, and the amount of gypsum precipitated. Lime and gypsum solubility results predicted with the computer closely agree with published experimental results. The program is suitable for assessing the sodium and salinity hazards of marginal quality waters using other independently developed parameters, such as the concentrating effects taking place in the soil solution due to evapotranspiration during the cropping cycle and partial CO_2 pressures developed under particular soil and cropping conditions.

c. Improving Irrigation Water Quality

1. Gypsum Addition to Water as Granules or Powder

Rates of dissolution of gypsum particles from .05 to 2 mm (Franklin, Appendix Item F) that gypsum saturation of the water is essentially achieved within 5 minutes if the gypsum particle size is $\leq$0.25 mm. When particle sizes were less than .05 mm, dissolution in turbulent water occurred within a few seconds. Equations for estimating the amounts of dissolved gypsum necessary to achieve a given SAR were developed for tubewell waters having more than 6 meq/liter of Na and HCO_3. This information can be used with ongoing field studies at Shahkot to develop quidelines for deciding how finely gypsum should be pulverized when it is to be mixed with irrigation water to improve the

water quality. Impetus for this study is that application of gypsum in the water rather than directly to the land can reduce spreading costs, and that coarsely ground gypsum generally costs about 10% less than finely ground gypsum.

2. Dissolution Rate of Large Gypsum Fragments in Flowing Water

The effects of fragments size (2 to 40 mm), solution velocity and ion content of the incoming water were determined on the rate of gypsum dissolution as water flowed through beds of gypsum fragments. (Kemper, Olsen and deMooy, Appendix Item D). Gypsum from deposits in Colorado and Pakistan gave essentially identical results. Hydraulic head losses were measured and dissolution coefficients (K) were obtained as a function of flow rate and fragment diameter for the following equation,

$$c_{ca} = c_{ci} + c_{ge}\,(1 - e^{-Kt_b}). \qquad (1)$$

where c_{ca} and c_{ci} are the calcium concentrations of water flowing out of and into the bed, respectively, and t_b is the time for which the water was in the bed. c_{ge} is the maximum concentration of Ca^{++} or SO_4^{--} which could be added to the initial solution by bringing that solution into equilibrium with the gypsum and may be calculated as

$$c_{ge} = -(c_{ci} + c_{si}) \pm \sqrt{(c_{ci} + c_{si})^2 - 4\,[(c_{ci} \times c_{si}) - c_s^{\,2}]} \qquad (2)$$

where c_{si} is the SO_4^{--} concentration of the inflowing water and c_s is the saturation concentration of gypsum solution (starting with pure water). These equations were developed using concentrations rather than activities of the ions involved and consequently are not precise. However, the experimental data indicate that equations (1) and (2) give reasonably good predictions of calcium ion increases as water flows through beds of gypsum fragments. Graphs of the gypsum dissolution coefficient needed for this calculation are plotted in Appendix D as a function of fragment size and volution velocity.

Our cooperators at Mona pointed out that in Pakistan almost half the cost of powdered gypsum applied to land is associated with the grinding that is done with expensive imported equipment. Local labor can break the gypsum into fragments an inch or two in diameter at about 1/10 the present cost of grinding. Consequently if the farmer can use the gypsum in the fragment form rather than the powder, his cost can be reduced by as much as 40 or 50%. An example is given in Appendix D of how to use knowledge of fragment size, allowable head loss (this can be less than 1 cm if desired) and initial Ca^{++} and SO_4^{--} concentrations

to design a bed of gypsum fragments in a watercourse to achieve a desired Ca^{++} concentration in irrigation water. This method of gypsum application will be field tested at Mona.

d. Gypsum Particle Size for Field Application

High carbonate concentration of some irrigation waters in Pakistan results in precipitation of significant amounts of Ca^{++} from gypsum as $CaCO_3$ before it can replace Na^+ from the surfaces of the soil minerals (e.g. see Rai and Franklin, Water Management Research Report #29). Since the amount of carbonate in the soil water at a given time is limited, rapid dissolution of $CaSO_4$ will result in less of the Ca^{++} being precipitated as $CaCO_3$ and more being available to replace Na^+ and improve the physical properties of the soil. Gypsum in smaller particles dissolves more quickly in soils, but is generally more expensive. The rate of gypsum dissolution in soils was determined as a function of particle size (Franklin, Appendix item F). These data can be used with local grinding cost data and data on carbonate concentration in the soil solution and irrigation water to determine the optimum particle size for gypsum.

e. Organic Matter Addition and Flooding as Reclamation Techniques

Because of the relatively high cost and frequent unavailability of gypsum in many areas of Pakistan, the farmers have used other materials in efforts to reclaim sodic soils. One of the most successful amendments has been organic matter. Realizing that CO_2 in the soil creates bicarbonite ion which solubilizes more Ca^{++} from $CaCO_3$, laboratory studies were designed to evaluate this effect.

Alfalfa and cow manure were added to soils which were then flooded. CO_2 contents up to 30% of the soil atmosphere were measured and Ca^{++} concentrations rose to levels equal to and greater than in gypsum saturated solution. This Ca^{++}, solubilized from lime in calcareous soils, should be just as effective in replacing Na^+ from the soils as is Ca^{++} from gypsum. Further studies are needed to quantify amounts of Ca^{++} solubilized per unit of organic matter added so cost comparisons can be made between gypsum and organic matter additions for reclamation of sodic soils. Details of this study will be available in a forthcoming manuscript by Franklin et al.

f. Phosphorous Effect on Corn and Sorghum Emergence from Soils Irrigated with Saline Water

In greenhouse and growth chamber studies, rates of emergence of corn and sorghum from soils irrigated with water at various salinity levels were measured as a function of P fertilization rate. Increasing

available P had no effect on emergence under nonsaline conditions but it increased emergence when the conductivity of saturation extracts of the soil exceeded 6 mmhos/cm. Although full recovery from the detrimental effect of salinity was not attained by the addition of phosphorus fertilizer, a high level of available phosphorus (>15 ppm by sodium bicarbonate test) overcomes much of the adverse affects of salinity when saturation extracts are in the 8 to 20 mmhos/cm range.

While this level of P fertilization is higher than is normally applied to the whole plow layer, concentrating P needed for fertility near the seed could achieve the P levels needed to improve emergence. Since Pakistan soils are generally low in available P, this research suggests the need for emphasis on P fertilizer studies, particularly where saline irrigation waters are used.

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

a. Water Management Decision Making

Mr. Ashfaq Mirza, a research assistant in Sociology (faculty member of UAL on educational leave) returned to Pakistan in March, 1973, to study farmer water management decision making. In villages on 10 watercourses with tubewell augmentation of their water supply and 10 without this augmentation, key inhabitants were interviewed to determine the background leading to decisions on: (1) when, and how well, to clean and maintain the watercourse, (2) changing scheduling of water turns from informal ("katcha") to the legal and rigid ("pucca") system, and (3) when to involve irrigation on government officials in water management decisions. The worst flood in Pakistan's history delayed data taking and the study has not yet been completely analyzed. The following tentative findings are abstracted from Mirza's data.

Added water from the tubewells generally exceeds the carrying capacity of the original watercourses leading to spillage and deterioration. At the same time, additional reliable water supplies create less willingness to invest time and energy in maintenance of the watercourse.

The primary criterion for leadership in decision making on watercourses is not age, education or personal honesty, but is size of land holding.

Frequency of cleaning watercourses ranged from twice a month to twice a year. Tubewell augmented courses were cleaned less frequently.

Switching from katcha and pucca warabandis is done to protect socially weaker farmers from exploitation by more powerful farmers. Individuals who proposed the change to pucca warabandi were: owners of moderate size holdings located toward the tail of the watercourse, who were members of the majority caste.

The time required for making a change in the system for scheduling water turns varied from 6 to 18 months.

Officials were looked upon as dispensers of favors (for a price) rather than as objective adjudicators of the laws. Standard prices for such favors are often common knowledge.

Economic Analyses of Land Leveling

Available literature on land leveling has been assembled and evaluation and abstracting are in process.

c. Economics of Saline Water Management in the Indus Basin

Analysis of tubewell and tile drainage costs for ameliorating waterlogging and salinization showed that operation and maintenance costs were approximately the same per acre served, ranging from $8 to $12/acre/year. However, capital costs were lower for tubewells, particularly in the Sind where they were down to $60/acre. While tile drains do a better job of skimming fresh water overlying saline water, their usefulness as a water supply is limited since their heavy flow occurs during heavy rains and during dry periods their flows are minimal. Specially designed skimming wells, though generally more costly, show potential for achieving both the desired drainage and best available water quality.

While the foreign exchange component of tubewells is still up around 60% (compared to 40% for drains) it is decreasing as Pakistan industry manufactures a continuingly larger portion of the pumps and casings.

Arguments for public vs. private tubewells are summed up. Available evidence indicates private tubewells mobilize more domestic resources and contribute more strongly to local industry. However, since their capital cost is high most private tubewells are installed by richer farmers, who reap the benefits of increased crop production, tending to hold down prices and generally increasing the disparity between the rich and the poor farmers. Public tubewells, on the other hand, are planned by the government to make extra water available to all farmers at the same cost.

Details of these and related analyses are contained in the report, "Economics of Saline Water Management in the Indus River Basin of Pakistan," by Ahmed Saeed Khan which is available from the Project Office on request.

d. Water Law and Institutions

The major product this year was a review draft of the report, "Institutional Alternatives for Local Water Management in Pakistan" (200 pp.), by G. E. Radosevich and Craig Kirkwood (available from

Radosevich on request). This report discusses the role of local organizational structures in water management and describes and analyzes illustrative water user organization arrangements from five selected countries and describes and assesses existing laws in Pakistan that can be used as vehicles for implementation of selected water user organizational arrangements. In order to properly analyze what organizational arrangements could be acceptable in Pakistan a discussion of the Pakistan land tenure system is included. In general, it was found that there are no serious legal impediments to the formation of water users organizations. However it was found that cooperative or mutual efforts in properly utilizing the public water resources are not encouraged by the laws. The final chapter sets forth the recommended structural requirements of a model water users organization for Pakistan.

George Radosevich was on leave with the United Nations as a water law specialist during most of the year. However, the cooperation was continued between him and David Daines to coordinate efforts on the water law seminar in Quito, Ecuador, organized by Daines to be held in January, 1974. Radosevich will present a paper on the influence of Moslem water law on Spanish water law systems.

As a result of Dr. Radosevich's consultation with officials in the province of Baluchistan, USAID was requested by the Pakistan Government to approve and support a water training fellowship at CSU for Mr. Atta Gaffar, an administrator in the Water Resources Department of Baluchistan. This fellowship was given approval and support by AID. Mr. Gaffar will arrive at CSU on Jan. 2, 1974. One of his major assignments will be to prepare a draft water code for the Province of Baluchistan.

e. Rational of Indigenous Irrigated Farming Practices and Benchmark Surveys

Considerable field work has been done to characterize the present state of, and reasons for, irrigated agricultural practices in several test areas. This information will be used at later dates to evaluate change resulting from planned dissemination with special emphasis on water management.

E. Dissemination and Utilization of Research Results

1. Dissemination of Results of Research

Research findings are printed in several forms for distribution to various audiences. In addition to these annual reports, findings are published in our Water Management Research Report series, as technical journal articles, in our Field Report Series, as informal reports for limited distribution, and as theses. A list, with abstracts, of these items which have been prepared this year is included as Appendix J. A list of known uses of materials produced by the project for seminars, conferences, speeches, etc., is attached as Appendix K.

One of Dr. Corey's first assignments in Pakistan was to assess the potential of improved water management for improving crop production. After extensive field observations with Dr. Schmehl and others he concluded that poor water management was the major constraint causing the poor stands and low yields. Although the Government of Pakistan had fully supported the tubewell program, they did not appear to be aware of the potential for increasing crop production through improved water management on the farms. Consequently Dr. Corey began a low key effort to increase the interest of Pakistani water management agencies in evaluating the potential benefits of improved water management from the canal outlet to the plant root zone. At least partially as a result of the efforts of the CSU field party, a growing awareness that "improved on-farm water management may be one of Pakistan's most profitable investments" is apparent in Pakistan. Evidence of this awareness are included in Appendix L of this report. This awareness has produced a ready market for our water management research results.

In general, a concerted effort has been made to design the work on the CSU campus to give guidelines for solution of specific problems in Pakistan. For instance, the work on skimming wells, gypsum application, water quality, irrigation and seedling emergence, irrigation methods to improve structure, economic analysis of land leveling, etc., are designed to give general guidelines for improved water management, but also to solve specific host country problems.

Utilizing his results of his theory and model studies of skimming wells, Dr. McWhorter spent 10 weeks in Pakistan consulting with agencies interested in water improvement and in planning, with Pakistani cooperators, the installation and testing of promising designs of skimming wells.

The first Pakistani Water Management Seminar, initiated and planned primarily by our field party in cooperation with the Agricultural Research Council, was held on January 22 and 23 in Lahore. Seventy-two official participants from the major agencies concerned with water management participated. About 50 other scientists and administrators were

also in attendance. Field party members led several of the discussions in this first seminar, but it is hoped that the many capable Pakistanis in attendance will play the major role in organizing and leading discussions, of the future seminars. The purpose of this seminar was to make Pakistani water management people aware of what is going on at other agencies within the country, to help them discuss and put priorities on water management problems in Pakistan and to show them where the CSU field party can work with them on these water management problems. This seminar can be considered the culmination of a low key "on-farm water management research" promotion campaign begun over two years ago by Dr. Corey to bring the importance of this research and its application to the attention of Pakistani government officials. The attendance, interest and participation of the relevant officials along with recent government emphasis on water management indicates that this campaign has been successful.

While there are several instances cited above where specific needs in host countries have generated CSU research, results of which are now being utilized in field applications, our field party has a broader responsibility to adapt all available water management research to the improvement of water management and crop yields in Pakistan. Consequently methods developed by Utah State and the U. S. Agricultural Research Service for measuring and estimating consumptive use have been initiated, along with studies to obtain the required data at eight research locations in Pakistan. Cutthroat flumes designed and tested at USU and CSU have been found ideally suited to Pakistan conditions because of their low head loss requirements.

In addition to the seminars, speeches, etc., based on our project findings, services of our staff members for planning and designing water management research and advising on water management problems have been sought frequently during the year. The following are a few examples:

1. The GOP and USAID requested advice from the CSU field party on a new water management study proposed at the University of Islamabad. The final result was a request that the field party become "permanent" consultants and cooperators.

2. Following the national Seminar on Water Management, eight research locations requested assistance and training from Dr. Clyma and Dr. deMooy in the measurement of water flow and soil water content to allow them to make quantitative studies of water use by crops.

3. The Farmers Technical Training and Extension Center at Mian Channu requested training on farm irrigation practices from Dr. Corey.

4. Dr. Eckert was asked by the USAID Mission Director to participate in (and chair) a committee studying the problems and potential use of rural labor.

5. Dr. deMooy was asked by the USAID Assistant Director for Agriculture to assist in planning an extensive (750 sites) study to develop treatments to increase barani wheat yields.

6. Dr. Schmehl was asked to come to the Philippines as part of a USAID sponsored team to look into the specific problems of the Bical River Development Project, help select and outline a development program for three pilot project areas and recommend research, training and other activities.

7. Dr. Bowers was asked by USAID/Saigon to assume administrative as well as technical responsibilities on the water management project for crop production on heavy clay soils of the Mekong delta.

The Mona and Shadab projects were conceived as a means for testing our water management technologies on farmers' fields and under practical farming conditions. The Shadab study is part of the GOP "Integrated Rural Development Program" which is planned to disseminate technologies which improve rural economies.

The Mona Center has an extension arm which is ready, willing and trainable in dissemination of the water management technologies which are adequately tested. Experience with farmers in Pakistan (and with those in the U. S.) indicates that an "irrigation adviser" will be necessary to make the calculations of consumptive use, watercourse flow and other requisite factors to calculate optimal water scheduling and crop planning. Proper training of such irrigation advisers will require an advisers training course and handbook. The research results of the CSU and USU projects should be combined with other relevant water management information, and knowledge of the farmers' resources, into a guide for such advisers. A training course for a group of such advisers, followed by an evaluation of their subsequent impact on the areas which they serve should be part of the long range program for dissemination of this research.

In all of our research, host country personnel play the major role in carrying out the research. We are often asked to take the lead in the initial planning, but we involve them in this activity as much as possible. We find it necessary to monitor the field studies at regular intervals with our cooperators to evaluate intermediate effects and make sure that planned treatments are occurring on schedule. The responsibility for analysis on reporting depends on the extent of our involvement. In most

of the projects we are there primarily as backup to help with this stage of the research if our cooperators do not get the job done. However, on some of our studies, such as those at Mona and Shadab, the extensive nature of the analyses will require that we play a major role in analysis as well as design.

When additional training of a cooperating host country scientist is the most efficient way to solve a particular water management problem, the scientist is brought to CSU for the minimum time to obtain adequate training and do the necessary library research. He will then return to his country to work on that specific problem under the direction of a field party member and his agency supervisor. A promising young staff member from the economics department of the University of Agriculture, Lyallpur, is presently at CSU studying and assembling the literature on factors affecting the economics of land leveling, as the first step of this program. Studies on use of saline tubewell waters for crop production, irrigation scheduling for conditions of limited water, irrigation and drainage of heavy clay soils and cropping patterns for efficient use of available water are anticipated for the coming year, with appropriate host country scientists. The CSU Graduate School has granted permission for these host country scientists to use the results of research in their home country as the material for their theses and for CSU field party members to conduct final examinations which may quality these scientists for advanced degrees from CSU.

F. Statement of Expenditures and Obligations and Contractor Resources

During the year the need became apparent for work on water conveyance, control and measurement (Objective #2). The AID project manager concurred in this need and consequently consultant funds were shifted to this Objective. Two man months were shifted from Objective #1 and four man months from Objective #5 to Objective #2, as may be seen by comparing the work plan budget with the budget on page 27 of this report.

Cooperation with the USAID Mission in Pakistan has resulted in funding of cooperators in agencies and locations where good research can be done and where the opportunities exist to evaluate technologies in terms of farmer acceptance, and to adapt these technologies to the farmers' resources. Support by the Pakistan USAID Mission of a program to encourage local manufacture of equipment used in water management provides an essential component for utilization of some technologies. Support by the respective USAID Missions is an essential and productive component of this project.

Dr. Sidney A. Bowers joined the project in May and is stationed at Can Tho where he is the Adviser to the Heavy Clay Soils Project. USAID/Saigon requested, shortly after Bowers' arrival on June 10, that he assume fiscal responsibility for the project in addition to his technical advisory responsibilities. Realizing that these fiscal responsibilities would detract from the time he has available for research advising, we still concurred on the basis that accepting this responsibility would get this project going. Sorting out responsibilities, writing the necessary PIO/P and the unexpected but necessary Contract amendments has taken six months. Despite the consequent delay of funds to implement the project, Bowers has developed enthusiasm for the project among his cooperators, has held several organizational sessions to delineate and initiate research responsibilities and has been able to initiate a modest research program among the graduate students at Can Tho. His effort and persistence in working out the implementation of this project are worthy of special commendation.

BUDGET BREAKDOWN BY OBJECTIVES

PROGRAM BUDGET FOR THE CURRENT BUDGET YEAR

jec-ve	Description	Man Months Including Secretarial	Salary	Consult	Fringe Benefits	Overhead	Travel and Transport	Allowance Differential and Education	Other Direct Costs	Equip. Material Supplies	Totals
1	Water conservation: Utilization and supplemental irrigation	6	9,767	-0-	835	2,415	2,730	2,624	1,500	3,152	23,023
2	Water conveyance, control and measurement	6	9,000	2,000	650	3,350	2,900	2,000	900	1,800	21,900
3	Drainage and wells	4	8,000		680	1,996	5,090	3,232		876	19,874
4	Land preparation and grading	9	15,484		1,316	4,956	1,210	3,305	1,910	3,652	31,833
5	Water application: methods, amounts and scheduling	13	18,904	-0-	1,326	8,636	5,963	3,804	1,060	3,009	42,702
6	Integration of water use factors into a productive cropping system	25	42,236	-0-	3,436	13,043	10,777	10,596	4,762	11,552	96,402
7	Water quality and salinity control	31	40,856	-0-	2,804	23,986	5,630	2,599	3,570	6,170	85,615
8	Institutional and policy factors which influence water distribution, management & utilization	27	27,186	-0-	1,618	14,380	1,000	2,884	2,300	2,289	51,657
9	Administration	40	56,987	-0-	4,843	36,638	4,200	1,656	2,970	-0-	107,294
	Totals	161	228,420	2,000	17,509	109,400	39,500	32,700	18,972	32,500	481,000

Appendix A

IMPROVING FARM WATER MANAGEMENT IN PAKISTAN

Field Report No. 1

by

Gilbert L. Corey and Wayne Clyma

Prepared under support of

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Water Management Research
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IMPROVING FARM WATER MANAGEMENT IN PAKISTAN

by

Gilbert L. Corey and Wayne Clyma*

The irrigation system of Pakistan represents one of the largest modern conveyance systems in the world and is a marvel of engineering skill and technology. The hydraulic features, dams, barrages, canals, distributaries, structures, and appurtenances have been fully described in other publications. There is however a paucity of information and, indeed, a lack of understanding of that portion of the irrigation system with which the farmer deals. This refers to the system from the canal outlet (mogha) through the irrigated field. The farmer operates and manages this water with little or no governmental assistance. The procedures, rules, resources and constraints at his disposal determine his on-farm water management** practices which determine the crop production per unit of irrigation water. A description of this farmer operated system, the rationale for its present condition, an evaluation of the problems, and suggestions for improvement are presented herein with the hope that increased production through improved water management will result. The potential for increasing production through water management is great.

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* Chief of Party and Agricultural Engineer, Colorado State University Water Management Research Project, Pakistan.

** On-farm water management was defined in a Water Management Research Workshop in Lahore (January 1973) as "the use of irrigation water from the mogha to and through the irrigated field". This definition is used throughout this paper.

The climate and soils of Pakistan are especially suitable for agriculture; however, precipitation is totally inadequate in some areas and insufficient in others for more than modest production. Without supplemental water this area would revert to deserts with only sparse vegetation. Irrigation is the key to a productive agriculture in Pakistan. The suitability of the soils and climate is evidenced by the fact that the first known practice of irrigation by man was undoubtedly along the Indus. Fifty centuries ago the Mohanjodaro civilization enjoyed the benefits of well designed water supply and drainage systems.* The broad, flat valley laced with five rivers was ideal for the inundation (sailaba) system or irrigation along the rivers. Though ancient, this system was very practical since the summer flood waters were utilized over the fertile lands adjacent to the meandering Indus river system. This type of irrigation, practiced for several thousand years, is still in use today to some extent along the Indus and its tributaries, the Jhelum, Chenab, Ravi and Sutlej.

A modern irrigation conveyance system was constructed by the British in the late 1800's and it is one of the largest in the world. There are about 40,000 miles of canals which command a gross area of over 33 million acres of fertile soils. About 25 million acres actually receive surface water. Today there are more than 80,000 tubewells supplementing the Indus system and providing water to an additional 8 million acres. Over 200,000 persian wheels also provide supplemental water. Therefore, there are about 33 million acres of deep alluvial soils under irrigation in the Indus Basin. This probably

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* Water - Yearbook of Agriculture 1955, The United States Department of Agriculture, U.S. Government Printing Office.

constitutes the greatest single agricultural potential in the world. These soils were brought into this great Basin primarily by water action from the young and rich Himalaya and Sullaman mountains.

The system is not only large with a vast potential but it is unique in several other aspects. One disappointing feature, however, is the present low production in light of the apparent highly suitable soil, water and climatic resources. These factors suggest a production potential many times greater than presently achieved. The "green" revolution increased production appreciably but even this appears to be far below potential and in many respects this so-called revolution today is stalled.

Many experts agree that the farming practices, including irrigation water management, must be modernized in order to achieve higher production. The White House-Department of Interior Panel on waterlogging and salinity in West Pakistan (Revelle Report) noted - "In West Pakistan we have the wasteful paradox of a great and modern irrigation system pouring its water on lands cultivated as they were in the middle ages..."* This observation is quite obvious to anyone acquainted with irrigated agriculture in Pakistan, but the causative conditions and factors are neither obvious nor simple. It is ironic that the only Revelle recommendation meeting with any degree of success was the one which enhanced the "great and modern irrigation (conveyance) system". Since the Revelle Report was made public in 1964, essentially nothing has been

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* "Report on Land and Water Development in the Indus Plain" by the White House-Department of Interior Panel on Waterlogging and Salinity in West Pakistan. October 1964.

accomplished relative to improving the irrigation farming practices which in fact today are still ancient and traditional and must be considered a part of the total irrigation system. The modern system ends at the "mogha".

The Pakistan farmer operates under a set of very difficult conditions. Given the same circumstances, services received, and resources undoubtedly few farmers could have performed more efficiently. Hard work, infinite patience, and tenacity mark his mettle, and where others would have undoubtedly given up in despair, he has persisted even today using methods unrelated to modern agriculture. The Pakistan farmer must make many difficult decisions which are imposed on him by the irrigation system and the very nature of the resources he must utilize without benefit of sufficient governmental services. His position is not readily comparable to that of farmers in irrigated regions of the world where water is more abundant. Often the comparison is made between Pakistan and the Imperial Valley in California. The soil conditions and the climate are similar which makes several of the irrigation problems identical; however, there are important differences which explain the tremendous gap in production. Some of these are: insufficient water supply, lack of proper land leveling, lack of irrigation water control, lack of salinity control, lack of water management extension services, use of ancient cropping systems with ancient tools, or in other words a very different on-farm water management system.

DESCRIPTION OF THE IRRIGATION SYSTEM

Annually, approximately 80 million acre feet of water are diverted through the canal system for about 25 million acres. It is estimated however that only 52 million acre feet reach the fields due to transit losses. This 2.1 acre feet per acre is further diminished by losses within the field due to nonuniform

application of water. Assuming 50 percent field application efficiency, which is conservative, there would be little more than one acre foot of water per acre annually available for plant consumptive use. Considering the climatic potential for at least two crops a year, this is certainly an inadequate water supply. Evidently, no attempt was made initially to determine water requirements or to design a system to meet those requirements efficiently. The canal system was developed to utilize available water supplies to irrigate as much land as was possible.

Government and private tubewells have been constructed in large numbers during the past decade. This has relieved the drought situation on approximately one third of the irrigated area. However, there are presently over 20 million acres of land which receive only the canal supply described above.

The irrigation system is so constructed that water flows from the minor canals through turnouts (moghas) supplying water to a village area. The farmers themselves operate and maintain their distribution system. There are no headgates at the moghas and if a particular canal has water in it, there is water in every watercourse (khal)* on that canal. It is like a giant river system flowing in reverse with each tributary getting an equal share. The farmers on the watercourse use the entire flow on a turn basis (warabundi). In other words, one has an allotted time interval for the flow based on his acreage and he has a fixed time each week, 10 days, or two weeks to use it. If there is insufficient water during a particular farmer's turn then he must forfeit his share of public canal water and wait for the next turn. There

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* Watercourse as used in this paper refers to all the channels through which water flows from the "mogha" to the fields where crops are grown.

are some variations which are unofficial but water on demand is essentially unknown except in those areas served by farmer operated tubewells.

The watercourse system does not always flow full depending on supplies in the canals; therefore water available on the "warabundi" is not always constant. Canal closures for repairs do occur and farmers are not usually notified in sufficient time to make alternate plans. Water charges are made on the basis of acreage of crop grown and water rates vary for different crops based on assumed consumptive rates. Mixed crops are assessed at the highest rates leviable on any one crop. If a portion of a field is irrigated the rate applies for the whole field unless such portion has been clearly demarcated by a well defined ridge. The assessment for irrigation water therefore is not based on the amount of irrigation water received; but on the acreage and species of crops grown in a particular season. The individual (potwari) who makes the levy for each crop is greatly underpaid and as a result of the vast amounts of water rates he levies he often finds it lucrative to reduce rates for special favors from farmers.

The topography of the Indus basin is flat. The general slope downstream averages from about nine inches to one foot per mile. Natural drainageways are not readily apparent since most of the area has low rainfall and runoff in the irrigated area is minimal. Practically no artificial drains have been constructed, therefore surface drainage for irrigation water is virtually non-existent either from artificial or natural drains. Irrigation water passing through each "mogha" is therefore utilized on that particular watercourse area as there is no provision to let it pass to an area of lower elevation.

The soils are characterized as having a special granulometric distribution. The ratio of silt to clay is high with some resemblance to loess soils. There

is a lack of structure which is perhaps related to the quantity of organic matter in the soil. This lack of organic matter, improper tillage methods, and a problem of cementation of the homogeneous soil particles result in low infiltration rates for most of the silty and sandy loam soils.

The irrigation system and resources provide the farmer with special problems not fully understood by the casual observer to agriculture in Pakistan.

DEVELOPMENT OF PRESENT PRACTICES

The inundation or level basin system of irrigation is used extensively in Pakistan. The flat topography might suggest this practice but actually the constraints are such that no other system is possible. The non-runoff restriction requires either a system in which water is applied precisely according to the infiltration rate or it must be ponded. The low infiltration capacities of most soils make it impossible to get sufficient water into the profile during one irrigation turn. The level basin system has been utilized because it exactly fits these resources and constraints. Furrow irrigation is practiced with some crops and it is interesting to observe that the furrows are constructed to provide for a great deal of storage. The ponding method, then, is also used with this system; the furrows are made very broad and will store sufficient water to fill the soil reservoir even though infiltration rates require that the opportunity time be much longer than the "warabundi" turn. Apparently, the furrow system is only used with these crops such as tobacco and vegetables which will not tolerate inundation for extended periods. Regardless of whether basins or furrows are used a ponding procedure requires a level system. Water must be stored on the surface during irrigation and allowed to stand and infiltrate into the plant root zone.

The farmer has attempted to farm his land on a dead level basis with traditional implements drawn by bullocks. He appreciates the very small tolerance in elevation difference required with such field design. A one inch difference in elevation frequently means more than a two inch difference in water stored in the root zone and this can be as much as fifty percent of the water needed for proper plant growth. His traditional tools for accomplishing land leveling have been less than ideal. Bullock drawn logs and boards (sohaga and karah) are commonly used. Tractor blades and bulldozers are now available to those with sufficient capital, however, none of these tools are appropriate for preparing fields precisely to a dead level tolerance. Precision land leveling can only be accomplished efficiently by utilizing known engineering principles and procedures for design together with proper machinery expertly handled. Machines which load and carry an appreciable amount of soil while scraping over a surface thin layer have proved ideal for this job. These machines act as planes and perform the very important job of compacting loose soil as well as cutting to a precise depth. Such machines which are usually called soil scrapers and land levelers are now manufactured in Pakistan and are increasingly available to the farmers.

Without this equipment or the technical skills required to design and construct a dead level field, the farmer has developed his own crude leveling procedure. He utilizes the water itself to provide a measure of levelness and by continually re-leveling with the "sohaga" and the "karah" he maintains a reasonably workable field. Of necessity he has had to develop a system of very small fields because he cannot maintain a small tolerance over a large land area. Ordinarily he selects a parcel only about one acre in size as a unit

for water control. He further divides this into four and frequently eight equal parts with dikes (bunds). It is common to observe a series of one acre benches each representing a separate irrigation unit.

A system utilizing small fields naturally results in an extensive water conveyance system. These open ditches supply water to practically every acre and it is difficult to find a point within an irrigated area which is more than three hundred feet away from a water supply ditch. The length of the watercourse per acre is very large due to the constraints of the traditional irrigation system. There is little alternative to such a system without external services and assistance to the farmer.

The prevalence of trees over the irrigated area is a natural consequence of the scarcity of wood in Pakistan which has only roughly 20 percent of the timber needed for a developing nation. Trees are allowed to grow along and in the ditch systems and in the fields and the general feeling is that these trees are a valuable by-product.

EVALUATION OF THE SYSTEM

Water management practices and procedures used today in the Indus Basin have developed logically over time but they do not represent an efficient or reliable system. An understanding of the problems associated with present practices is necessary before intelligent, reliable and workable recommendations can be made. On-farm water management problems can be divided into categories according to sequence of use; water supply, delivery, application, and use by crops.

Water Supply - The water supply is inadequate regardless of acreage of holdings except for areas receiving supplemental tubewell water. Available water is

divided on an acreage basis and since the canal system delivers annually little more than 2 acre feet per acre year around production is not possible on all the land even though the climate suggests otherwise. By comparison, over 10 acre feet per acre is diverted into the Imperial Valley of California each year; more than four times that supplied the Pakistan farmer. With water so scarce he operates under a virtual drought situation all the time and this has been the case for centuries.

The water supply is not readily predictable. Spills, seepage, wastage, and location of "mogha" all contribute to variable flows. The irrigation schedule is rigid being fixed by the "warabundi" system. A particular farmer must take his "turn" even though the water might not be needed at a specific time and this leads to over irrigation. There is limited incentive for efficient use of water under such a system especially when water charges are based on acreage irrigated and not on water used. Drainage systems are inadequate or non-existent in most areas creating the necessity to utilize all the canal flow from a "mogha" all the time that water is in the system.

On about two thirds of the arable land, therefore, the farmer is supplied with little more than one-half the amount of water needed. It is supplied on a rigid schedule, unpredictable, and with no opportunity to vary the quantity or time received. The farmer is faced with a constant dilemma. It is next to impossible with such a system for him to improve production by utilizing this precious resource efficiently especially since the Government has not provided him with technologies to suggest improvements. The Agriculture Department is administered separately from the Irrigation Department and neither has the responsibility for teaching improved farm water management practices. The irrigation system is viewed essentially as a water disposal system and not a

system to provide water to crops when needed. Its capabilities are measured in terms of acres served and cost of operation not in crop production. The Pakistani farmer then is forced to operate the system as best he can. His present position is a logical consequence of the constraints he faces.

Water delivery - The Irrigation Department has jurisdiction past the "mogha" or outlet for the watercourse but does not exercise physical control of the water past that point. Thus, the watercourse is the community property of the farmers served by it. It was built and maintained largely by the skills, knowledge and efforts of the community of farmers on the watercourse. A major problem is the lack of knowledge to operate and maintain it properly. As a result many farmers are deprived of substantial quantities of water.

Seepage is not completely understood and it deprives many farmers of a valuable water supply. Water which seeps from a watercourse is not lost from the water delivery system of Pakistan since it goes to ground water and is available for reuse. However, to the farmer farther down the channel without a tubewell and without an adequate supply, the water is lost just as if it were piped to the sea. That farmer suffers from an inadequate water supply whatever the benefits someone else gets from the seepage water.

Losses from watercourses range from essentially nothing to most of the available flow. Table 1 presents some recently measured values of seepage losses. It is recognized that the procedure of converting to a rate of loss per mile tends to overestimate the true value; however, many watercourses are 20-30 miles long so large amounts of water can be lost. Water saved by reducing seepage has equal or greater value than tubewell water and equivalent costs are justified.

Table 1. Values for seepage loss from Watercourses in Pakistan

ource	Distance	Discharge Total	Discharge Loss	Percent Per Mile
(1)	Average for several watercourses			50
(2)	4000	2.48	.46	25
(2)	1000	2.48	.21	45
(2)	1500	4.00	.75	65
(2)	3000	2.25	0.10	5

(1) Ali, Arshad. Address to the Water Management Research Workshop, Lahore (January 1973).

(2) Unpublished data from Wayne Clyma.

Considerable leakage occurs because the farmer is concerned with delivery of water only during his turn. When a poorly maintained channel breaks, a farmer repairs it only sufficiently enough to insure that it will deliver water during his irrigation turn. Thus, breaks and corresponding spills of water are common. The water gradually seeps through the thin channel bank or abruptly spills from a broken dike and is lost to the farmer who has that turn.

The water lost by a spill may go to a field that does not need water and become deep seepage or a wet spot that will be over irrigated the next time the field receives a planned irrigation. Either way the water is a waste that brings little or no benefits to any farmer. It may even result in a loss to the farmer who regularly receives spills from the watercourse. Spills may equal or exceed deep seepage losses and should be justification for rehabilitation of a watercourse. Even watercourses that have little direct seepage loss will benefit from rehabilitation through reduction of spills.

The intricate tortuous system of channels used to deliver water from the "mogha" to a field may cause seepage losses to be four times as great as from a well aligned watercourse. Most fields presently have a maximum length of 220 feet and require nearly three times as much watercourse length as would be needed if the fields were constructed 800 feet in length. Since alternate wetting and drying increases seepage and other water losses, a long channel will have a proportionately higher average loss than will a short channel.

Trees, grass and weeds growing along and within watercourses have several specific effects that result in loss of water. They use tremendous quantities of water since they can transpire wastefully if water is readily available. This water is lost from the water delivery system and cannot be recovered. The process also leaves a residual of salts that increases the rate of salinization of the soils and water. The evapotranspiration lowers the water table under the channel and increases seepage losses. Roots penetrate the soil to the side and below the channel making the soil more permeable and increasing seepage losses. Weeds, trees, and sediment combine to increase channel roughness and reduce delivery to the farm. The increased depth of water caused by this vegetation in the channel increases the seepage because of increased flow area. The increased depth of flow also decreases the head difference across the "mogha" which usually operates submerged. The flow of water through the "mogha" and into the watercourse is therefore reduced. Trees also shade crops, harbor birds, and are hosts to many insects. The trees are valuable but the loss in crop production by allowing them to grow haphazardly may be an uneconomic use of water and land resources.

Watercourses in Pakistan are generally constructed in the manner illustrated in Figure 1(a). Soil is excavated from below the ground surface and

piled on each side to increase the height of the sides. When water flows through the channel, the water level is at or near the ground surface. To irrigate, the farmer builds a dike across the channel high enough to raise the water level above the ground so water can flow onto the field. As a result, for several hundred feet the water level is near the top of the sides of the channel. This is one factor that results in many spills from the watercourse. The other major result of such construction is that water in the channel cannot be completely drained onto the field at the end of the turn but remains in the watercourse where it evaporates or seeps into the ground. In either instance that water is lost to the farmer.

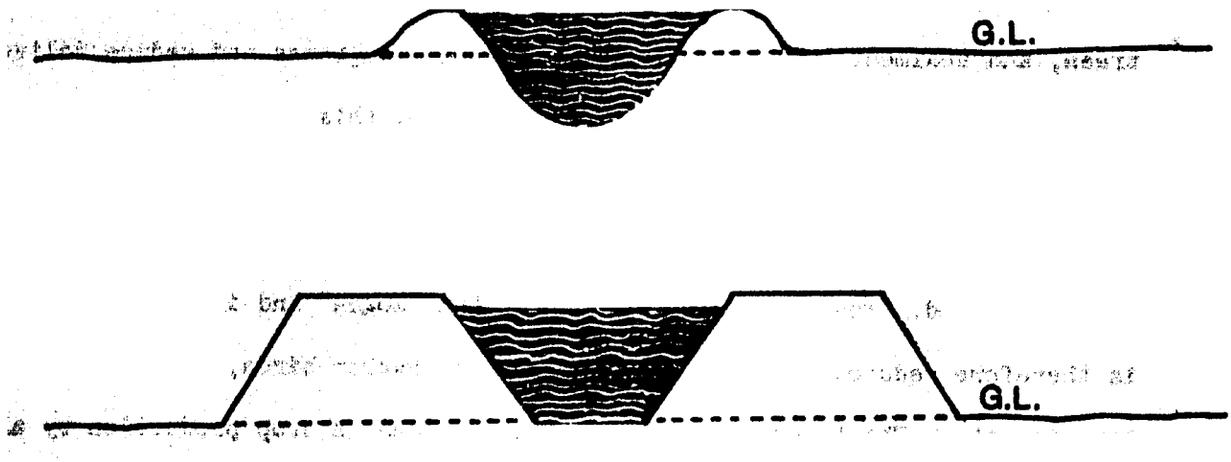

Figure 1. (a) Typical cross section of most watercourses; and
(b) Desirable cross section.

An estimate of the amount of water lost by in-channel storage below the ground level has been made in Table 2. The average cross section below ground level was estimated from field observations of flow cross sections. The value presented is very conservative as many channels have two square feet below ground level. The number of acres per mile of water course is a judgment factor and was arrived at by estimation. An alternate procedure of assuming average dimensions for fields was used and 20 acres per mile of watercourse is a conservative estimate. These calculations indicate that from 3.5 to 7 million acre feet of water may be lost each year in channel storage below ground level.

Tarbela Dam is estimated to store 8 million acre feet of water when construction is complete. Undoubtedly no more than one-half of the water (4 million acre feet) released from Tarbela will reach the farm field. Tarbela cost approximately ten billion rupees. This simple calculation indicates that rehabilitation of watercourses to raise them above ground level could make more water available to farmers than a ten billion rupee Tarbela dam. A simple construction such as indicated in Figure 1(b) would also reduce many of the losses previously described as being common for watercourses in Pakistan.

The intricate system of ditches serving farmer fields results in another type of water loss. Some of the time allotted to a farmer is lost because of the time required to fill the ditch system in changing from one field to another. The time loss to fill the ditch is a water loss to that particular farmer. The amount of this loss varies depending on field position but in one case was noted to be almost 40 percent of the particular farmer's tur

Table 2. Water loss from in-channel storage below ground level in watercourses in Pakistan.

Average cross section below ground	1 square foot
Volume below ground per mile	0.12 acre feet
Number of acres per mile of watercourse*	20
Acres of irrigated land	30 million
Miles of watercourse	1.5 million
Volume of storage below groun	182,000 acre feet
Average number of times a watercourse is filled each year:**	
High estimate	
Low estimate	
Annual water loss by in-channel storage below ground level:	
High estimate	7.2 million acre feet
Low estimate	3.6 million acre feet

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* Estimated by measuring the length of channel in a watercourse and dividing into the number of acres served.

** Watercourses rotate on a one week to three week basis. Some canals are closed six months of the year. Maximum number would be 52 fillings and a minimum would be 20. A small portion of the watercourse has water flowing all the time and therefore not subject to this loss.

Water Application - When to irrigate; how much water to apply; and how to apply the water are questions basic to irrigation water application. Farmers consciously or unconsciously answer these questions and their answers determine whether or not they apply water properly to a field.

Irrigation application timing is frequently a question of waiting one, two or three weeks between applications with the rotation system of Pakistan. Many farmers, during the winter season, adjust the frequency of their wheat irrigations to three or four week intervals understanding that less frequent irrigations are needed during these cooler months. But some farmers irrigate on fixed schedules and pay no particular attention to rain or other climatic factors. Preliminary observations indicate that farmers irrigate all crops too frequently during the winter months.

How much water must be applied during a given irrigation depends on a number of factors. First in importance is how much water can the soil reservoir store. Other factors such as leaching of salts, depth to goundwater, providing moisture for germination, or minimum depth of application to cover all the field are also important.

Farmer criteria for how much water to apply appears to be that all the field must be covered with water including an adequate depth over any existing high spots. In some fields high spots are not adequately covered consistently but farmers are aware that the result is salinization of these spots resulting in little or no yield of crop on that area.

The answers to the two questions of when to irrigate and how much to apply are interrelated, but farmers in Pakistan generally do not have adequate information to arrive at correct answers. A number of field application efficiencies have been measured in Pakistan by the authors. In fourteen trials

the efficiencies varied from 10 to 50 percent with the majority of them being less than 25 percent. Efficiency was calculated as the ratio of the water needed to fill the root zone to the amount applied on the field. The most important factor causing low application efficiencies relates to the procedure followed in applying the water.

Most irrigation systems in Pakistan consist of one-eighth to one acre basins usually assumed to be level (zero grade). The maximum length or width of any basin is usually 220 feet while the actual dimensions vary dependent upon many factors. Small basins have been considered by many to be the most efficient system of irrigation for Pakistan.* Under conditions of poorly leveled land and limited water control, small basins are convenient, but not efficient.

The farmer wants to cover all his field including the high spots. This results in over application on most fields during each irrigation and a waste of water. It is paradoxical that over irrigation occurs where water is a scarce resource. The obvious explanation is that some land lies idle during peak consumptive seasons and/or the irrigation interval is extended resulting in droughty conditions between irrigations.

Water Use by Crops - Water delivered and applied to a field is available for plant use, salinity control or other purposes. The water for plant use is stored in the soil and must be replenished throughout the growing season.

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* Husain, Mohd. Studies on Scientific Irrigation and Agricultural Practices in West Pakistan. Research Publication, Vol. II, No. 10, Directorate of Land Reclamation; Lahore 1964.

Quantitative data on how soil moisture is maintained for proper plant growth are inadequate in Pakistan.

Water is applied to a field initially to supply moisture for tillage to prepare the seedbed. After tillage the surface is very loose and infiltration rates are high. The "rauni" irrigation, applied just before planting, is excessive because of the high infiltration rate of the soil and the small amount of moisture needed; usually not more than an inch. The first irrigation after the crop is planted is often excessive because of the relatively high infiltration and the limited soil water depletion. These irrigations also leach excessive amounts of nutrients from the soil furhter reducing the potential yield of the crop.

Soils that have severe infiltration problems, and there are many in Pakistan, restrict water penetration during irrigation and farmers are unable to effectively apply enough water for proper plant growth. Shallow rooting depths also limit the available supply of water and crop yields are low because of excessive moisture stress. This explains the common recommendation of light frequent irrigations, up to ten during the growing season for wheat. Even though not understanding all the implications of low infiltration and shallow rooting depths farmers have learned that frequent irrigations will improve yields.

Over irrigation also occurs in fields where soils exhibit moderate infiltration rates since as crop growth increases the surface retardance of the plants causes the necessity for larger and larger applications of water to force the water across the field. Over irrigation reduces fertility and crop yields. Infrequent applications of the large amounts of water result in plant water stress during the peak consumptive use periods. Water stress and low fertility both limit crop yield.

The fertilizer requirements of high yielding varieties are usually more than commonly applied by farmers. This is further complicated by the early over applications of water which leaches nitrates from the soil. Water management to eliminate over irrigations and optimum applications of fertility will do much to improve the low crop yields in Pakistan. The crop producing potential of water is wasted when it is applied to inadequately fertilized crops.

Salinity control is recognized by farmers as being important for good crop yields. The efforts invested in land leveling attempts and irrigation of high spots are evidence of farmer concern and knowledge. Management to control salinity is difficult because of improperly leveled land but also there is a lack of understanding that the leaching requirement is related to the amount applied, soil salinity, water quality and other management practices.

SUGGESTIONS AND RECOMMENDATIONS

An irrigation system should be managed with the object of increased agricultural production. Too often the water resource is considered to be of such importance that its mere presence will insure increased production. It is important, but it is only one input necessary for modern agriculture and its proper management on the farm cannot be neglected without disappointing results. Planners the world over have commonly divided irrigation system management into the engineering and the agricultural phases. This is a costly mistake since, under such an arrangement, no one is responsible for the entire system from the water source to the harvested crop. The result is the creation of several agencies, each responsible for certain phases and ordinarily not coordinating efforts in the interest of efficient use of water for maximum production. All governmental agencies in Pakistan dealing with the water and/or soil resources

should dedicate themselves to realizing the greatest possible production per unit of water.

In Pakistan there is need to increase the supply of water available at the farm, discovering new sources is only one possible solution. Supplies can be increased by proper management and utilization of the water as it proceeds through the irrigation system to the harvested crop. To do this it is necessary to analyze the present practices which have developed from the rigid, inadequately supplied system. To utilize increased flows it may be necessary to alter some procedures. Several recommendations seem apparent and several less apparent ones will require detailed research to discover proper procedures and practices. The following are offered as possibilities for enhancing the irrigation system as well as modernizing farming practices to match the system. They are based on increasing available water and utilizing it more effectively and in most respects these are inseparable since efficient use means more water available.

1. Research programs dealing with on-farm water management should be given high priority.

A viable extensive agricultural research program is essential to modernize methods and techniques. It is a proven fact that money spent on agricultural research is returned to the economy many times over.

Irrigation water is only one input to successful agricultural production. However, its interactions and relationships with practically all of the other necessary inputs are important enough to warrant a full-scale research program in its own right. Irrigation water management and the associated soil-water-plant relationships are so vitally important that full benefits from other research can never be achieved until these are optimized. For example, potential yields from breeding programs will always be limited by

the soil, water, and fertility management factors and if these are not given full attention results will be disappointing.

Researchers must use imagination and be willing to explore the unknown. Farmers are very flexible and research indicates that they will adopt practices which are proven to be profitable if the constraints facing them can be reduced. The planner or researcher cannot without research determine whether or not a given practice will be adopted by farmers. Too often the statement is made that the farmer cannot afford a given modern practice. Farmers are accomplishing many practices in Pakistan which are considered uneconomic in most of the so-called developed countries. Bench terracing, utilizing valuable irrigation water on fields containing less than fifty percent stands, irrigation pumping plants operating at efficiencies below fifty percent, and growing crops with practically no weed or pest control are all practices which are expensive. They would appear to be practices farmers cannot afford, yet in Pakistan they are practices today.

Optimum use of water will require further refinement of all factors influencing crop yields and conversely the full benefits to be derived from other factors such as fertilization will not be realized unless the crop has adequate water. When properly combined the right amount of water and fertility can double, triple, or even quadruple present yields. Other factors such as plant stands, weed, insect and disease control are equally important. When all inputs are put in proper combination maximum yields will be approached.

Much research is necessary before quantitative data are available on how best to manage soil moisture for maximum crop production. Moisture management in the soil is complicated and many crop cultural practices affect its distribution, retention and movement. Seed bed preparation, tillage practices,

frequency and amount of irrigation, weed control, plant population, method of irrigation, disease control, rooting depth, fertility level, salinity, alkalinity, and climatic factors all have important effects on soil-water relations.

With such a complicated process it is obvious that maximum yields are not achieved, they can only be approached. The necessary research to find the proper combinations of inputs including amounts, methods and timings is a continuing process. The work is never complete. New approaches uncover new problems requiring research. The important benefit a viable research program creates is an ever increasing agricultural production. Yields approaching maximum today will be woefully small tomorrow.

2. Conjunctive use of ground and surface waters should be encouraged.

Tubewells represent a rather modern innovation which enhance the public irrigation system by supplying more water while maintaining ground water levels sufficiently low to permit land reclamation and increased agricultural production. Since most of the present irrigation system operates under a drought condition, supplemental tubewell supplies are exceedingly valuable.

A planned program of conjunctive use of ground water and surface water can make water available when needed as well as increase the total supply. Therefore benefits could be derived from better management of the total supply. Privately owned and operated wells should be encouraged since the farmer could control scheduling. Examination of ground water aquifer reservoirs in all locations will be needed so that excessive mining of water will not result in the exhaustion of the ground water resource.

Shallow, low discharge tubewells should be encouraged as new programs are adopted. Small discharges are easier to control and facilitate precise

water control. This type of well is cheap to construct, does not require large power units, and more importantly does not drastically disturb the saline water underlying the sweet water aquifer.

Better methods of well construction and operation to skim sweet water need to be designed and tested. There are great quantities of good irrigation water lying in a rather thin layer on top of the very saline water beneath.

The entire river flow and irrigation system needs to be analyzed with the idea of utilizing to advantage all available water. Perhaps storage underground by water spreading is worthwhile. There is, in fact, sufficient water in the Indus system if properly apportioned, stored and utilized.

3. A national program of precision land leveling should be launched.

Precision land leveling and water control through systems designed to deliver the right amount of water in relation to the length and width of the field, the infiltration rate of the soil and the water needs of the crop would improve water application efficiencies in Pakistan. Greater lengths of fields would decrease the length of watercourses and facilitate other farming operations. A good job of leveling and water control would allow irrigation application efficiencies to increase to over 50 percent, more than doubling the water supply which is available for plant growth.

Farmers, especially those with smaller holdings, will require governmental assistance in order to do a completed job of precision land leveling. The program must include the engineering technical assistance to survey and design the fields as well as to insure the completed job meets design specifications. Research on the methods of applying water to the fields is needed to provide better design criteria for land leveling under Pakistan conditions.

Watercourses should be rehabilitated for more effective field delivery.

Rehabilitation of the watercourses should be done to provide increased capacity, improved cross sections, removal of unnecessary vegetation, protection against unnecessary spills and seepage. In areas where seepage losses are large, lined channels should be constructed to further reduce losses.

Seepage losses from watercourses can range from essentially zero to ninety percent of the flow at the "mogha". Water recovered by rehabilitation of watercourses has the same or greater value as water obtained from tubewells and equivalent costs are justified. Apparently, most farmers do not appreciate this economic fact since they generally adopt the tubewell alternative.

While renovation of all watercourses in Pakistan will require a long term effort, the benefits make the effort imperative. A country that can build the worlds largest earth filled dam can renovate 1.5 million miles of watercourse. The procedures can be labor intensive and the benefits are immediate improvement in food production through increased water availability. Such a program logically can be accomplished in conjunction with a land leveling program.

5. Rules and procedures for water delivery to the farmer should be reviewed.

The procedure of irrigating on a fixed schedule is not conducive to the development of a knowledge of plant needs for water as related to climatic factors and stage of growth. If water is only available at fixed times, plant needs cannot be effectively met. This practice causes wastage of water at times while a drought situation occurs at others. The result, of course, is reduced production per unit of water.

The feasibility of modifying the rules by which water is delivered should be investigated. Provisions of trading turns, for using only part of the flow of a watercourse, and the ability to store water in holding ponds on the watercourse for use at a later time need consideration and research. Methods of charging for and assessing water rates should be investigated. Making some segment of the Government of Pakistan responsible to farmers for efficient system operation could prove beneficial. One avenue to accomplish this would be through farmer Water Users Associations.

Appendix B

WATERCOURSE LOSSES - CASE STUDY #1

by

WAYNE CLYMA
Colorado State University
Water Management Research Contract/Pakistan

and

ARSHAD ALI
Department of Irrigation and Drainage
University of Agriculture
Lyallpur

Prepared under support of

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Preliminary Report - Not for Publication

WATERCOURSE LOSSES - CASE STUDY #1

This represents the first in a series of reports of case studies of what happens to water on watercourses in Pakistan. These preliminary data are the result of specific studies for short intervals of time. They are presented in this manner so that the data can be made available now because of an increased interest in water management in Pakistan. When sufficient data become available, a formal report will be prepared.

Water for irrigation is a valuable and scarce resource in Pakistan. Annual canal water supplies average two acre-feet per acre[1/], but that available for actual direct use by crops is probably less than one acre-foot per acre. With an annual water requirement of at least five acre-feet per acre for year round cropping, water must be utilized as effectively as possible.

The watercourses* in Pakistan supply water from a distributary through an outlet or "mogha" to all fields in the area served by the mogha. A more detailed description of the problems of water delivery with recommendations for a solution have been given recently by Corey and Clyma[2/]. Some of the more important problems are reviewed here and data are presented on water losses for a watercourse.

Watercourse losses through seepage, spills, unnecessary evapotranspiration and other factors probably result in more than a fifty percent reduction in discharge between the mogha and the farmer's fields. Primary among these losses are seepage and spills. Seepage losses are not always lost from the water system of Pakistan as the water enters the ground water and is available for pumping. Water lost by seepage usually deteriorates in quality by salt accumulation while flowing to the ground water and/or by mixing with poorer quality ground water. Storage of water through seepage losses is often uneconomical because of this quality deterioration. When the farmer has an inadequate supply of water, seepage losses are a direct cost to the farmer because of reduced crop yields. Provision of additional capacity for watercourses and installation of a tubewell to supplement the water supply may be

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*Watercourse as used in this paper refers to all the channel through which water flows from the "mogha" to the fields where crops are grown.

1/ Ahmed, Nazir. 1972. A few suggestions to conserve flood runoff and to recover fresh water from the saline water zones of the Indus plains. Proceedings of the West Pakistan Engineering Conference, Vol. 53.

2/ Corey, G. L. and W. Clyma. 1973. Improving Farm Water Management in Pakistan. Colorado State University, Water Management Research, Field Report #1, Pakistan.

more expensive than reduction of the watercourse losses. When all the advantages of a properly designed watercourse are evaluated, renovation and possible lining may prove to be the best alternative for providing more water to farmers.

Spills involve the loss of water from the watercourse to the ground surface either by overtopping, slow seepage through the side, breakage of the bund and direct flow. Borrowed use of the water is not an overall loss, but represents an adaptation of the rotation system of water distribution toward a water on demand system and probably results in more effective use of the water. Borrowed use of water in Pakistan may be a frequent practice. Stolen use of water is a loss to the farmer who has that particular warabandi turn. To the farmer who has the irrigation turn spills have the same effect as seepage because he loses the water. However over irrigation to fields adjacent to the watercourse which receive these spills may cause reductions in yields.

To examine in detail the nature and magnitude of seepage losses and spills on watercourses, flow measurements of the watercourse at tubewell 122, Mona Project, were made on the eighth and ninth of May, 1973. This was the beginning of the Kharif season and represents a period of relatively low demand for water. Water is used primarily for fodder crops in preparation for planting and for irrigation of cotton or sugarcane in the early stages of growth. Potential evapotranspiration is high, but actual water use is low. Assistance was provided by Zahid Saeed Khan, Amir Shah, and Mohammed Irshad, students in Agricultural Engineering, Agricultural University, Lyallpur.

Figure 1 is a map showing the location of the two Parshall flumes. Flume #1 was located 930 feet from the tubewell-mogha area and the two flumes were 1350 feet apart. A cross-section of the watercourse about 50 feet from flume #1 is shown in Figure 2.

The width of the watercourse is quite large in comparison to its depth. The water level shown is the dominant water line indicated in a dry channel. When 5 cusecs flow through the channel the freeboard is a few tenths of a foot. The wetted perimeter shown in Figure 2 is 7 feet with an additional foot of wetted perimeter when the channel flows full. This means the wetted area ranges from 7 to 8 square feet per foot of channel length.

Flume #1 was installed on June 7 for use in connection with irrigation evaluations for sugarcane. Figure 3 shows the discharge measurements from 0800 to 1200 on June 8. Flume #2 was installed the afternoon of June 8 after an investigation of the time and sequence of the warabandi.

Measurements of discharge were obtained for the two flumes from 2100 on June 8 until approximately 1300 on June 9. Measurements were obtained at least every hour and on flume #2 more frequently when possible. Flow through flume #1 during this time was free flow, but some of the measurements on the morning of June 8 were with as much as 70 percent submergence. Flow in flume #2 was always submerged with a maximum submergence of 89 percent.

Figure 3 shows a maximum discharge of 3.95 cusecs for the watercourse. The tubewell was operating during all of the time interval between 0300 and 1200. The maximum discharge measured at flume #1 was 5.14 cusecs. The difference between 5.14 cusecs and the discharges shown in Figure 3 was caused by seepage losses, and borrowed or stolen water.

The "warabandi" system of turns in Pakistan specifies the time interval on a particular day of the week that each farmer has water. The "kucha warabandi" operates as a warabandi, but the system of turns has not been registered and made official by the Irrigation Department. The "pucca warabandi" is official and has been registered by the Irrigation Department. Most watercourses in Pakistan operate on the "pucca warabandi" system.

"Sanctioned borrowing of water" between farmers is when two farmers agree that one farmer may use all or part of the water in the watercourse during the other farmer's turn. The sanctioning is between the two farmers and is a violation of the warabandi rules. Unsanctioned borrowing or stealing of water generally consists of a farmer constructing a small "nakka" such that a portion of the flow of the watercourse is taken and is a form of water theft. Sanctioned and unsanctioned borrowing, or planned spills account for an appreciable portion of the water used on a number of watercourses where observations of farmer irrigation practices have been made. Tubewell 122 has a "kucha warabandi."

On TW 122 between 0800 and 1300, water was used to irrigate a fodder field that had been irrigated previously (between 0700 and 0800) as well as a berseem field. The tenant who had the irrigation turn between 0800 and 1300 did not worry about this loss of water and so these spills were presumably planned spills. Small "nakkas" were constructed to take about 1.25 to 2.5 cusecs from the flow of 5.14 cusecs and this flow was used to irrigate the fields. This borrowed use of the water, largely planned, and seepage in about 900 feet of watercourse as shown in Figure 3 was 33 percent of the flow of 5.14 cusecs.

Figure 4, which shows the variation in discharge with time for flumes #1 and #2, can be used to illustrate a number of losses that occur in a watercourse. The difference in flow from flume #1 to flume #2

between 2300 and 0400 represents largely seepage losses of approximately 0.8 cusecs, although there was a small amount of spillage from the channel into the ditch at the side of the road. The seepage loss would be represented as follows:

Discharge, cusecs		Channel Distance	Wetted Perimeter	Loss	Seepage Rate
Flume #1	Flume #2	ft.	ft.	cusecs / 1000 ft	cusecs / ft^2 perimeter
3.90	3.10	1350	7	0.6	9×10^{-5}

The decrease in flow at flume #1 just after measurements began probably represents borrowed use of the water. The fluctuating flow at flume #2 from 2100 to 2300 hours represents the period of beginning flow through flume #2. The reading at 2215 may represent an error in measurement.

Sometime between the reading at 0350 and the reading at 0455, when there was enough light to see, the farmer came up the watercourse stopping all the spills he could find. The increase in flow from 4 to near 5 cusecs at flume #1 is an increase in flow that occurred because of the inability to control spills properly during the night time hours. Even when the farmer attempts night maintenance spills are substantially greater at night since only the large spills can be easily located.

The delay in improvement of discharge at flume #2 is related to the time of travel for an increase in flow. The flow at flume #1 improved nearly one cusec to near 4.9 cusecs, but the flow at flume #2 improved to about 3.4 cusecs or only one-third the improvement that occurred at flume #1. Between 0700 and 0900 it was observed that the flow in the channel above flume #2 was continually exceeding the capacity of the channel. First the nakkas used the previous evening to irrigate several fields overtopped as well as the sides of the channel adjacent to a berseem field. Then the sides of the channel in several places overtopped and water flowed into the ditch at the side of the road. The farmer spent considerable time repairing the major spills but some of the minor spills were ignored. The lack of increase in flow at flume #2 was definitely related to inadequate hydraulic capacity of the channel and spillage of the water from the channel. This spillage nearly equals the seepage loss for the earlier period.

About 0800 a farmer was observed to construct a nakka at point "A" in Figure 1 and divert about one cusec of water for irrigation of several fields. The water diverted must have had the sanction of the farmer who legally had the turn since during this time he patrolled the channel

several times and at no time was the water stopped. Instead, the farmer who borrowed the water went up the watercourse to the tubewell and stopped all the leaks he could find. Several leaks were stopped that we had noted on the previous day. The improvement in flow after 0800 at flume #1 is related to these reductions in spills that the farmer made. Nearly half of the water borrowed through the nakka at point "A" was added back to the watercourse by the elimination of small spills from the watercourse upstream from point "A".

Around 1100 as indicated by the flow at flume #2, two other farmers borrowed water above flume #2 to water fields. This is reflected by a further reduction in flow at flume #2. While the authors asked several persons why so much water was being borrowed, one farmer stated that the farmer who owned the irrigation turn (at about 1300) had gone on leave because of a death in the family. Consequently it is concluded that the decrease in flow after 1100 caused by additional borrowed use is not normal, but is the result of an unusual circumstance.

The apparent approval of borrowing of water at point "A" all of the morning was a normal kind of borrowed use. If the wide scale borrowing that occurred most of the 7th, 8th and 9th and evidenced by the reduced discharge of flume #1 in Figures 3 and 4 is common, then borrowed use is an important part of water use in the operation of a watercourse. With 5 cusecs available at TW 122 and a relatively low demand for water because of the end of the wheat season and just the beginning of sugarcane, cotton, and fodder, water demands are not great and farmers seem to know, even if the Irrigation Department does not, that a "pucca warabandi" does not result in effective use of water. By their unofficial agreements these farmers are approaching a "water on demand" type of distribution.

The total discharge through flume #1 was 72 acre feet and through flume #2 was 48 acre feet. For 16 hours, of the water that reached flume #1 one third was lost in the 1680 feet before reaching flume #2. Approximately half of this loss was estimated as seepage and the remainder was spills and borrowed or stolen use of the water. At a point 930 feet from the tubewell and mogha 10 acre feet of 82 acre feet was lost, substantially as borrowed use, which represents 12 percent of the flow.

Total flow in 2600 feet of a watercourse due to seepage, spills, and borrowed or stolen use was approximately 40 percent of the flow at the tubewell and mogha. Losses are important. Seepage and spills represent losses to farmers in Pakistan. Borrowed and stolen use are an important means of water distribution on TW 122.

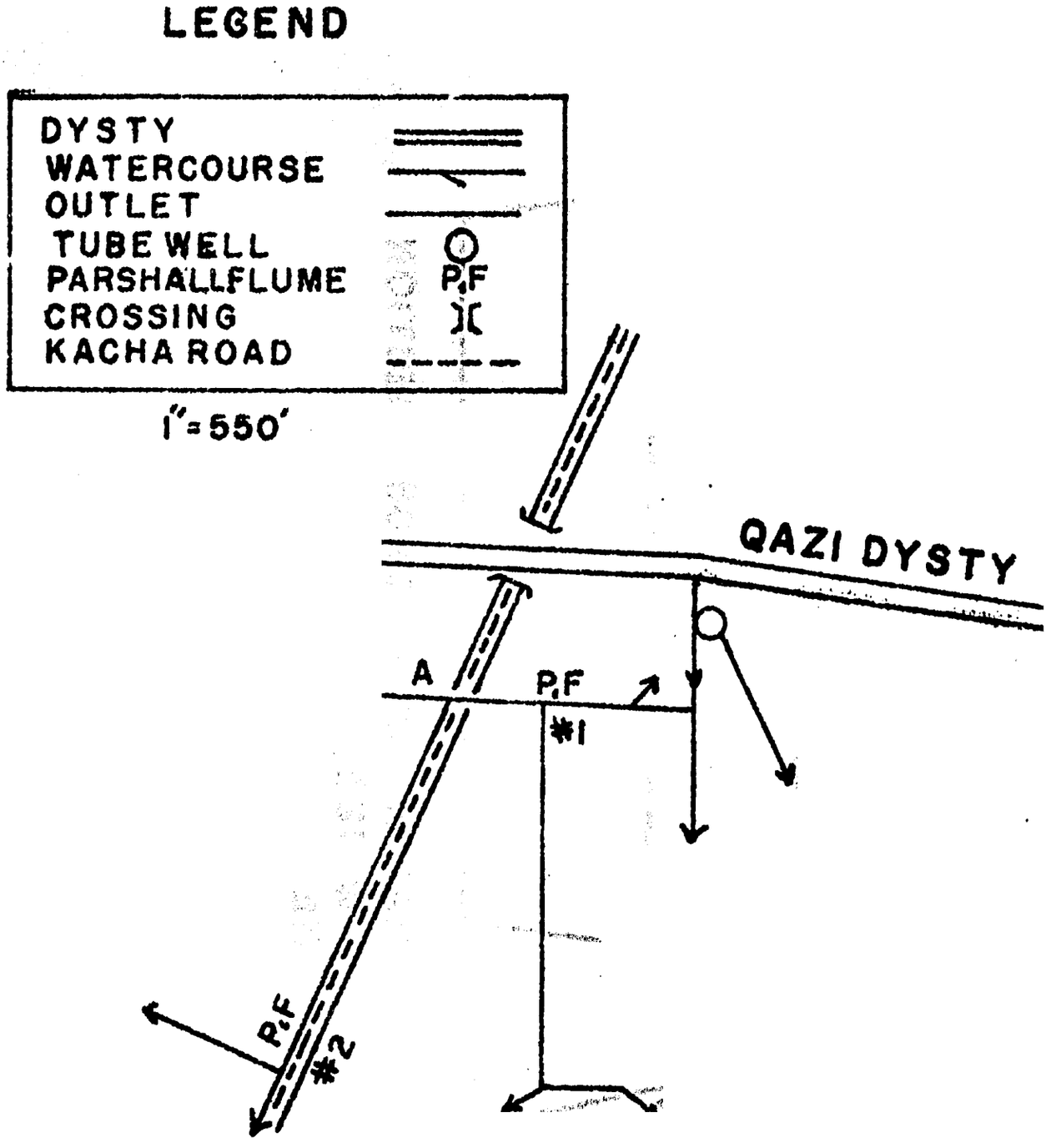


Fig. 1. Location map for Parshall flumes #1 and #2 at TW 122.

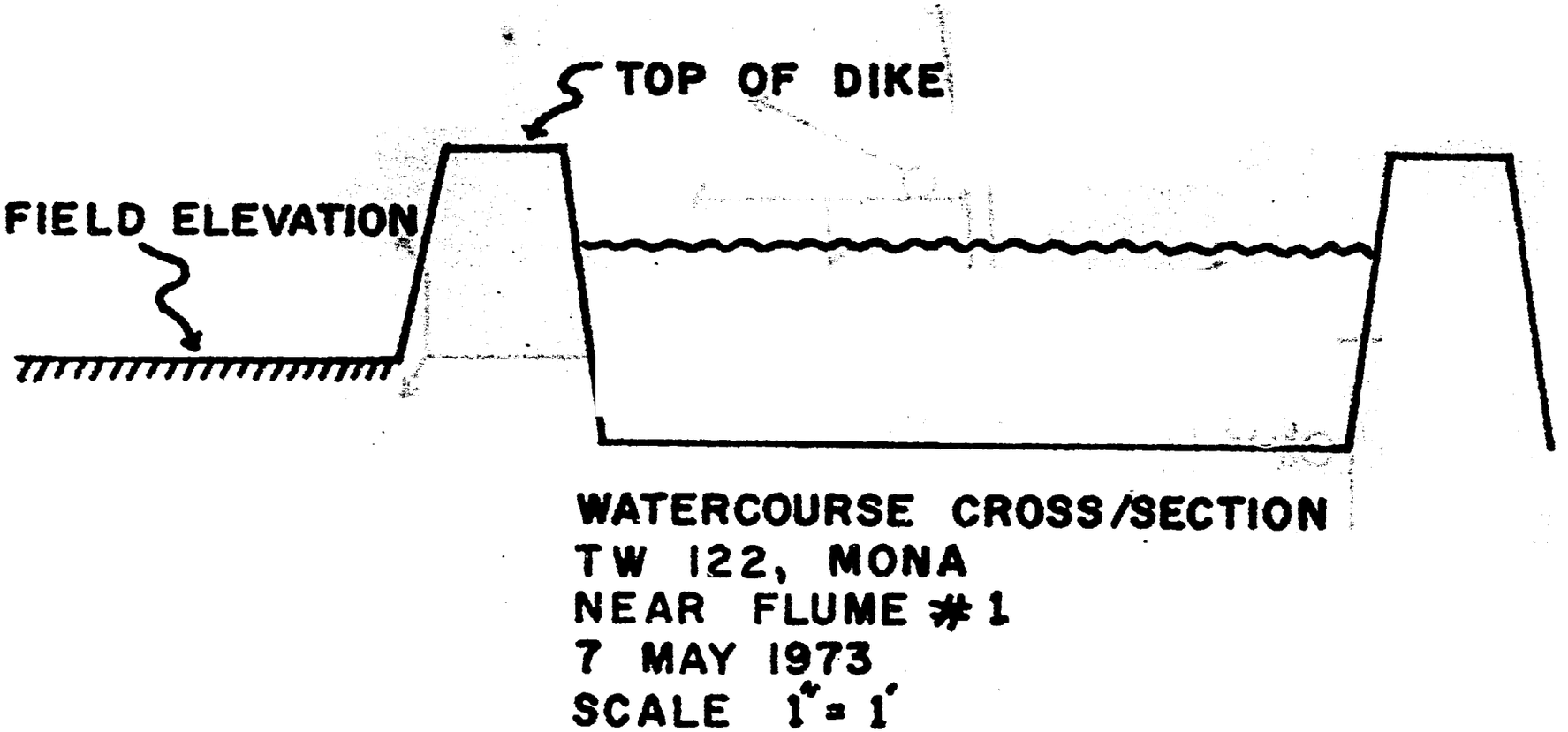
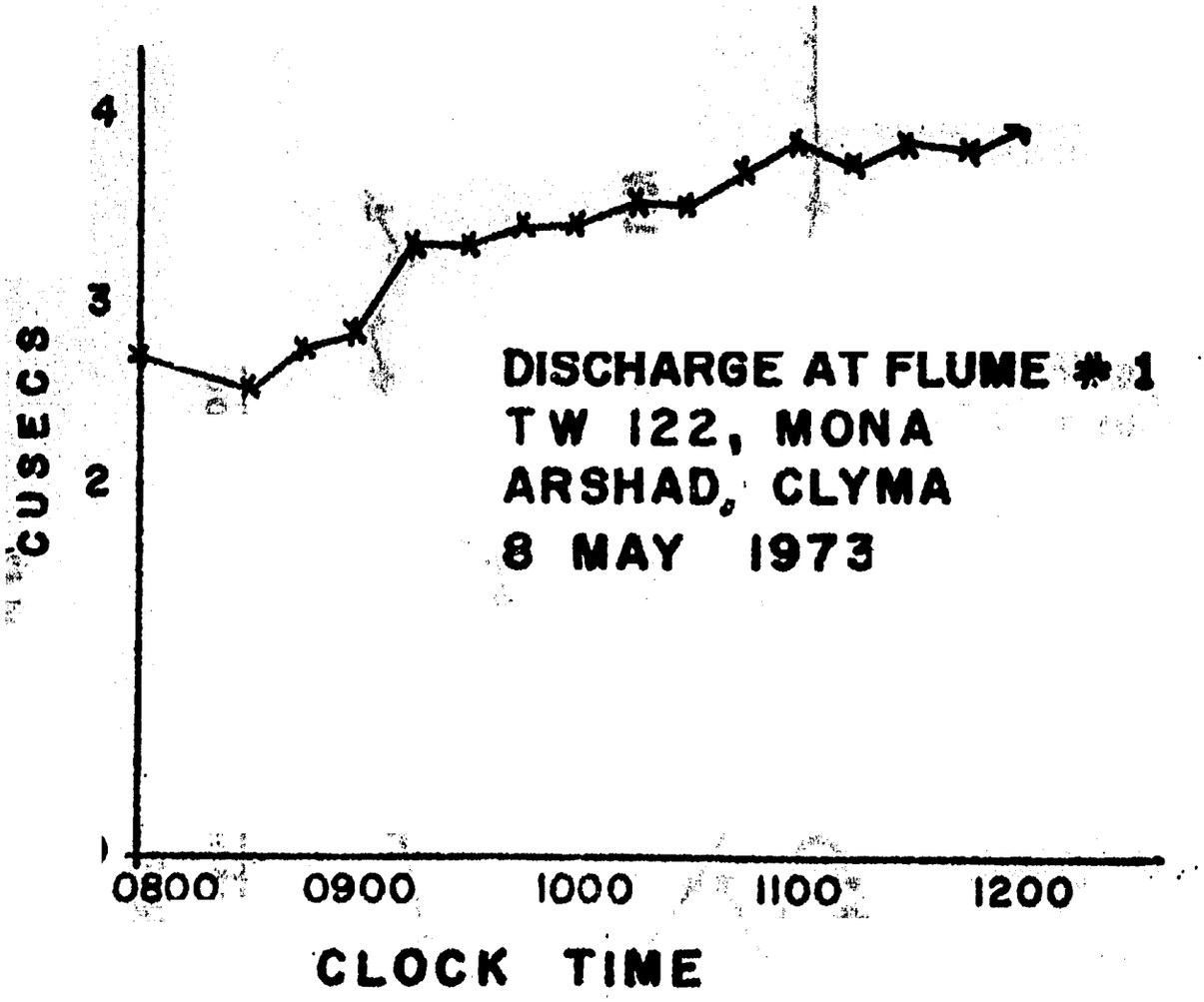


Fig. 2. Watercourse cross section and most frequent water level for TW 122.


DISCHARGE AT FLUME # 1
TW 122, MONA
ARSHAD, CLYMA
8 MAY 1973
CUSECS
4
3
2
1
0800
0900
1000
1100
1200
CLOCK TIME

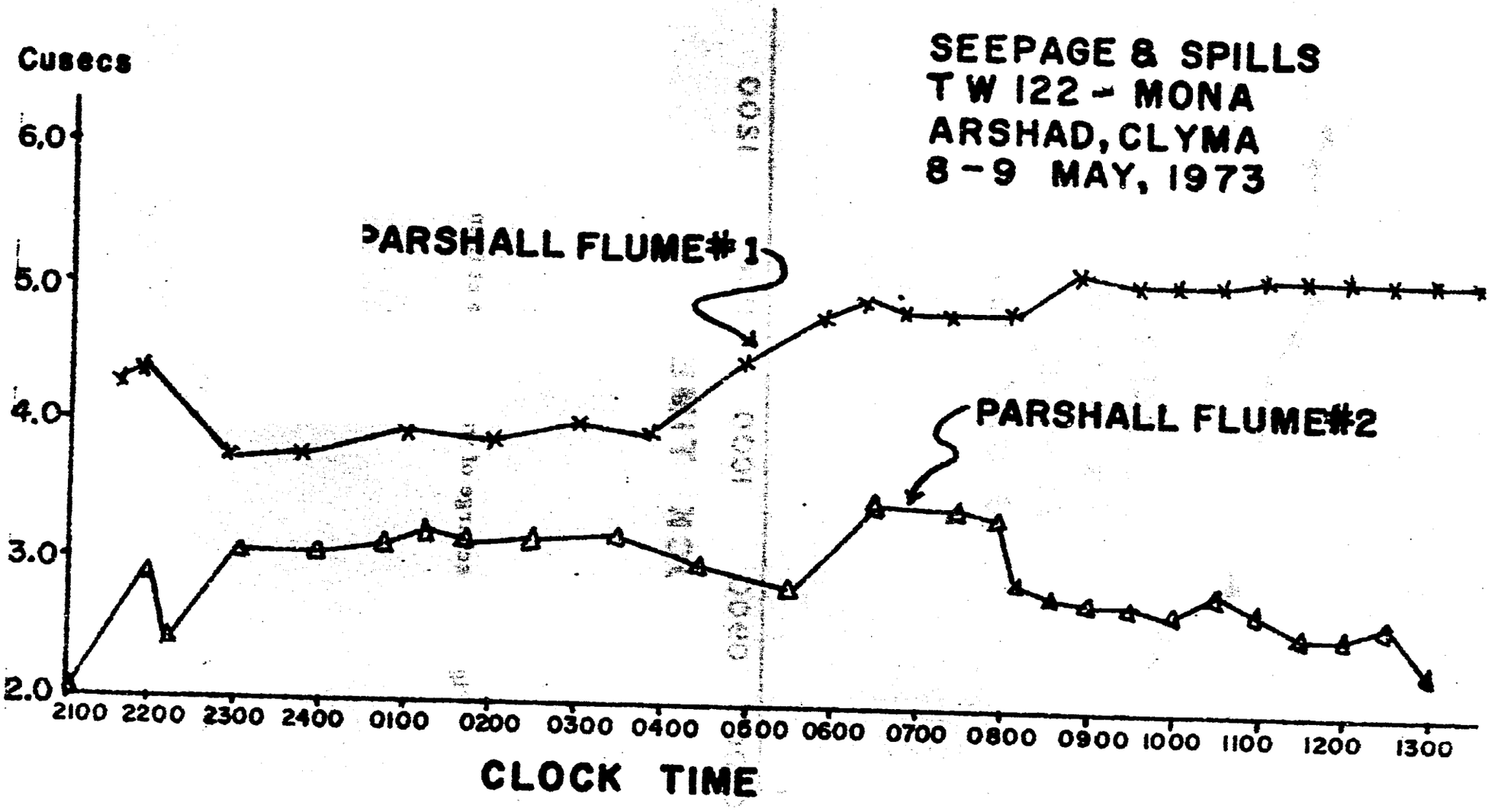


Fig. 4. Discharges of watercourse at flumes #1 and #2.

Irrigation Method as a Determinant of Pore Space and Crust Strength of Cultivated Soils*

W. D. Kemper, John S. Olsen and Alan Hodgdon**

I. Introduction

Adequate supply of oxygen to the root system of most crops is dependent on maintaining gas phase continuity from the atmosphere, or the air in the soil below the root zone, to the vicinity of the roots. Most plants can survive short periods of oxygen deficiency but will be damaged if this period is prolonged. The presence of water in the soil pores is the primary cause of blocked gas phase continuity. However the time for which water fills enough of these pores to block this continuity is decreased if there is an abundance of large pores which are drained at low tension. Adequate amounts of this large size pore space are particularly important in poorly drained soils where the capillary suction is normally low.

Following plowing, and other cultivation, a major portion of the cultivated layer is composed of large pores between the disoriented clods and aggregates. This loose matrix is consolidated by the first wetting and drying cycle in which the wetting tends to weaken the clods and aggregates, and allows gravitational and surface tension forces to squash them into more intimate contact. Drying stabilizes this new configuration. The degree to which the aggregates and clods break down completely, leaving the soil as a monograin structureless mass, is determined by bonding with the aggregates and by the manner in which the soil is wet (Kemper and Koch, 1966). Rate of wetting has been observed (Keller, 1967, and Ghavami, 1966) to have a marked effect on the persistence of large size pores.

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**Professor of Agricultural Engineering and of Agronomy, and Research Technicians, respectively, at Colorado State University.

Breakdown of the aggregates and pores into a structureless mass with few large size pores, when followed by drying, generally results in a strong hard soil which can restrict seedling emergence or root extension. The restrictive roles of crusts are discussed in detail by Carey et al.(1974) and of dense soils by Taylor et al.(1971), and appear to be a major factor limiting crop production on weakly structured fine grained soils.

The purpose of this study is to determine the degree to which different wetting procedures, characteristic of common irrigation methods, can affect the amount of large pores and the dry strength of soils. This study is designed as a first step to identifying or developing irrigation methods which will optimize the pore size distribution and dry strength of soils for crop production.

II. Materials and Methods

A. Soils

The soils chosen for this study were Nunn clay loam with an organic matter content of about 2%, montmorillonitic clay and a stable structure and Billings silt loam with an organic matter content of about 1%, dominantly illitic clay and an exchangeable sodium content of about 5%. The Nunn is recognized as a soil with essentially no physical problems, while seedling emergence and generally dense structure are commonly a problem on the Billings soil. The problems associated with the Billings soil are similar to those of river laid soils in many of the river basins of the world. The soils used in this study were air dried and fragmented by forcing them through screen with 3 meshes per inch. Some of this soil was further separated into the portions retained, or passing through a 5 mesh sieve.

B. Measuring Amounts of Large Size Pores

These fragmented soil materials were placed in lucite cylinders similar to that shown in Fig. 1 and wetted by:

Capillarity (bringing the water level in the beaker up to the level of the blotting paper and maintaining it there for several hours while the soil became wet.)

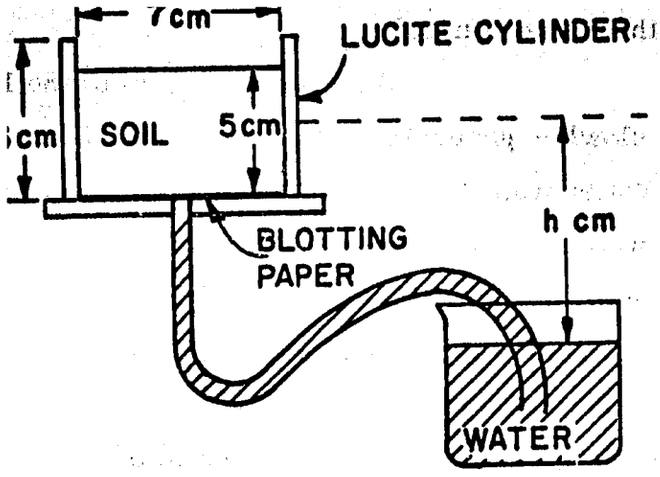

Fig. 1. Equipment for pore size determination

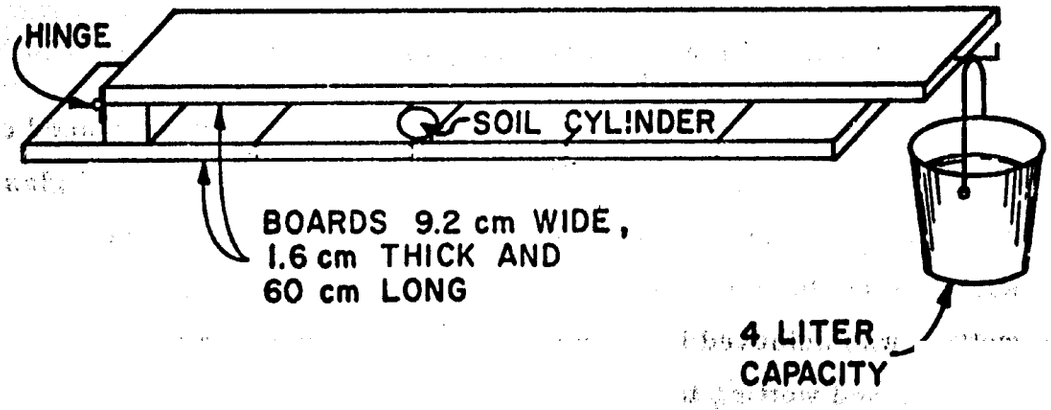

Fig. 2. Equipment for determining modulus of rupture.

Immersion (Bringing the water level in the beaker above the soil level and wetting the soil as rapidly as possible--generally wet in less than 10 seconds.)

Slow Immersion (Bringing the water level up to the level of the soil surface slowly--generally wet in less than 30 minutes.)

Flooding (Water was flooded over the soil surface until the soil was wet and water remained on the surface.)

When all of the soil wet by capillarity was visibly moist, the water level was raised to the surface. After an hour the water was removed from the beaker and the tube was placed so its open end touched the bottom of the beaker whose bottom was situated at the level of the bottom of the cylinder. This gave an average tension (h) on the soil of about 2.5 cm of water. The water drained at this tension was measured. The Erlenmeyer flask was lowered till its bottom was 10 cm below the midpoint of the soil (h = 10 cm), and when drainage had ceased the amount of water was measured again. This procedure was repeated with h = 20 cm.

C. Modulus of Rupture Determination

Cylinders 5 cm long and 3 cm in diameter were placed on top of absorbent tissue paper on a brass plate and about 2 mm of glass beads were placed in the bottom of the cylinder. The cylinder was then filled with fragmented soil and the assembly placed in a pan. Capillary wetting was achieved by pouring about 2 mm of water in the bottom of the pan, and wetting to the top of the cylinder generally occurred within three hours. "Immersion" wetting was accomplished by placing a set of samples on a brass plate in the pan and raising the water level to the tops of the cylinders as rapidly as possible. Wetting was usually complete within 5 seconds. The third treatment involved wetting the samples by capillarity and then raising the water level so they were immersed.

After wetting, all the samples were drained by removing them from the tray of water and were dried to equilibrium at 65°C. The dried soil cores were then removed from the lucite cylinders, using a thin flat piece of spring steel to loosen the soil from the lucite where necessary. These soil cylinders were then placed in the apparatus outlined in Fig. 2. Water was poured slowly into the bucket shown in Fig. 2 until the soil core ruptured. The weight of the water was then added to the weight of the bucket and half the weight of the top board and this total weight was multiplied by the appropriate lever ratio to obtain the force, F, required to rupture the cylinder. This procedure is essentially that used by Kirkham, et al. (1958). The force is related to the modulus of rupture (strength), S, of the sample by the equation

$$F = (\pi/2)\, SDL \qquad (1)$$

where D is the diameter of the sample and L is its length, that is

$$S = 2F/\pi DL \qquad (2)$$

If F is in kilograms and D and L in cm, then S is in kilograms/cm^2. Modulus of rupture is also expressed in bars. One bar = 1.023 kgm/cm^2.

Some of the soil cylinders, particularly those wet by capillarity, were extremely fragile and portions of them fell apart when the soil was removed from the lucite cylinder. In these cases the length L of the cylinder used in equation (2) was taken as the depth of the soil in the lucite cylinder, which gives the same "average modulus of rupture" as adding the force necessary to crush the intact portion of the cylinder to the zero force needed to destroy the uncohesive portion and dividing by the total length L.

III. Results and Discussion

A. Persistence of Large Size Pore Space

Slow, capillary wetting of the fragmented samples generally leaves most of the aggregates intact and a major portion of the volume is large size pore space.

The persistence of more large size pore space following capillary wetting than following rapid immersion is illustrated in Fig. 1. While the amount of pore space remaining in the strongly structured clay loam following capillary wetting was more than doubled compared to that following rapid immersion, the greatest differences due to wetting procedure were found in the weakly structured silt loam where the large size pore space was almost quadrupled. The vertical lines in the center of each bar represent the 95% confidence interval for the observed mean.

Flooding the soil from the top resulted in less large size pore space than wetting the soil rapidly from the bottom (immersion). Greater disintegration during flooding may be partially due to shearing force as the water runs over the surface. However the surface flooding also gets water into the main body of the soil faster than the rapid immersion procedure. Generally, as the rate of wetting increased, disintegration of the aggregates was more complete, and smaller amounts of large size pore space persisted.

There are several mechanisms by which rapid wetting may weaken and destroy aggregates. Air entrapped within aggregates during rapid immersion is compressed by capillary forces pulling water into the aggregate until its pressure becomes high enough to rupture the water weakened aggregate. The dramatic effects of such action are readily observed by dropping a dry aggregate of weakly structured soil into a beaker of water and watching the destruction of a major part of the aggregate as the air bubble escapes. However, even when no air bubbles are entrapped (e.g. slow immersion such as SI in Fig. 3) considerable loss of large size pore space occurs, compared to the slower capillary wetting. The surface tension of water and slight tension in the water probably helps hold weakly structured aggregates together when the sample is wet under a slight capillary suction. On the other hand our measurements of pore size

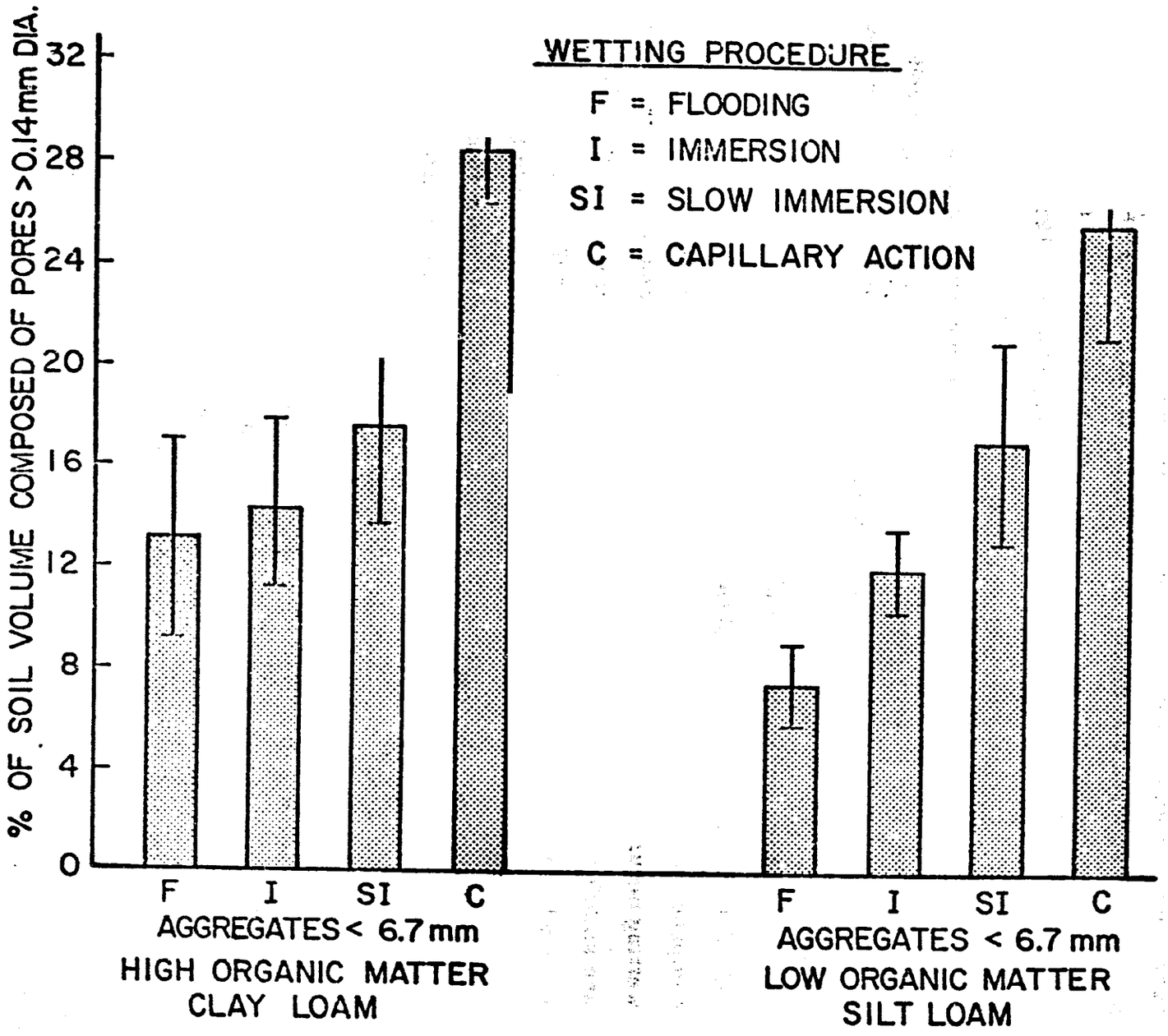

Figure 3. Persistence of large size pores as affected by wetting procedure.

distribution involved bringing the water table to the surface of all the samples for a few hours to saturate the whole sample prior to measuring the drainage at given suctions. During this period of saturation little observable breakdown occur in the samples wet initially by capillarity. Consequently it appears that rapid rate of wetting is the primary cause of aggregate disintegration and destruction of the large size pore space. This conclusion is also in accord with the observations of Keller (1967) who wet columns with controlled sprinkling rates.

During rapid wetting the gradient of water content across aggregates at the wetting front is very steep, often dry on one side of an aggregate and near saturation on the other. Since the aggregates of most soils swell as they become wet, such steep water content gradients generally cause marked expansion of the wet portion of the aggregates with respect to the dry portion. This drastic dislocation of aggregate components from their neighboring components apparently breaks bonds and weakens the aggregates. When wetting occurs more slowly the water content gradients and swelling gradients are smaller, shear stresses at right angles to the direction of wetting are reduced and the aggregates remain considerably more stable.

Amount of large size pores persisting after wetting should bear some relation to the amount of large size pores in the soil prior to wetting. To gain an estimate of such effects, some of the soil passing through a 3 mesh sieve ($<$ 6.7 mm diameter aggregates) was used directly, while all the aggregates smaller than 3.9 mm were removed from another portion. The loose bulk densities and pore space of these soils prior to wetting are shown in Table 1. There were obviously many more large pores in the "soils" from which the small aggregates had been removed (Fig. 4). The percent of the soil volume consisting of large size ($>$ 0.29 mm diameter) pores after wetting by flooding and by capillarity is shown in Fig. 4. In every case the soils with the most large pores prior to wetting (3.9 $<$ aggregates $<$ 6.7 mm) also had the most large pores following wetting.

These data indicate that cultivation practices designed to leave a loose, coarse soil will generally provide more persistent large size pore

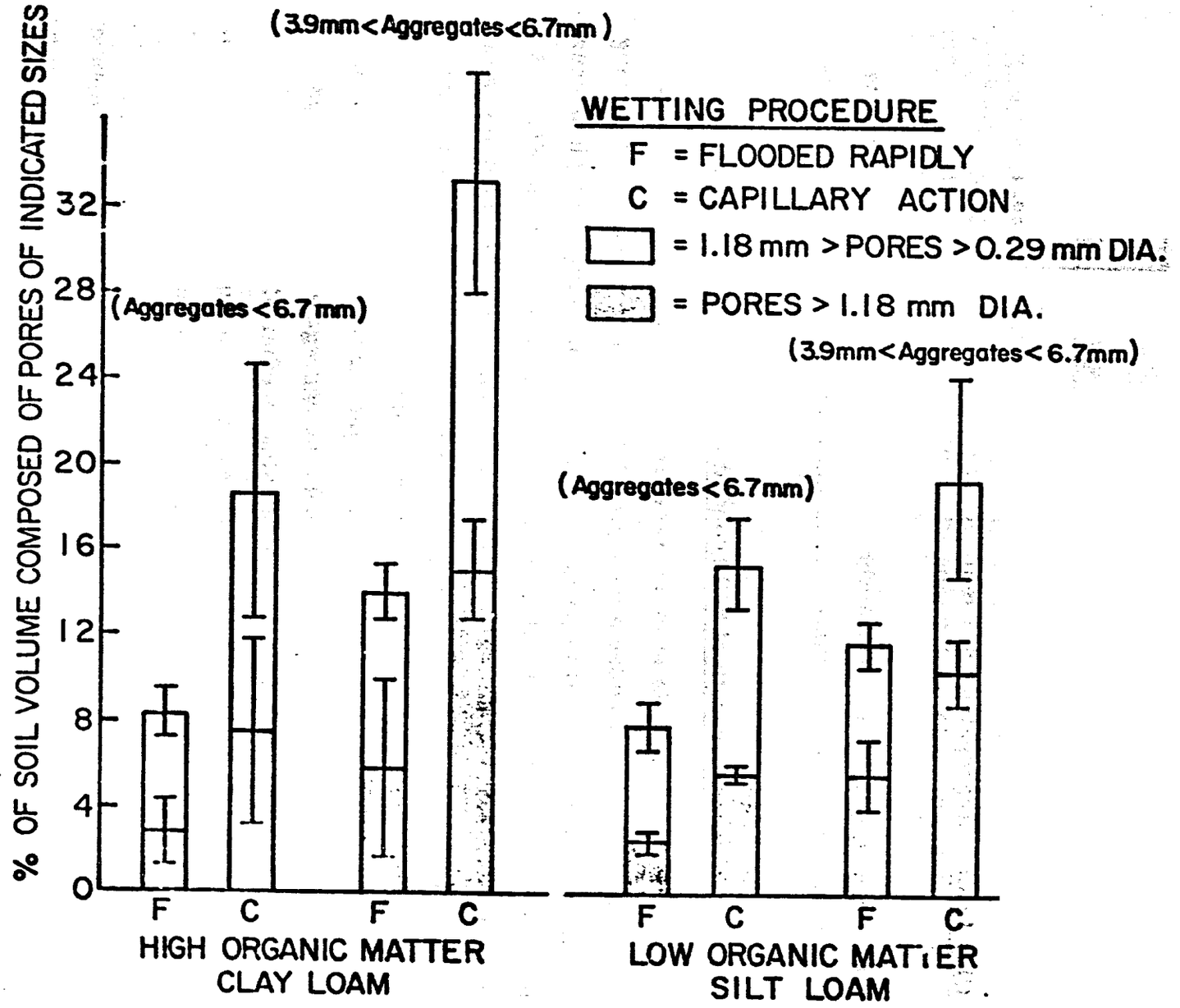

Figure 4. Effect of aggregate size range on amount of large pores in soils wet by flooding or by capillary action.

Table 1. Bulk Densities and Porosities of Loose Soil Prior to Wetting As Affected by Range of Aggregate Size.

		Bulk density (gm/cc)	% Solid	% Pores
Silt Loam	Aggregates < 6.7 mm	1.04	39.2	60.8
	3.9 mm < Agg. < 6.7 mm	.91	34.3	65.7
Clay Loam	Aggregates < 6.7 mm	1.13	42.6	57.4
	3.9 mm < Agg. < 6.7 mm	.90	33.9	66.1

space than cultivation practices which grind the soil to smaller fragments, when followed by flooding (fast), furrow (slower) or trickle (slowest) types of irrigation.

B. Breaking Strength of Soil Dried at 60°C Following Wetting

This characteristic is inversely related to seedling emergence. The procedure also provides a measure of the effect of immersion following capillary wetting, since it is possible to make the breaking strength measurement with or without saturating the sample. It is apparent from Figs. 5 and 6 that immersion, following wetting, increases the subsequent dry state modulas of rupture of these cylinders. These measurements indicate that while most of the large size pore space does appear to persist during immersion following capillary wetting, absence of the air water interface and surface tension of water, which tends to hold the aggregates together, does allow considerable disintegration or melding together of the aggregates. These data illustrate that capillary wetting, avoiding subsequent immersion, is the preferred wetting method if maintaining low moduli of rupture and large amounts of pore space are desired objectives.

Careful capillary wetting was able to reduce the modulus of rupture of the low organic matter silt loam to values lower than those found following immersion in the high organic matter clay loam when the initial soil materials consisted of 3.9 < aggregates < 6.7 mm (Fig. 6). However, when the soil material consisted of all the aggregates < 6.7 mm, the modulus of rupture of the silt loam soil wet by capillarity was greater while

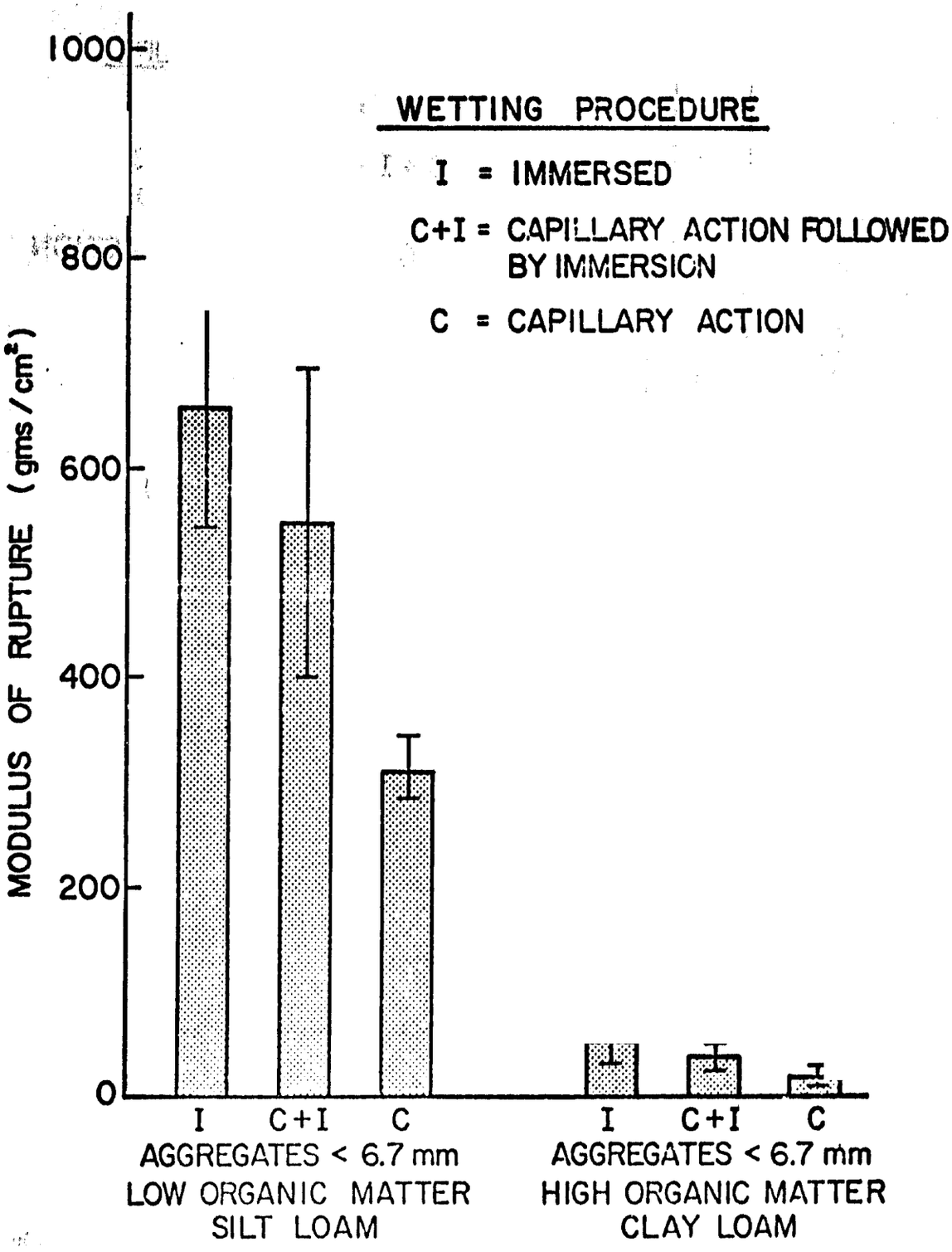

Figure 5. Strength of dried soils as affected by method of wetting prior to drying.

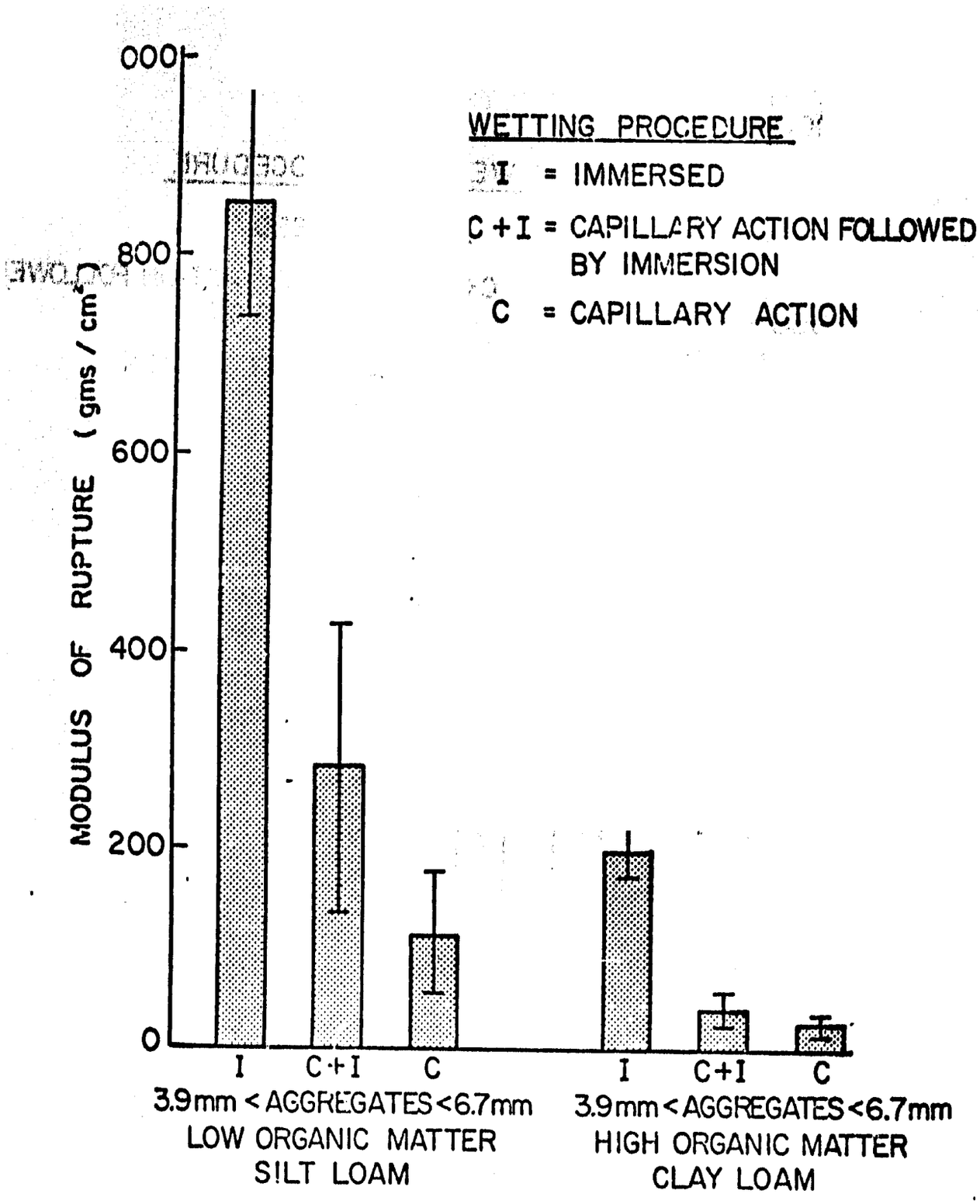

Figure 6. Strength of dried soils as affected by prior wetting method when aggregates < 3.9 mm are removed prior to wetting.

that of the clay loam wet by immersion had decreased. The increased modulus of rupture of the silt loam wet by capillarity is apparently due to the soil being denser (see Table 1) and greater opportunities for aggregate to aggregate contacts and bonding. The observed reduction in modulus of rupture of both soils when immersed is probably an artifact of the wetting procedure. Immersion consisted of letting water in at the bottom of the soil filled cylinders at a head approximately equal to the top of the soil. It was observed that the 3.9 < aggregates < 6.7 mm were wet within 5 seconds and air was occasionally trapped within individual aggregates, while in the aggregates < 6.7 mm the water entered more slowly, taking 10 to 25 seconds to wet all the soil and seldom if ever entrapping air within aggregates.

C. Corn Seedling Emergence

To gain an estimate of whether these different moduli of rupture achievable by different methods of wetting in the silt loam soil (aggregates < 6.7 mm) spanned a practically important range as far as seedling emergence is concerned, 9 corn seeds were planted at depths from 2 to 4 inches on ridges next to the furrow from which the ridge was wetted by capillarity. Fifteen corn seeds were planted at a depth of about 2 inches on a flat surface which was wetted by flooding with 2 or 3 inches of water. This study was duplicated, and in each case all the seedlings planted in the ridges wet by capillarity emerged while only about 50% of the seedlings wet by flooding emerged. Most of the flooded seedlings which emerged were planted near the edges of the lysimeter where the soil cracked, allowing the seedling to emerge through these cracks. In the field it is unlikely that the coincidence of seed placement and cracking would be this high unless special methods were developed to achieve cracking over the seed row. Such possibilities should be investigated for problem soils where flood irrigation is the most commonly used method of irrigation, since 70 to 80% of seedlings planted within an inch (horizontally) of where a crack developed emerged. Less than 10% of the seedlings emerged when they were positioned at greater distance from these cracks.

This preliminary study on seedling emergence does point out that capillary wetting of a weakly structured soil of this type can avoid the formation of crusts which are strong enough to prevent seedling emergence.

IV. Conclusions

The method by which a soil is wetted following cultivation is a major determinant of the amount of large size pores which persist in a soil. This is particularly true of weakly structured soils. Slow wetting increases the proportion of the large aggregates and pores which persist as a soil is wet. Apparently slow wetting reduces the gradient of the water content, which reduces the gradient in swelling induced displacements which are a primary factor in causing shear stresses in aggregates at right angles to the direction of wetting.

Strength of a poorly structured soil, dried following wetting, can be kept at levels which allow seedling emergence if the fragmented soil is wet by capillarity. Saturation of the soil, even when this occurs after capillary wetting, markedly increases the subsequent dry soil modul of rupture. Apparently this increase is due to greater slump and disintegration of the aggregates as air-water interfaces and surface tension holding the aggregates together are eliminated as the pores are completely filled with water.

The texture of a soil, its mineral content and its organic matter content all influence its aggregate stability, persistence of large size pores and crusting. However, these data indicate that adequate large size pores and sufficiently low crusting strength for seedling emergence and crop growth can be maintained in at least some soils with low inherent aggregate stability if the soils are wet slowly by capillarity.

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Appendix D
D-1

Dissolution Rate of Gypsum in Flowing Water*

W. D. Kemper, John Olson and C. J. deMooy**

I. Introduction

The infiltration rates of soils become much smaller if the normally dominant Ca^{++} on the surfaces of the soil particles is replaced to an appreciable extent by Na^{+}. Consequently when reasonably rapid rates of infiltration are essential and the incoming waters contain Na^{+} as the dominant cation, addition of extra Ca^{++} to the soil is often necessary to maintain reasonable infiltration rates and satisfactory soil structure. One of the least expensive sources of Ca^{++} is gypsum (i.e. $CaSO_4 \cdot 2H_2O$). This mineral is commonly applied in a powdered form to soils to help restore their Ca^{++} saturation and improve their structure and infiltration rates. In many areas of the world the cost of powdering and spreading the gypsum is a major portion (e.g. 50%) of the total applied cost, whereas breaking the gypsum into fragments one or two inches in diameter by hand labor is relatively inexpensive.

This study was designed to determine the effects of fragment size, solution velocity and salt content of the solution on the rate of gypsum dissolution as this solution percolates through beds of gypsum fragments. These data will indicate the feasibility of hydraulic dissolution and distribution of gypsum.

II. Materials, Methods and Equations

Gypsum was obtained from commercial deposits in Colorado and Pakistan. When powdered and mixed with water, both samples gave equilibrium saturation solutions whose electrical conductance at 23°C was about 2.2 mmhos/cm, indicating that neither sample contained appreciable amounts of other soluble salts.

Mineral gypsum was fragmented and sieved through standard screens to obtain fragments 25 to 40 mm in diameter, 12 to 25 mm in diameter and 2 to 6 mm in diameter. The 2 to 6 mm fragments were placed in a lucite

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**Professor of Agricultural Engineering and of Agronomy, Research Technician, and Professor of Agronomy, Colorado State University.

Figure 1. Tubes for gypsum dissolution studies.

tube 142 cm long and 3.2 cm inside diameter. Ports made of 3 mm ID lucite tubing were constructed at the center and near the ends of the large lucite tube as indicated in Fig. 1 to facilitate taking solution samples and measuring hydraulic head while solution was flowing through the large tube.

Fragments 12 to 25 mm in diameter were placed in a lucite tube 142 cm long and 6.4 cm in diameter. Fragments 25 to 40 mm in diameter were placed in a tube 150 cm long and 10 cm in diameter. In each case ports, as indicated in Fig. 1, were constructed for taking solution samples and measuring hydraulic head.

Tap water with an electrical conductivity of about 0.07 mmhos/cm, or solutions of known concentration, were percolated through these gypsum fragments at various velocities. Concentration of solution coming out of the outflow end was estimated from the electrical conductivity of the solution. The study was conducted in a room maintained at $23^{\pm o}$. Where feasible, the top water was supplied from 4 liter jugs fitted as mariotte siphons which had previously been filled with water and brought to room temperature. The elevation of the air inlet into the jug with respect to the elevation of the outflow was adjusted to obtain the indicated flow rates. In the larger tubes at the high rates of water flow, hot and cold water were mixed in an effort to keep the water temperature near 23°. While the average was kept near 23°, the fluctuations were as much as 5°. All solution samples were brought to room temperature for the conductivity determinations. The tubes delivering the water to the gypsum filled tubes were less than 1/5 the diameter of the gypsum filled tube. Consequently the water often jets into the large tube at a high velocity--which might cause mechanical abrasion of the gypsum. To ascertain whether this was a major factor affecting the rate of dissolution, about 30 cm on the inflow side of the large tube was filled with gravel to dissipate the jet energy before the water came to the gypsum. Any changes in rate of dissolution as a result of eliminating this localized jet force were so small as to be negligible.

Some gypsum powder was adsorbed on the fragments. This powder was dissolved by running water through the gypsum fragments at a constant rate until there was no observable powder left and the resistance of the outflowing

solution was constant with time. Since the gypsum was dissolving, it was occasionally necessary to add gypsum to keep the cylinder full. This fresh gypsum was added at the inflow end where any powder dissolved quickly.

During the runs to determine dissolution rate, at least two pore volumes of water were passed through the gypsum at a constant rate prior to taking samples. Maintaining the same flow rate, from 3 to 5 samples of outflowing solution were taken as the next 3 or 4 pore volumes passed through. Heights of water in manometers attached to the small tubes indicated in Fig. 1 were used to measure the head loss.

To determine the fragment characteristics shown in Table 1 volumetric cylinders with about the same diameters as the lucite cylinders were filled to the 100 cc level with gypsum fragments of the indicated diameters. The weight of these fragments was determined, their number was counted, and their average weight calculated. Assuming that these fragments were cubicle and that their density is 2.32 gm/cc, the indicated surface areas were estimated. The fragments tended to have two dimensions larger than the third, and measurement of the sum of the surface areas on all faces of 3 representative fragments indicated that assuming cubicle shape causes about 15% under estimate of surface area.

To evaluate the effect of salts in the water on the dissolution rates of the gypsum and to evaluate equations designed to describe these dissolution rates, solutions containing various initial gypsum, $CaCl_2 \cdot 2H_2O$ or $Na_2SO_4 \cdot 10H_2O$ concentrations were passed through these gypsum beds. Their electrical conductivity, before and after passing through the beds,

Table 1. Characteristics of Gypsum Fragments Used in this Study.

Pore space	Diameter	Average weight of fragments	Estimated average surface area/fragment	Fragments/ 100 cc of bed volume	Estimated surface area of gypsum/cc of bed volume
	(mm)	(grams)	(cm^2)		(cm^2/cm^3)
54%	2- 6	0.137	.9	785	7.1
58%	12-25	3.7	7.9	26	2.1
60%	25-40	13.0	14.0	7	1.0

was determined and compared to the conductivity of tap water before and after passing through the bed at the same velocity.

The net rate, dc/dt, at which gypsum comes into a volume of solution passing through the bed should be some function of the difference between the solution concentration c_s at saturation and the solution concentration, c, at that particular time. Assuming this relation to be proportional,

$$dc/dt = K(c_s - c), \tag{1}$$

where K (the dissolution coefficient) will be a function of fragment size and solution flow velocity. The assumption that rate of dissolution is proportional to $(c_s - c)$ may be tested by keeping fragment size and flow velocity constant, varying $c_s - c$ and measuring dc/dt. Experimentally this is simpler to check using integrated forms of equation (1). Separating the variables of equation (1) in preparation for integration yields

$$\int dc/(c_s - c) = K\int dt \tag{2}$$

Integrating this equation between time t = 0 when the increment of solution of concentration c_o enters the bed of fragments to the time $t = t_b$ when it leaves the bed of fragments at concentration c_b yields

$$\log \frac{c_s - c_b}{c_s - c_o} = Kt_b \tag{3}$$

$$c_s - c_b = (c_s - c_o)\, e^{-Kt_b} \tag{4}$$

$$c_b = c_s - (c_s - c_o)\, e^{-Kt_b} \tag{5}$$

Gypsum solutions of various initial concentrations, c_o, were passed through a bed of gypsum 20 cm long with fragment diameters 2 to 6 mm, concentrations of emerging and entering solutions (c_b and c_o respectively) were estimated conductometrically and used in equation (3) to determine values of K. The flow velocity was maintained at 0.3 $cm^3/cm^2/sec$ during this time. The porosity of the gypsum bed was 54% and the solution took 34 seconds (i.e. t_b = 34) to pass through the 20 cm bed.

III. Results and Discussion

A. Dissolution Rate Proportional to Saturation Deficit

Checking the assumption of a proportional relation between dissolution rate and the difference in concentration of the solution and a saturated solution (i.e. equation (1)) equation (3) was used to calculate K using the initial gypsum concentrations and measuring the emerging gypsum concentrations indicated in Table 2.

The constancy of K through this range of initial solution concentrations indicates that the rate of dissolution is proportional to the "unsaturation" (c_s-c) of the solution when particle size and solution velocity are constant.

Table 2. Values of K calculated at constant flow rate and fragment size as initial concentration, c_o, was varied.

c_o*	c_t*	K
0.08	1.36	0.028
0.75	1.67	0.029
1.20	1.83	0.028

* All concentrations are expressed in terms of mmhos/cm (i.e. electrical conductivity).

B. Dissolution Coefficient as Affected by Fragment Size and Surface Area and Solution Velocity

The amount of gypsum dissolved by the water as it passed through the 120 to 140 cm beds at the indicated flow rates is shown in Fig. 2. These data show that plenty of gypsum can be dissolved in the irrigation water to distribute it hydraulically to the field. For instance, saturated gypsum solution contains 2300 ppm $CaSO_4 \cdot 2H_2O$ or 230 kgm/hectare cm of water. Assuming applications of 50 cm of irrigation water per crop, it is apparent that a couple of tons of gypsum per hectare per cropping season could be applied, even at the lowest rates of gypsum dissolution observed.

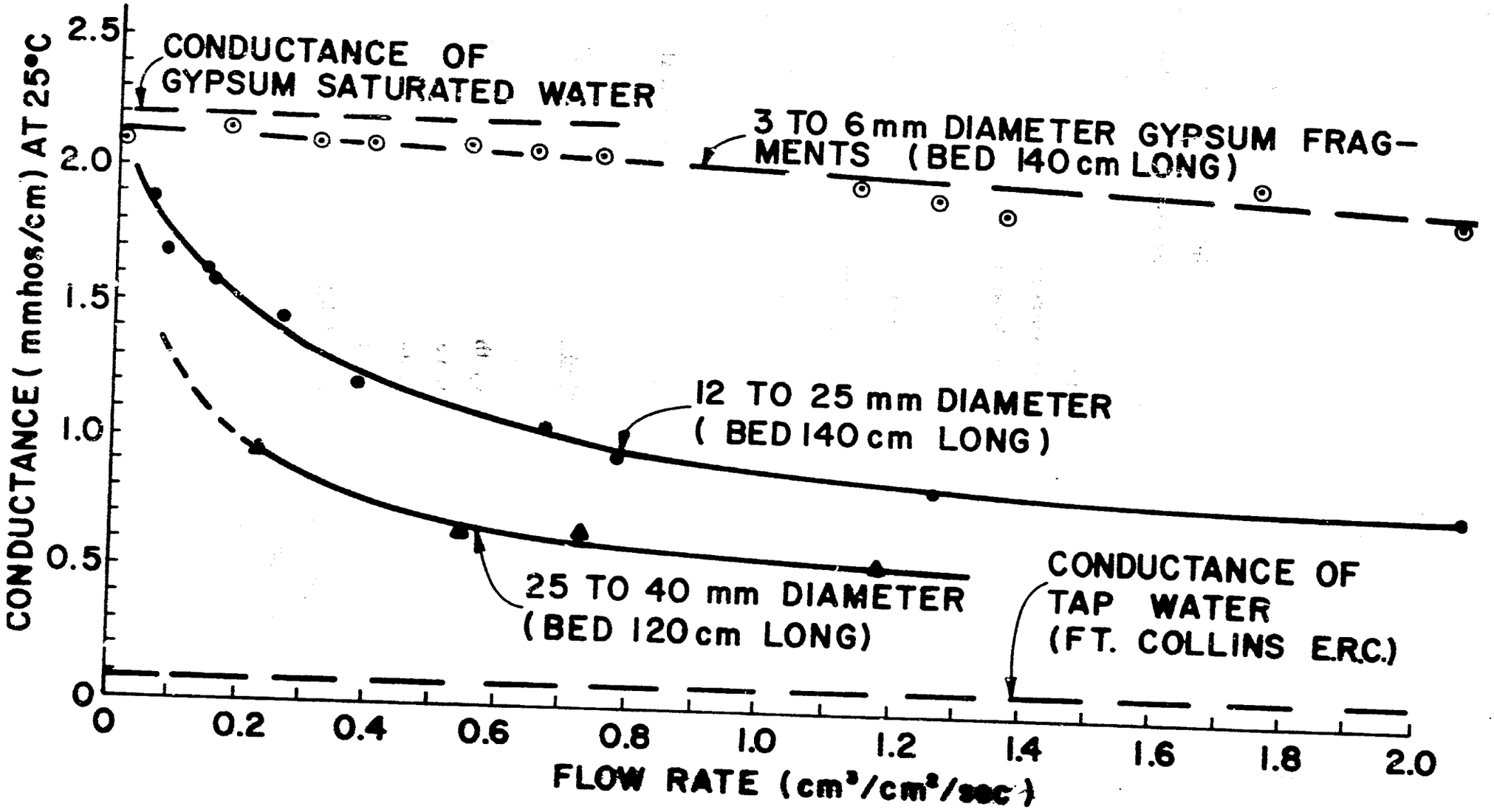

Figure 2. Concentration of gypsum in water that has passed through a bed (of the indicated length) of gypsum fragments of the indicated sizes as a function of the flow rate at which the water goes through the bed.

If the amount of gypsum dissolved was directly related to the time the water spent in the bed, a directly inverse relation would exist between concentration (conductance in Fig. 2) and flow rate. The manner in which the two bottom curves tend to flatten out at the right side of Fig. 2, indicates that although increasing velocity decreases the time (t_b) for which water is in the bed, it must increase some other factor which accelerates dissolutions.

Using equation (3) to compute the dissolution coefficient K at various flow rates from the curves in Fig. 2 yields the curves drawn in Fig. 3. The dissolution coefficient increases rapidly as the solution flow rate increases. This is partially due to the fact that Ca^{++} and SO_4^{--} ions in the vicinity of the particle surface are swept away more rapidly when solution is moving faster, which gives them less opportunity to adsorb to charges on the solid surface. In addition to the more rapid laminar movement of water along the mineral surfaces, currents flowing toward and away from the mineral surfaces begin to occur in this range of flow rates. Table 3 shows the flow rates at which ($N_R = 10$) inertial forces become significant compared to viscous forces and the range ($100 < N_R < 500$) through which visually apparent turbulent flow generally develops. Since the range of flow rates shown in Fig. 3 includes this range in which turbulent eddy currents at right angles to the mineral surfaces are becoming important, it is likely that the increases noted in the dissolution coefficient as flow rate increases are at least partially a result of the developing turbulence.

Table 3. Flow Rates in the Gypsum Beds at the Indicated Reynolds Numbers

Fragment diameter	$N_R = 10$	$N_R = 100$	$N_R = 500$
2- 6 mm	0.135	1.35	6.75
12-25 mm	0.032	0.32	1.60
25-40 mm	0.018	0.18	0.90

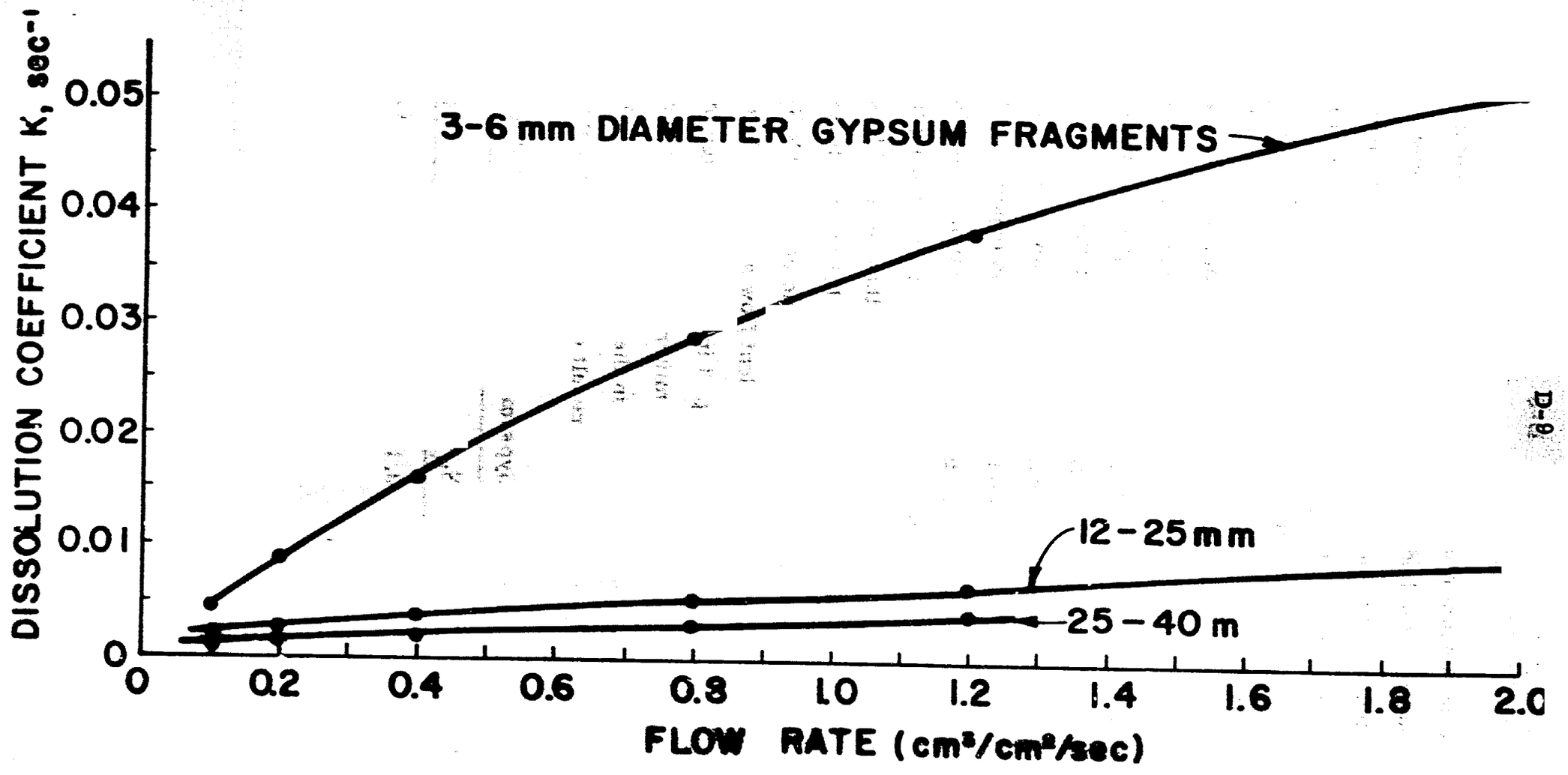

Figure 3. Dissolution coefficients (K) related to solution flow rate.

The effect of fragment size on the dissolution coefficient is shown in Fig. 4 at several flow velocities.

Since dissolution is a surface phenomena linked to solution flow rates, we suspected that at a given flow rate K might be proportional to the surface area of gypsum in the bed. The procedure described in the methods section was used to estimate the surface area of the fragments/cc of bed as given in Table 1. These surface areas are plotted against the dissolution coefficient at several flow rates in Fig. 5. In general, the dissolution coefficient increases more rapidly than the surface area at a given flow rate as the fragments become smaller. The shear forces of the fluid on the solid surfaces become greater as the fragments and pores become smaller at a given flow rate, but the energy of these forces on any given ion are still very small compared to the average force of thermal motion bombardment in terms of dislodging Ca^{++} or SO_4^{--} ions from the solid surface. Consequently the increase in K associated with larger shear stress in the smaller pores at a given flow rate must be due to more rapid movement of ions away from the surface after they have been dislodged.

Hydraulic head was measured in manometers attached to the ports indicated in Fig. 1. The average head loss through 100 cm of the beds of fragments are shown in Fig. 6 as a function of flow rate. Had all the flow been laminar Darcy type, these curves would have been straight lines. Some of the curvature is probably due to the initiation of turbulent flow as the flow rates increased. However, when head losses were appreciable the head loss across the half of the bed on the inflow side was smaller than on the outflow side. This difference was as great as a factor of 2 at the largest head losses and indicated compression of the gypsum into a denser bed on the outflow side by the flowing water at the largest head differentials.

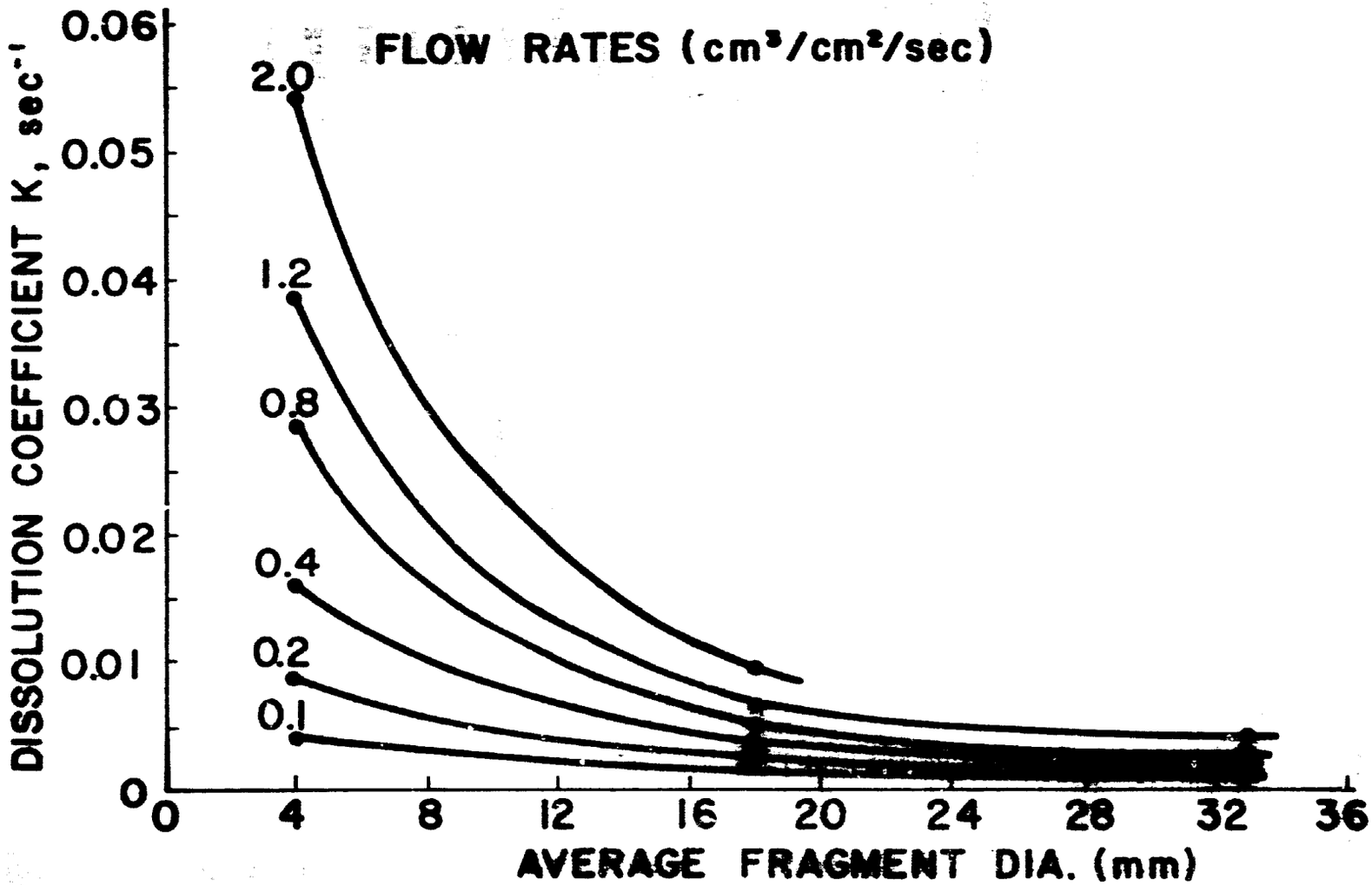

Figure 4. Dissolution coefficients as affected by fragment size.

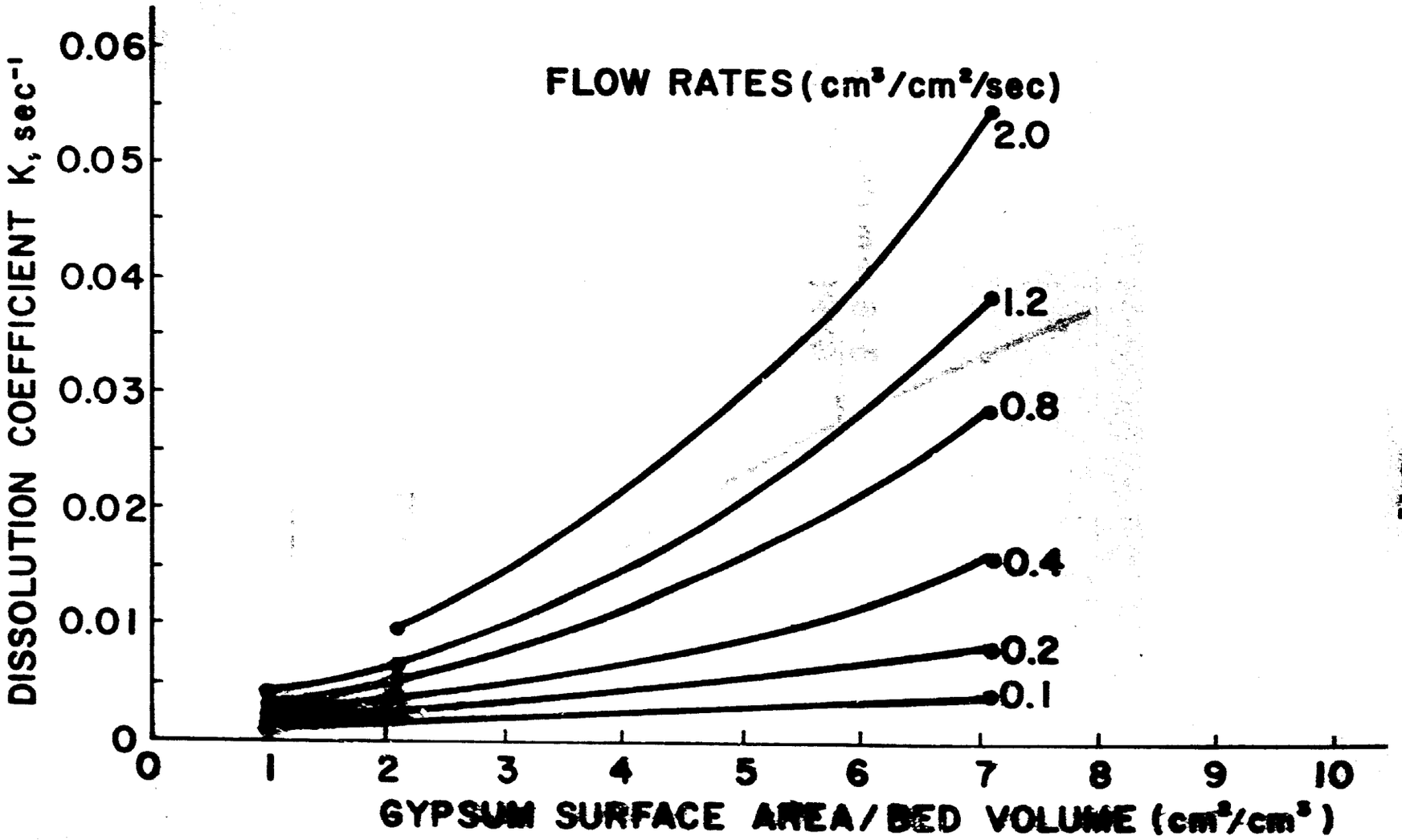

Figure 5. Dissolution coefficients as affected by surface area.

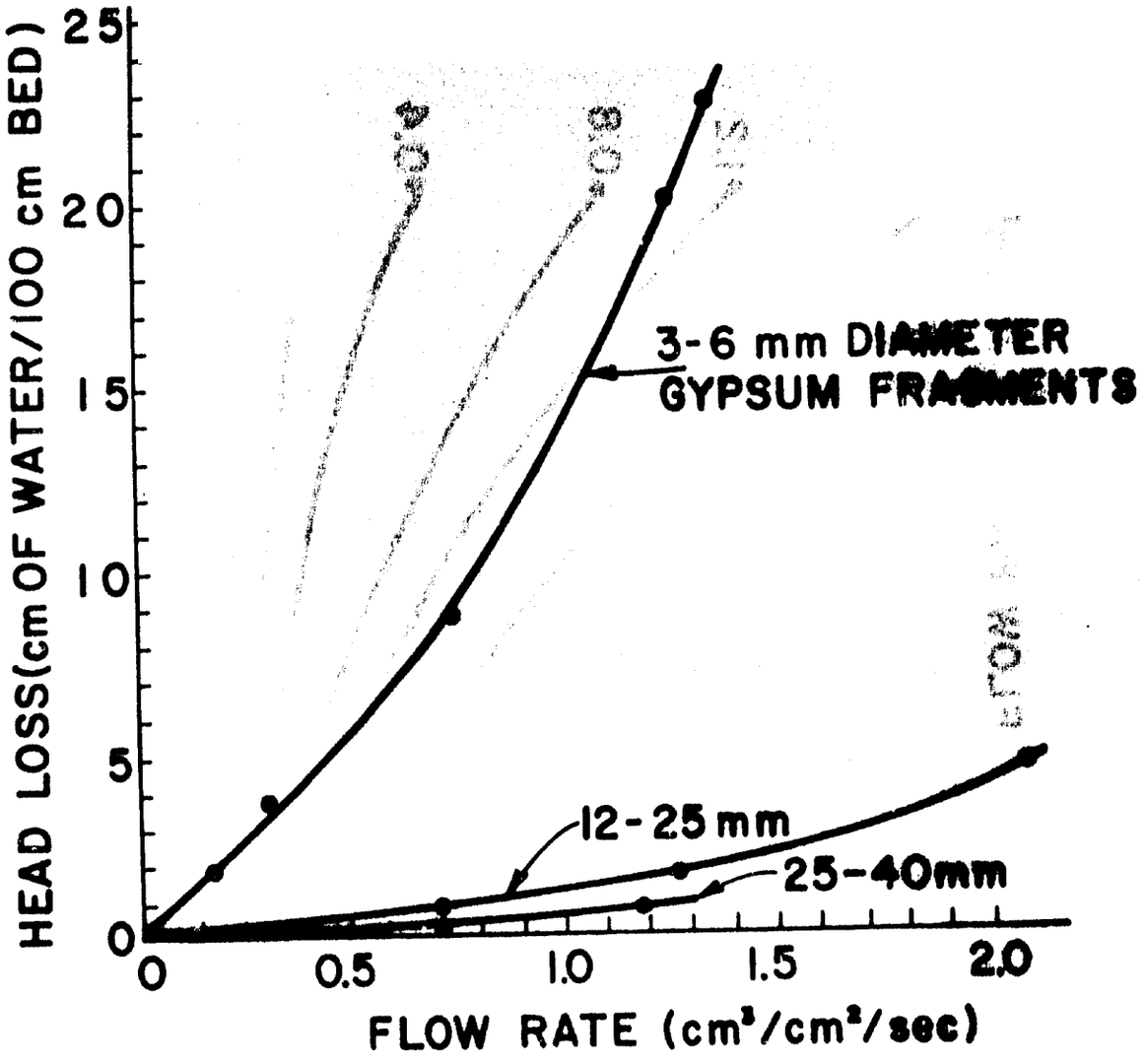

Figure 6. Head loss as a function of flow rate and fragment size.

C. Effect of Common Ion Salts in Water on Dissolution Rate of $CaSO_4 \cdot H_2O$

Equation (1) does not account for the presence of common ions in the inflowing solution which would generally reduce the amount of gypsum going into solution as solutions pass through a bed of gypsum fragments.

Modifying equation (1) to account for the effect of common ions on the concentration of gypsum (c_g) that has come into solution from the solid phase, it may be written as

$$dc_g/dt = K(c_{ge} - c_g) \tag{7}$$

where c_{ge} is the concentration of gypsum in equilibrium with the solid phase (i.e. the maximum amount of gypsum with can go into solution).

At equilibrium with the solid phase, the relation between the saturation concentration c_s (0.015 M for gypsum) with no common ions interfering and c_{ge} is given (approximately since the precise equation would be written in activities rather than concentrations) by

$$c_s^2 = (c_{ge} + c_{si})(c_{ge} + c_{ci}) \tag{8}$$

where c_{si} and c_{ci} are the initial concentrations of these ions in the solution before the solution is brought into contact with the gypsum. Using the general solution to quadratic equations on equation (8) to solve for c_{ge},

$$c_{ge} = \frac{-(c_{ci} + c_{si}) \pm \sqrt{(c_{ci} + c_{si})^2 - 4[(c_{ci} \times c_{si}) - c_s^2]}}{2} \tag{9}$$

where c_{ge} is a constant for specified values of c_{ci} and c_{si}.

Separating the variables and integrating equation (7) between the time to when the solution enters the bed and $c_g = 0$ to the time t_b when it leaves the bed and $c_g = c_{gb}$,

$$-\ln (c_{ge} - c_{gb})/c_{ge} = Kt_b \tag{10}$$

multiplying both sides of equation 10 by -1, raising them to exponents and rearranging terms,

$$c_{gb} = c_{ge}(1 - e^{-Kt_b}) \tag{11}$$

Note that the total concentration of Ca^{++} is $c_{gb} + c_{ci}$ and of SO_4^{--} is $c_{gb} + c_{si}$. When $c_{ci} = c_{si} = c_o$ it can be shown that equation (11) reduces to equation (5), where $c_b = c_{gb} + c_o$.

Equation (11) was used to predict the gypsum coming into solution as estimated from conductivity measurements on solutions flowing out of our gypsum beds. An example of how these predicted values (c_{gb}) compared with measured values (c_{gb}) is shown in Fig. 7. Imprecisions involved in estimating concentrations from conductivity data prevent conclusion from our data that equations (7) and (11) are exact descriptions of the relationship between gypsum dissolution rate and common ions present in the solution that enters the bed. However predictions of equation (11) are apparently good estimates of the amount of gypsum that will be picked up as irrigation waters containing appreciable Ca^{++} and SO_4^{--} pass through beds of gypsum fragments.

IV. Potential Application of Findings

A. Hydraulic Dissolution and Application of Gypsum to Agricultural Lands

As indicated in Fig. 2, the amount of gypsum going into solution can be more than adequate to distribute needed gypsum to the field. These data on hydraulic head loss through beds of gypsum fragments (Fig. 6), on dissolution coefficients (K) at different flow rates and fragment sizes, coupled with equation (11) to account for the effect of salts in the irrigation water on the rate at which gypsum dissolves in the flowing water; can be used to design sections of watercourses, which when filled with gypsum fragments will give practically any concentration of Ca^{++} in the irrigation water between the initial concentration, c_{ci} and $c_{ci} + c_{ge}$.

For instance if a Ca^{++} concentration of 0.005M is desired in irrigation water flowing from a well pumping 2 cubic ft/sec (.054 cubic meters/sec), and the initial concentration of Ca^{++} is 0.001M and of SO_4^{--} is 0.010M, the cross section may be designed as follows. Assuming that 25 to 40 mm diameter fragments will be used and that we wish to avoid

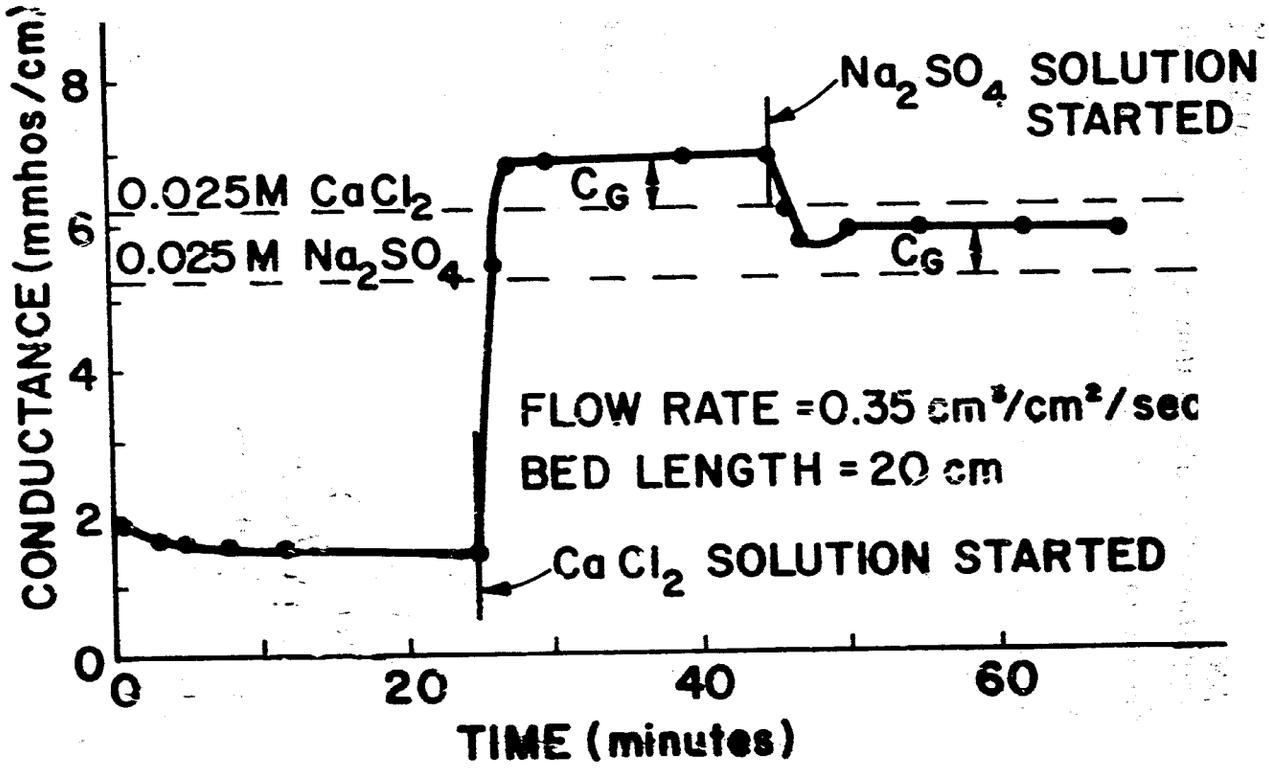

Figure 7. Influence of common ion salts on dissolution rates.

appreciable head loss the flow velocity through the bed should be about 1 $cm^3/cm^2/sec$. Consequently the cross sectional area in square meters should be about (0.054 cu meters/sec) x (100 cm/meter)/(1 $cm^3/cm^2/sec$) = 5.4m^2 (i.e. 2.7m wide x 2m deep). Since c_s = 0.015m, c_{ci} = 0.001m and c_{si} = 0.010m, equation (9) tells us that c_{ge} = 0.010m. Since we wish to achieve an increase in Ca^{++} of c_{gb} = .004m, Kt_b can be calculated from equation (10) and is 0.51. From Fig. 3, we estimate that K = 0.0035 and therefore the irrigation water should stay in the gypsum bed for the time t_h = 0.51/0.0035 = 141 seconds.

The bed length (L_b) needed to achieve this contact time is given by

$$L_b = (t_b \times dq/dt)/\theta \qquad (12)$$

where dq/dt is the flow rate in $cm^3/cm^2/sec$ and θ is the porosity of the bed. Assuming θ = 0.5 for the case under consideration (t_b = 141 and dq/dt = 1.0) equation (12) indicates that L_b would be 242 cm.

Head loss through this bed would be less than 1 cm of water under the flow conditions described. If a few cm of head loss could be afforded in the system, the cross section of the channel could be reduced and the length increased. If the cost of breaking the gypsum to 25-40mm fragments is a large portion of the total gypsum cost, longer beds of coarser fragments could achieve the desired gypsum saturation. The possibility exists of getting adequate gypsum into the irrigation water for many purposes by lining the watercourse with large gypsum (10 to 30 cm diameter rocks). This needs further study.

As the gypsum in beds dissolves, its average fragment size decreases, porosity of the bed changes and consequently quantitative predictions of Ca^{++} content of gypsum concentration in irrigation water after passing through a bed of gypsum fragments is practically impossible over an extended period of time. On the other hand, estimates good enough to design watercourse cross sections for gypsum application can be derived from this data and these equations. Data on larger size fragments would be helpful, but can best be collected from field installations of the type

planned by our cooperators at the Mona Reclamation Center in Pakistan. We would like to express our appreciation to them for pointing out the practical potential of hydraulic distribution of gypsum for decreasing crushing and application costs in developing countries.

B. Maintaining Infiltration Rates of Septic Tank Tile Fields

Continued successful operation of septic tank systems depends on maintaining infiltration rates at reasonable levels. The normal effluent from a home contains large amounts of Na^+ from soaps and detergents. Water softeners designed to replace the Ca^{++} in water by Na^+ also contribute to make the Na^+/Ca^{++} ratio high. These high Na^+/Ca^{++} ratio waters, when applied for prolonged periods of time, disperse the soil in the tile fields and thereby often reduce its infiltration rate to low values. As a result the effluent breaks out at the soil surface, and does not receive the filtration oxidation and other cleansing actions normally afforded when it passes through soils. Addition of a tank or pit of gypsum fragments to "harden" the water back to reasonably low Na^+/Ca^{++} ratios could help maintain reasonably high infiltration rates. The size of such tanks or pits and the fragment size of gypsum to be used could be estimated from expected flow rates, ion concentration of the waters coming from the home and recommended Na^+/Ca^{++} ratios.

Assuming 100,000 gallons (approximately 400,000 liters) of water per year through a septic system, saturation with gypsum would be approached by adding about 90 kgm of gypsum to the water. In general this would be more than enough Ca^{++} to maintain reasonable Ca^{++} levels in the soil around the tile lines in the field.

Fertilizer or Salt Leaching as Affected by Surface Shaping and Placement of Fertilizer and Irrigation Water*

by
W. D. Kemper, John Olson and Alan Hodgdon**

I. Introduction

Appreciable amounts of irrigation water pass by, or through, the plant root zones to the ground water. In this process, these waters can remove a large portion of the nitrates, chlorides and other soluble salts. The pollution potential of nitrate removal has been of considerable concern in the U.S.A. and other developed countries. In the lesser developed countries nitrate fertilizer is often the largest economic input in crop production and leaching of a major portion of this nitrate from the root zone of the plants is a major economic loss. There is also a growing realization that nitrate loss is a major energy loss in agricultural operations.

The dominant method of fertilization in developing countries is broadcasting. The dominant method of irrigation is flooding areas which have been diked to allow ponding of the water. In the developed countries the dominant irrigation systems tend to be furrow irrigation, sprinkler irrigation and trickle irrigation. Comparatively low levels of fertilizer nitrogen recovery from basin irrigation research plots in the developing countries have been observed. Such observations raise the question as to whether broadcasting nitrogen fertilizer followed by basin irrigation tends to displace nitrogen fertilizer from the root zone more effectively than other combinations of fertilization and irrigation methods.

Recent observations in trickle irrigation systems indicate that plants will take a major portion of their water supply from a small portion of

*This study was supported by the United States Agency for International Development through Contract No. AID/csd-2162 on Water Management Research for Developing Countries.
**Professor of Agronomy and Agricultural Engineering, and Research Technicians, respectively, at Colorado State University

their root zone in which the tension of water is low (wet). A wet zone of this type allows plants to satisfy their water requirements without depleting water from the other reasonably moist, but drier, portions of the root zone. In the drier root zones, nitrate is reasonably mobile and can diffuse to the roots where it can be taken up in amounts adequate to supply plant requirements. Thus it appears that separation of the routes by which nitrogen and water enter the plants may be a management procedure which can avoid some of our leaching losses.

Common row crop practice in the U.S.A. is to furrow and ridge the land, seeding and fertilizing at and near the center of the ridges and distributing water through the furrows. Looking at flow nets from electrical analogs designed to simulate water movement from furrows (e.g. Corey 1965), this practice appears, to a large extent, to have separated the routes by which water and fertilizer are introduced into the plant root zone.

This study was designed to determine whether irrigating in furrows and fertilizing in the ridges does leave more of the soluble unadsorbed fertilizer in the root zone under conditions of overirrigation than does broadcasting fertilizer, followed by flood irrigation.

II. Materials and Methods

The soils used were: Crook loamy sand with an organic matter content of 1%, Nunn clay loam with an organic matter content of 2% and Billings silt loam with an organic matter content of 1%.

These soils were placed in lysimeters which were 45.7 cm wide, 10.2 cm thick and 110 cm deep. A layer of glass beads 3 cm deep was placed in the bottom of each lysimeter and 6 perforated plastic tubes were inserted in this layer of beads from the front of these lysimeters to provide drainage into six two liter glass jugs. The front of each lysimeter was constructed of 1.3 cm thick lucite which allowed observation of packing patterns, wetting patterns and changes in soil structure as wetting proceeded.

The surfaces of the soils were left flat, or shaped to represent a section from the midpoint of a furrow to the midpoint of a ridge. In most cases the top of the ridge was 15 cm higher than the bottom of the furrow prior to wetting. Soil having passed through a 5 mesh sieve was used to fill the lower 85 cm of the lysimeter while the upper 20 cm was filled with soil that had passed through a 3 mesh sieve. This gave the upper portion of soil more pore space than the lower soil, in an arrangement similar to the subsoil and surface layer of cultivated soils.

"Fertilizer bands" of $CaCl_2 \cdot 2H_2O$ were placed in the ridges of the soil at the depths indicated in Table 1, or the fertilizer was scattered on the surface to represent broadcasting.

Water was added to the soil from calibrated Mariotte siphon jugs which held 3700 liters each, and maintained the water levels at the height indicated in the respective figures. Generally, between 7 and 10 cm of water were applied per "irrigation." Such irrigations were generally followed by a period of several hours during which up to 100 cm of tension developed in the surface soil, and then by another irrigation.

During the course of this study, the question arose as to whether the soil solution, which dissolves the salt, would have sufficiently greater density than adjacent soil solution to cause downward convective movement of the dissolved fertilizer. To gain a measure of this mechanism, pairs of lucite cylinders each 6 cm in height, 7 cm in inside diameter and capped on one end were filled (actually overfilled about 2 mm) with Nunn soil to bulk densities of about 1.2 and gravimetric water contents of 30 or 35%. Five or 0.5 gms of $CaCl_2 \cdot H_2O$ were placed in a circle less than 1.2 cm in diameter on the soil surface in the middle of half of these cylinders. The soil surfaces on the open sides of two cylinders, containing soils of equal water contents, were then placed in contact and pushed together till the lucite was in contact, which resulted in a compaction of about 3% and firm initial contact between the soils and the salt. The cylinder pairs were taped together and left in contact, one above the other for 48 hours. At the end of this time the cylinders were separated and two cores (1.5 cm

in diameter and 5 cm long) were taken from the center of each cylinder. These cores were weighed and dried at 65°C to determine their water content and were then shaken with twice their weight of water, allowed to settle and electrical conductivity of the supernatant solution was determined. Water and salt content of soil from the portion of the cylinders outside the central core was determined in a similar manner.

III. Results and Discussion

For the purpose of the following discussion, water and salt which came out of the ports at the bottom of the lysimeter is equated to water and fertilizer that is leached from the root zone. For simplicity this effluent water is all referred to as "overirrigation."

Leaching from a Loamy Sand

When the salt was broadcast on the surface and the water was applied as basin flooding, as indicated in the left hand curve of Fig. 1, half of the salt had been leached from the root zone by the time 30 cm of "overirrigation" had been applied.

When water in the irrigation furrow was 10 cm deep and its surface was 5 cm above the band of salt, the leaching curve was surprisingly similar to that for the basin type irrigation. Apparently the average solution velocity of water in the streamline which intercepts the fertilizer band in this configuration is only slightly less than the velocities along stream lines that go straight down below the furrow.

Placing the salt band at the same elevation as the bottom of the furrow and maintaining 5 cm of water in the furrow exposed more of the soil surface to evaporation, which was accentuated by a sun lamp which was evaporating water from the soil surface at a rate of 0.05 cm/hour. This combination of factors prolonged the time during which the salt was in the root zone. Almost 60 cm of irrigation passed through the root zone before half the salt had been removed.

Removing the sun lamp, with the configuration of the soil surface, water and fertilizer the same as in the previous paragraph, did not change the leaching curve appreciably.

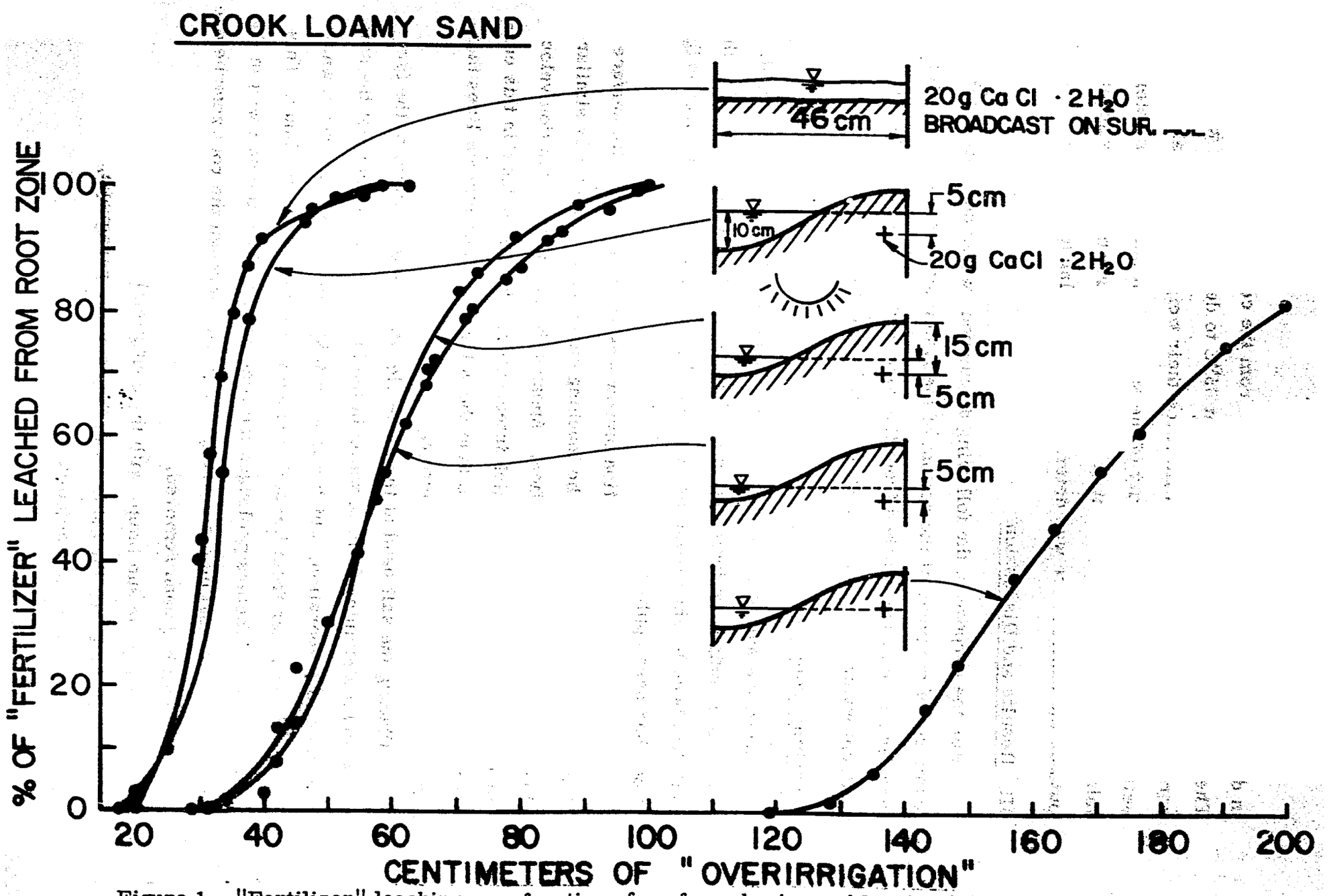

Figure 1. "Fertilizer" leaching as a function of surface shaping and levels of the fertilizer band and the irrigation water in a loamy sand.

Raising the level of the fertilizer band to the level of the water surface in the furrow delayed elution of the salt till more than 120 cm of overirrigation had been applied. The critical relation between level of water in the furrow and level of the fertilizer band in these sandy soils is apparent from considering the elution curves when the band was at the water level in the furrow as compared to 5 cm below that level.

Subsequent runs indicate that this relation can change with successive irrigations. The top of the ridge was disturbed each time a new band of fertilizer was placed in position, but the furrow was not generally disturbed. Several runs after the last run shown in Fig. 1, the configuration shown as the last run in Fig. 1 was repeated, and the elution curve shifted to the vicinity of the curves representing the 3rd and 4th runs in Fig. 1. Looking at close-up pictures of this soil taken during these runs it appears that successive irrigations tended to compact the soil under the furrow into a denser mass which would decrease the permeability below the furrow (which was indicated by reduced infiltration rate from the furrow), and shunt a larger portion of the infiltrating water toward the fertilizer band. Manometers inserted through the right hand side of the lysimeter indicated that the water table never developed in this portion of this sandy soil. However capillary water travelling through this unsaturated soil was able to leach essentially all of the salt from the band and out of the root zone rather quickly when the band was at the same level as the water surface in the furrow and permeability below the furrow was reduced.

Moving the fertilizer band 5 cm higher than the level of the water in the furrow allowed over 120 cm of overirrigation to pass through this soil before the salt began to come out of the root zone in this sandy loam.

Leaching from a Clay Loam

When the salt was applied by broadcasting and followed by basin irrigation (Fig. 2), most of the salt was eluted from the soil after 40 cm of irrigation, which was about the amount required to leach the salt from the loamy sand. Assuming displacement of the inhabitant solution by the

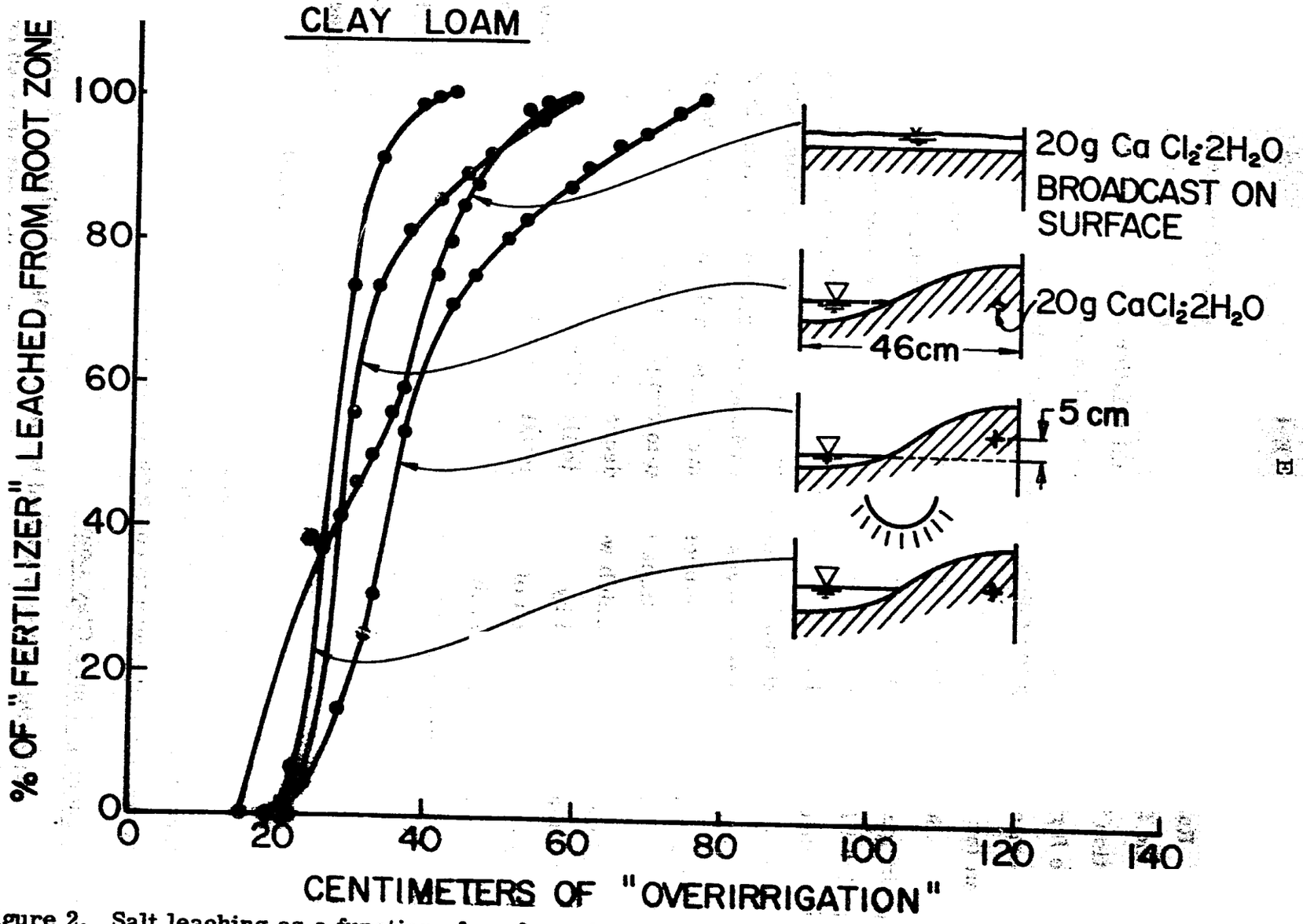

Figure 2. Salt leaching as a function of surface shaping and elevations of the salt band and irrigation water surface in a clay loam.

intruding water as the mechanism of salt displacement from the profile, the clay loam, with a volumetric water holding capacity of about 43% (at 50 cm of suction) would have required more overirrigation to displace the salt than would the loamy sand with a water holding capacity of only about 30%. The fact that the salt came through at about the same level of overirrigation for soils of the two textures is probably explained, at least in part, by anion exclusion from water held in small pores and from water immediately adjacent to mineral surfaces. This water from which anions are excluded moves much slower than water in the bigger pores and in the middle of pores and consequently the anion bearing water bypasses the water without anions. Thomas and Swoboda (1970) measured an average of 37% bypass of anions pass resident water as they leached chloride through clay soils. Such a percentage of bypass in the clay loam soils would account for the salt going through the clay loam soil as rapidly as it went through the loamy sand.

Placing the band of fertilizer in a ridge at the elevation of the water in the furrow did not delay its average departure from the soil compared to broadcasting and surface flooding.

Elevating the fertilizer band 5 cm above the water level in the furrow caused some delay in the departure of the salt from the soil. However the delay was much less than occurred in the loamy sand.

Drying the surface with a sun lamp at the rate of 0.05 cm of water/hour was expected to bring more of the water and salt to the surface or at least bring the salt higher in the ridge and delay its departure from the soil. As indicated in Fig. 2, the departure of the salt appeared to be accelerated rather than delayed.

Intuition is badly deflated when salt tucked away under a ridge is leached out of the root zone by irrigation from a furrow more rapidly than salt broadcast on the soil surface and flooded. Mechanisms which might explain this apparent anomaly were evaluated as follows.

Two days after the salt was placed at the centers of cylinders (described in methods section) it was found to be distributed as shown in

Fig. 3. Downward displacement of the centroid of the salt by about 1.5 cm had taken place in the soil at 35% water (by weight which is equal to 42% by volume) when 0.5 gm of salt was applied. About 2.5 cm of downward displacement of the centroid occurred when 5 gm of salt were added. Burns and Dean (1964) found that when NO_3 fertilizer was placed in bands in soils near saturation with water, the fertilizer was quickly dissolved by the soil solution and the nitrate migrated downward. This downward migration of nitrate is believed to be due to the greater density of the nitrate solution, compared to adjacent soil solution, and possibly due to higher water contents around the nitrate band. Higher water contents in the immediate vicinity of salts applied to soils were measured by Qayyum and Kemper (1962). Raats (1969) developed a theory from this type of downward movement of fertilizer from a band, from which downward velocity of the salt can be predicted when the hydraulic conductivity, the densities of the solutions are known. Since these parameters were not easily measured in our lysimeters, and since the magnitude of the downward movement in our trials and those of Burns and Dean were appreciable, it was decided that in the rest of the studies the weight of salt in the bands should be comparable to the weight of fertilizer applied to a similar length of band in the field. An application rate of 4 gm/10 cm of band with 90 cm row spacing is the equivalent to 445 kgm/hectare (400 lbs/acre) and was used in the subsequent studies.

Apparently when fertilizer is spread widely over the surface, as in broadcasting, the concentration of the soil solution is increased by such a small amount that the density differences and consequent downward convective movement of the nitrate is negligible.

Another factor which apparently assists the downward movement of banded nitrate in the ridges, irrigated by furrows, is the higher hydraulic conductivity of the cultivated layer of soil compared to the underlying soil. As water was applied in the furrows of the clay loam it moved down rapidly until it hit the denser noncultivated layer which had fewer large pores and lower conductivity. A perched water table developed in the

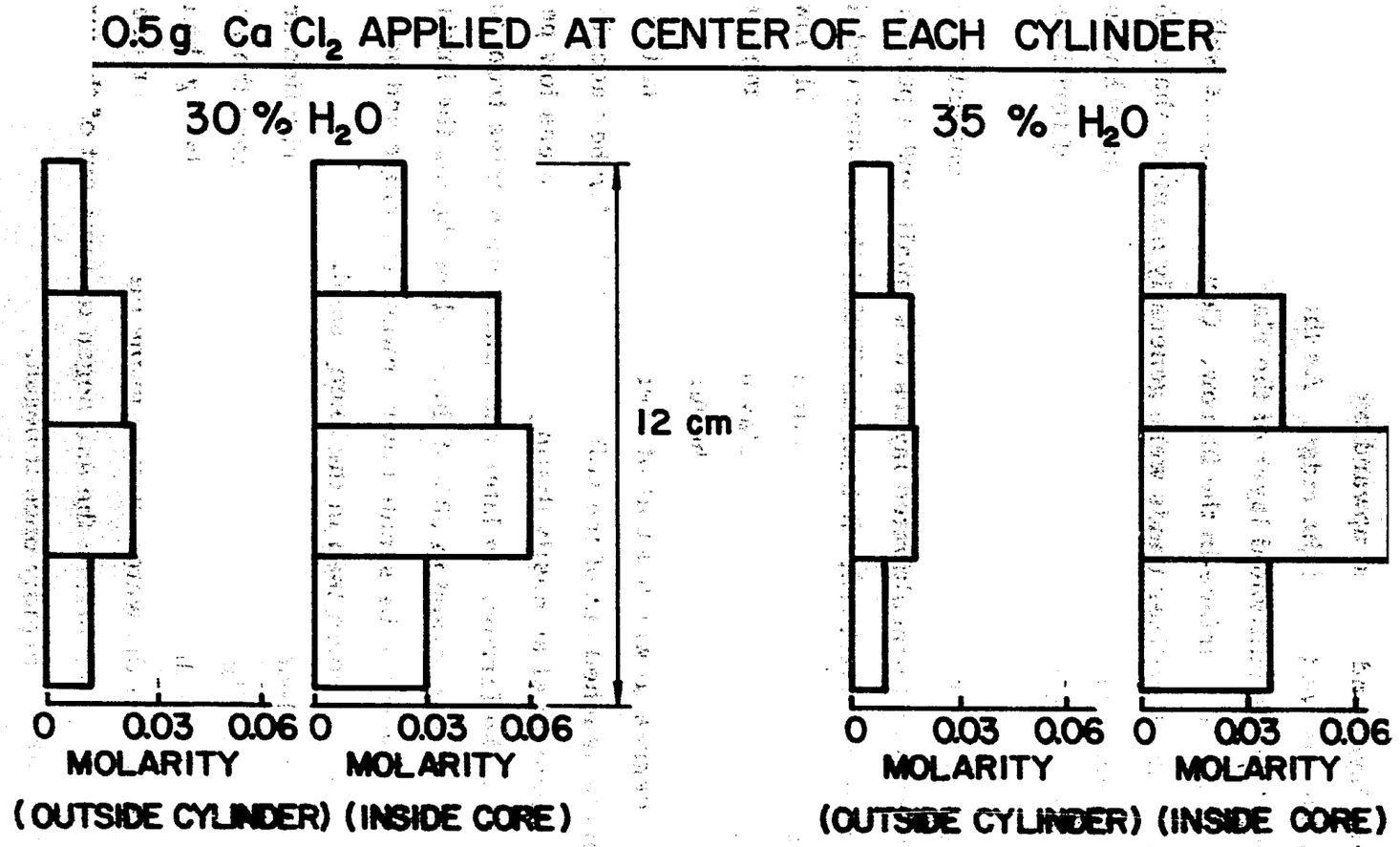

Figure 3. Distribution of salt in the outside cylinder and the central core of soil two days after salt had been applied at the center of the soil.

bottom portion of the cultivated layer. Water moved relatively rapidly across to the center of the ridge in this saturated lower portion of the cultivated layer and moved upward more slowly in the unsaturated state to complete the wetting of the ridge. As the irrigation continued, the water table in the cultivated layer of the clay loam often approached the level of the water surface in the furrow. Consequently the soil water suctions at the fertilizer bands were generally no more than a few cm and were often near zero. Under these conditions the data of Burns and Dean (1964) indicate relatively rapid downward movement of fertilizer from a band.

In the sandy loam, the difference in hydraulic conductivity between the cultivated and noncultivated layers was small, and a perched water table was never observed. It is probable that the unsaturated hydraulic conductivity of the area near the salt band was considerably lower than that around the salt bands in the clay loam soils at the same elevations relative to the water surface in the furrows.

The degree to which a unit of overirrigation causes salt to leave the band and be leached out of the soil appears to be further accelerated by the development of an easily distinguished structureless low permeability layer below the furrow. In later runs infiltration rates from furrows in the clay loam decreased to 30% of their values during the initial run, and the water appears to be shunted over toward the ridge and salt band even more in the clay loam than in the loamy sand.

Additional leaching rates as a function of overirrigation are shown at the left side of Fig. 4 for cases with the band at or near the level of the water surface in the furrows in a clay loam soil. Placing the salt band 5 cm higher than the water surface in the furrow allowed more overirrigation to take place before the salt began to come out of the furrow, but the salt came out rapidly once it began.

Elevating the band to a level 10 cm higher than the water surface in the furrow (ridge 20 cm high) did delay salt movement out of the profile till over 120 cm of overirrigation had been applied. The fact that 4g of

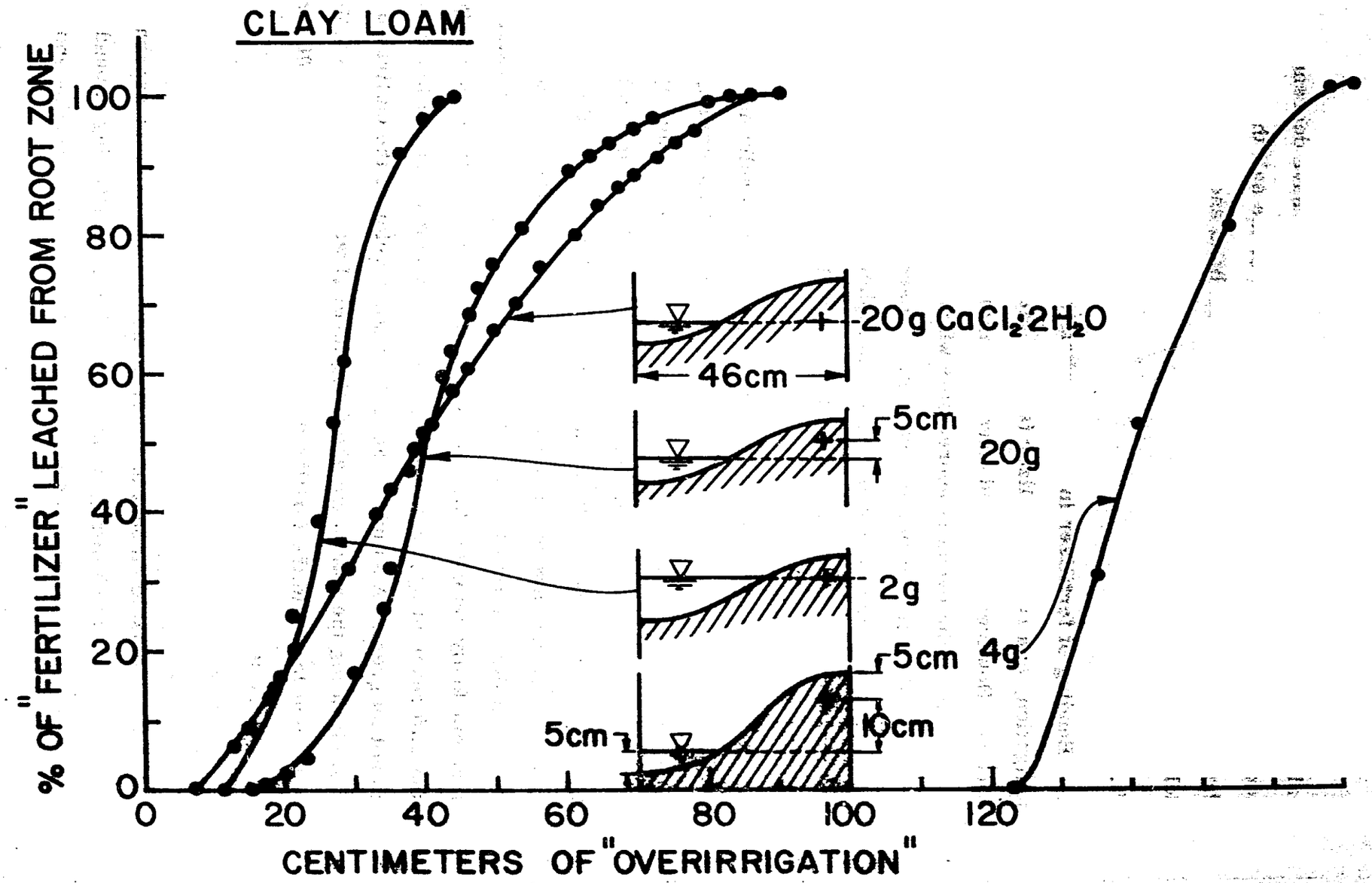

Figure 4. Salt leaching as a function of surface shaping and levels of the fertilizer band and irrigation water in a clay loam (second series).

salt was applied in the band rather than 20 gm may have decreased the downward portion of the convective movement of the salt that was due to the higher density of solution around the salt band and contributed to the delay.

IV. Conclusions

Banding of fertilizer in ridges, when water application is by furrow irrigation, can retain fertilizer (salt) in the root zone when overirrigation occurs. However downward convective movement of the heavier salt solution near the bands is appreciable when the soil water suction is low and the hydraulic conductivity is high. Consequently it is generally necessary to place the bands 5 to 10 cm higher than the water surface in the furrow to keep the fertilizer out of the main stream of the downward water movement.

In finer textured soils, the cultivated layer generally has a higher conductivity than the lower layers. Irrigation of these soils generally develops a perched water table in the cultivated layer which approaches the level of the water in the furrow. This condition causes a lower soil water suction at the middle of the furrow which increases the hydraulic conductivity and downward convective movement of the salt applied in the band. In these soils elevation of the band to 10 cm above the water surface markedly retarded the salt removal. In coarser textured sandy soils, the difference in hydraulic conductivity of the cultivated and lower layers is not as great. A saturated zone does not develop in the cultivated layer and elevating the band 5 cm above the level of water in the furrow was sufficient to retain the fertilizer in the root zone during over 100 cm of overirrigation.

The rapidly climbing cost of nitrogen fertilizers and the difficulties of achieving adequate irrigation in all parts of a field without overirrigating an appreciable amount of the area indicate the need for separation of the routes by which nitrogen enters the plant. Fertilizing in bands in ridges between irrigation furrows can achieve this separation and reduce

nitrate leaching. The effects of this type of water and fertilizer management on crop yields and nitrogen recovery should be determined in the field, under practical conditions of growing plants, and occasional rainfall.

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Appendix F

WATER QUALITY IMPROVEMENT AND GYPSUM SOLUBILITY

by

William T. Franklin

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Water Management Research in Arid and Subhumid
Lands of the Less Developed Countries

Agronomy Department
Colorado State University
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Franklin, William T. Water Quality Improvement and Gypsum Solubility. Council of U.S. Universities for Soil and Water Development in Arid and Sub-Humid Areas Water Management Technical Report No. 30. (Fort Collins: Colorado State University), August, 1973.

ABSTRACT

Methods of improving the quality of high-salt and high-SAR waters by blending with better quality water and by adding gypsum are discussed. Blending formulas which can be used to calculate resultant or desired qualities from mixing two or more different quality waters are given. Methods of calculating the amount of gypsum to apply in water to lower the SAR to a desired level are presented. The results of gypsum solubility studies with gypsum particle sizes ranging from 2.0 - <0.05 mm (10 - <300 mesh) in a mechanical shaking experiment simulating turbulent flow and in two different-textured soils are reported.

Precise control of calcium concentrations necessary to lower SAR levels to specific values should be obtained with <0.25mm (<60 mesh) gypsum metered in flowing water. Coarser sizes which could be placed in cross sections of ditches exhibit sufficient solubility to be useful for reducing the water SAR. Solubility rates and calcium concentration levels in soil solutions can be controlled to a considerable degree by mixing gypsum particle sizes >0.5 mm (>35 mesh) in the soil and, thus, is an alternative method for reducing water SAR. Dissolution of <0.1 mm (<140 mesh) gypsum in soil was comparable to previously published values. For the purpose of removing exchangeable sodium in soil reclamation, the application of gypsum particle sizes greater than about 100 mesh would significantly reduce gypsum dissolution efficiency.

INTRODUCTION

Monitoring studies of salt compositions of tubewells in several areas f Pakistan show a significant increase in the sodium-adsorption ratio (SAR) ith time and indicate a trend for increase in total dissolved solids. Continued deterioration of groundwater quality poses a threat to irrigated agriculture in Pakistan, and other areas of the world, since pumping is necessary to maintain desirably low groundwater tables and to supplement deficient surface supplies

The quality of high-salt and high-SAR water can be improved if the proper resources are available. In Pakistan, it is a common practice to mix high-salt and high-SAR tubewell waters with low-salt, low-SAR canal water which results in a blend safer for irrigation. With continued groundwater deterioration and with increased demands for more water, it is expected that the practice of blending will increase. Careful planning is necessary to maximize the total useable amount of suitable quality blended waters. Blending formulas which can be used to calculate resultant or desired qualities from mixing two or more different quality waters are given in the following section.

Waters with high SAR values can be improved by the addition of gypsum ($CaSO_4 \cdot 2H_2O$) to increase the amount of dissolved Ca. Formulas for calculating the amount of gypsum to add for desired SAR values of water are given in the following section. Gypsum can be applied by several different methods. The most accurate method is to add the necessary gypsum from a hopper system at a calibrated rate. A finely-ground grade of gypsum is generally necessary in this case because of the low solubility rate of coarse gypsum particles. The high cost of finely-ground gypsum places severe economic restraints upon

applying metered amounts of gypsum into water. Less costly coarser grades or lumps of gypsum can be placed in cross-sections of ditches, but the solubility rate is more difficult to control. Dissolving more gypsum than necessary not only would be economically undesirable, but also, would cause an undesirable increase in the total salt content of the water and soil. Also, gypsum can be applied and worked into the soil at rates equivalent to the amount of water used. The solubility rate is difficult to control in this case, also. In addition, the costs of spreading the gypsum and incorporating it into the soils must be considered.

There is little information in the literature concerning the dissolution rates of different particle sizes of gypsum in water and soil. Therefore, the solubility rates of different gypsum particle sizes were determined in a mechanical shaking experiment simulating turbulent flow of water and in two different-textured soils. The objective of these experiments was to obtain solubility data which would serve as useful guidelines for water quality improvement and efficient soil reclamation.

BLENDING FORMULAS AND CALCULATION OF GYPSUM ADDITIONS

Blending Formulas

The salinity content and SAR resulting from blending two or more measured quantities of water with known water analyses can be calculated as a simple averaging effect from the following formulas:

$$S_b = \frac{Q_1S_1+Q_2S_2+Q_nS_n}{Q_1+Q_2+Q_n}$$

$$SAR_b = \frac{Q_1 SAR_1 + Q_2 SAR_2 + Q_n SAR_n}{Q_1 + Q_2 + Q_n} \quad (2)$$

where: Q = quantity of water measured in any common units - cubic feet per second (cfs), gallons per minute (gpm), etc.

S = salinity content of water measured in micromhos/cm or parts per million (ppm)

$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$ - Na (sodium), Ca+Mg (calcium + magnesium) in milli-equivalents per liter (me/l)

b = blend

n = quantity and analysis of the nth number of water sources.

If it is desired to blend two sources of water to obtain a specific salinity level or SAR, then the following formulas apply:

$$\frac{V_g}{V_p} = \frac{S_p - S_b}{S_b - S_g} \quad (3)$$

$$\frac{V_g}{V_p} = \frac{SAR_p - SAR_b}{SAR_b - SAR_g} \quad (4)$$

where: V = volume of each water to be blended in cfs, gpm, etc.

g = good quality; p = poor quality; and b = blend

S = salinity level; SAR = sodium adsorption ratio

For example, if two water sources of 400 and 4000 ppm TDS are available and it is desired to obtain a blend of 1000 ppm, the necessary proportions of each are calculated by formula (3) in the following way:

$$\frac{V_g}{V_p} = \frac{4000 - 1000}{1000 - 400} = \frac{5}{1}$$

Therefore, 5 volumes of 400 ppm water must be added to 1 volume of 4000 ppm water to produce a 1000 ppm blend.

Calculation of Gypsum Additions

The SAR formula is transposed to calculate the me/l of Ca + Mg necessary to achieve a desired SAR by the following formula:

$$Ca+Mg = \frac{2(Na)^2}{SAR_d^2} \qquad (5)$$

where: Ca+Mg - in me/l

Na - in me/l

SAR_d - desired sodium-adsorption-ratio

The amount of Ca (me/l) to be added in the water as gypsum is the difference between the Ca+Mg necessary to achieve the desired SAR_d and the amount of Ca+Mg initially in the water. The Ca (in me/l) to be added multiplied by 234 gives the pounds of gypsum (chemically pure) to be added to an acre-foot of water to achieve the desired SAR.

As an example, if a water initially contains 8 me/l of Na and 1.15 me/l of Ca+Mg, it has an SAR of 10.5. If an SAR of 6 is desired, the gypsum required to obtain $SAR_d = 6$ is calculated as follows with equation (5) and the steps outlined above:

(Step a) $Ca+Mg = \frac{2(8)^2}{(6)^2} = \underline{3.55 \text{ me/l}}$ = Total Ca+Mg required for $SAR_d = 6$

(Step b) Ca = 3.55 me/l (total Ca+Mg) - 1.15 me/l (initial Ca+Mg) = <u>2.40 me/l</u> = Ca added as gypsum

(Step c) Gypsum = 2.4 me/l Ca x 234 = <u>562 pounds per acre-foot</u> of water needed to attain $SAR_d = 6$.

The same results can be approximated by using the nomogram in Figure 1. The Ca to obtain a desired SAR can be found by using a ruler to connect Na (scale A) and SAR (scale C) and read from scale B. The gypsum to be added is found from scale D and subtracting the Ca+Mg initially present

This method of calculating gypsum to lower the SAR is economically feasible for waters in which the sodium or bicarbonate (HCO_3) ion content is not very high or where blending of high sodium water with low salt content water can be used to lower the Na or HCO_3 contents. The gypsum addition calculation is not accurate for waters with large quantities of carbonate (CO_3) and bicarbonate anions because waters of this type precipitate Ca as lime ($CaCO_3$). Additional gypsum above that calculated with equation (5) must be added to waters of this type to attain the desired SAR. For waters containing more than 6 me/l of Na and HCO_3, an approximation of the total gypsum which must be added to correct for precipitation of $CaCO_3$, assuming incomplete Ca and no Mg precipitation by HCO_3, and to obtain a particular SAR can be calculated (in me/l) by:

$$\text{Total gypsum (me/l)} = (CO_3 + HCO_3 - Mg - 1) + (\text{Ca calculated for } SAR_d \text{ from equation (5)}).$$

Use of equation (6) is illustrated in Table 1 with tubewell waters of the indicated analyses (Land Reclamation Directorate, Lahore, Pakistan) and blends of one-half tubewell water and one-half river water. The gypsum required to reduce the SAR of the waters to 10 was calculated by equations (5) and (6). Then, the predicted SAR was calculated after correcting for the precipitation of lime ($CaCO_3$). The precipitation of lime was predicted with a computer program developed to predict equilibrium Ca concentrations in calcareous and gypsiferous systems (Rai and Franklin, 1973). The predictions

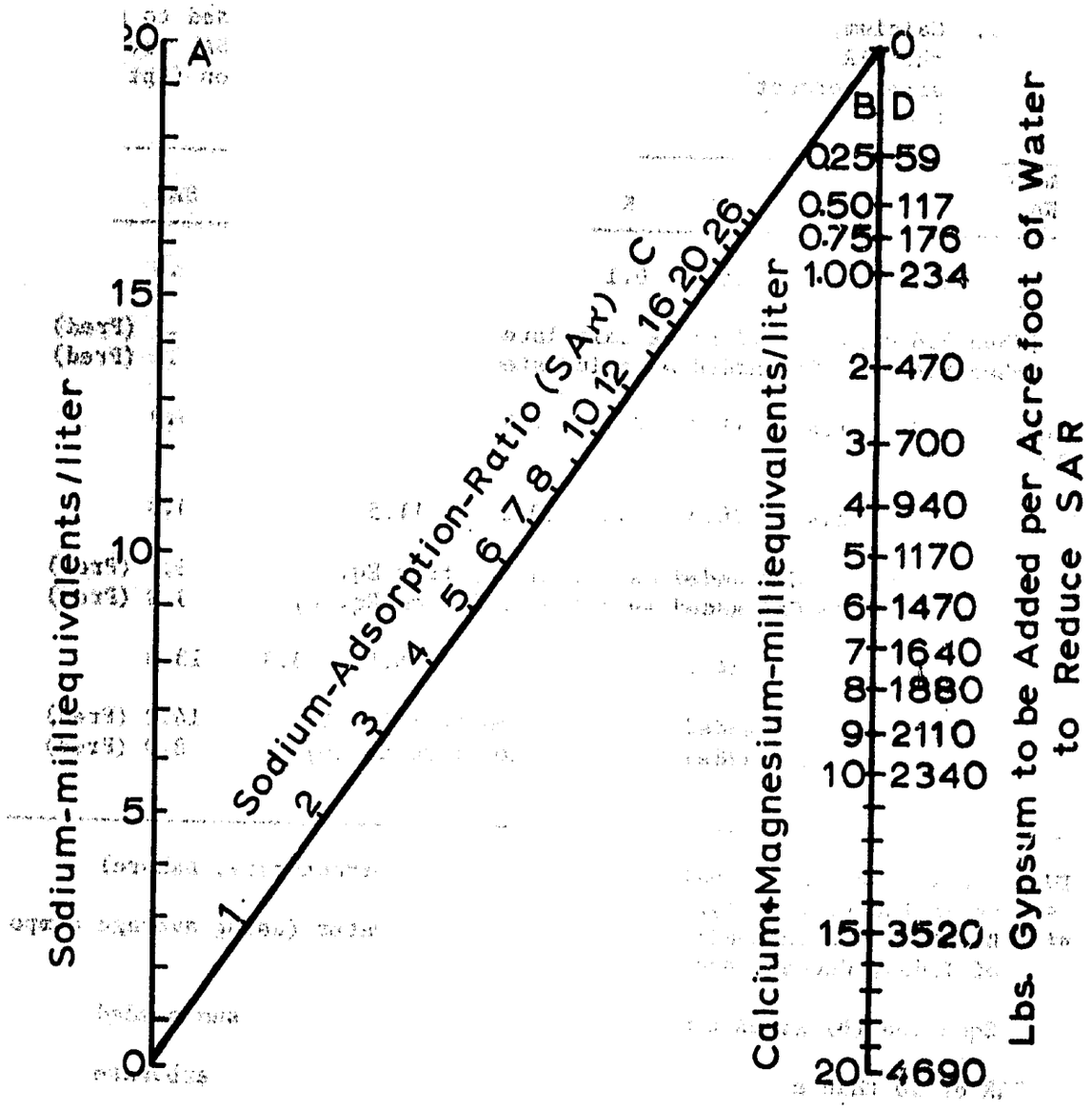


Figure 1. Nomogram for determining the SAR value of irrigation water and for estimating the addition of gypsum per acre-foot of water to reduce the SAR to desired levels.

of lime precipitation were computed at a temperature of 25° C and partial CO_2 pressures of 3 and 16 matm for tubewell and blended waters, respectively.

Table 1. Calcium, calculated by equations (5) and (6), needed to reduce the SAR to 10 in tubewell and blended waters and SAR obtained after correcting for predicted (Pred) precipitation (Ppt) of $CaCO_3$.

Sample No.	Ca	Mg	Na	K	HCO_3	Cl	SO_4	SAR	Pred $CaCO_3$ Ppt
	- me/l -								
TW 1	1.6	2.0	21.5	0.1	6.0	10.5	8.7	16.0	-
[When 5.6 me/l Ca* added as calculated from Eq. 5]								11.3 (Pred)	2.26
[When 8.6 me/l Ca* added as calculated from Eq. 6]								9.6 (Pred)	2.73
Blend 1**	1.7	1.4	11.0	0.1	4.2	5.3	4.6	8.9	-
TW 2	0.6	1.4	28.3	0.2	13.0	11.5	6.0	28.3	-
[When 14.0 me/l Ca* added as calculated from Eq. 5]								15.7 (Pred)	9.27
[When 24.6 me/l Ca* added as calculated from Eq. 6]								9.9 (Pred)	10.20
Blend 2**	1.2	1.0	14.5	0.1	7.7	5.8	3.3	13.8	-
[When 2.0 me/l Ca* added as calculated from Eq. 5]								14.2 (Pred)	1.82
[When 7.7 me/l Ca* added as calculated from Eq. 6]								8.9 (Pred)	4.24

TW - Tubewell water analysis (Land Reclamation Directorate, Lahore)
* Ca in the form of gypsum
** Blend of 1/2 tubewell water and 1/2 river water (using average compositions of Indus, Chenab, and Jhelum Rivers).

Equation (6) gives a much closer estimate of the gypsum needed to attain an SAR of 10 than equation (5) for these high SAR, high bicarbonate waters. Approximately 54% (No. 1) and 76% (No. 2) more gypsum than calculated with equation (5) would be necessary to reduce the SAR of the tubewell waters to 10. Predicted Ca precipitation as $CaCO_3$ amounted to 40 and 66%, respectively, of the gypsum added to water No. 1 and 2 according to equation (5) and 32 and 41%, respectively, of the gypsum added according to equation (6). Thus, the addition

of gypsum to tubewell waters with qualities similar to No. 1 and 2 would be inefficient and not economically favorable, especially for water No. 2. Mixing the tubewell waters with equal proportions of canal water would eliminate the need for gypsum to attain an SAR of 10 in Blend 1 and would decrease the gypsum required in Blend 2 by about 70%. Therefore, waters with similarly high Na and HCO_3 should be blended as much as possible with better quality water before attempting to alter the SAR by adding gypsum.

GYPSUM SOLUBILITY STUDIES

Materials and Procedures

A mill-run agricultural gypsum from Salida, Colorado was obtained for the experiments. The particle size distribution of the material after sieving is shown in Table 2. The calcium and sulfate contents of each particle size of gypsum were determined. A powered reagent grade $CaSO_4 \cdot 2H_2O$ (gypsum) was used in one part of the studies.

Table 2. Particle size distribution of the Salida gypsum.

Size-mm mesh	1-2 10-18	.5-1 18-35	.25-.5 35-60	.1-.25 60-140	.05-.1 140-300	< .05 > 300
%	20.1	16.6	10.2	34.2	10.4	8.5

Gypsum Dissolution by Shaking

Ten grams of each particle size of gypsum were added to 1 liter of distilled water in shaking flasks in concurrent runs. After adding the gypsum to the water and shaking the flask by hand for about 10 seconds to obtain a suspension, a sample was withdrawn for centrifuging and analysis. Then the flasks were shaken in a high-speed Everbach horizontal shaker. Two different

runs were made for each particle size. In the first run, the shaker was stopped after five minutes to withdraw a sample and then sampled at 10-minute intervals. In the second run, the shaker was stopped for sample withdrawal after 10 minutes and 10-minute intervals thereafter. Thus, by combining the two runs a sample was withdrawn at shaking intervals of 5 minutes. Each sample withdrawn was centrifuged and the clarified solution decanted within a 5-minute period. The solutions were analyzed for calcium by EDTA (Versene) method (Heald, 1965).

Gypsum Dissolution in Soils

Two soils differing in texture, Gunbarrel loamy sand and Nunn clay loam, were used. The soils were first leached with distilled water to remove sulfate ions from the soils and reduce effluent discoloration which was found to interfere with the chemical analysis of the effluent solution. The soils were then dried, crushed, and remixed. Gypsum of each particle size equal to 1 gram of chemically pure $CaSO_4 \cdot 2H_2O$ (equivalent to a 1.6 T/A rate) was thoroughly mixed in the top half (2-in depth) of each individual soil sample and placed on top of an equal depth (2-in) of gypsum-free soil in 2.75-in I.D. lucite columns. Each sample was then mechanically compacted to a 4-in depth to achieve a predetermined bulk density. In additional soil samples chemically pure reagent grade gypsum was used in place of the agricultural gypsum. Distilled water was added with a mariotte syphon arrangement and the effluent solution was collected in 50-ml aliquots in volumetric flasks (equivalent to 0.51 in of water). Three different runs were made using the same procedure. Sulfate ion concentration was used as the measure of gypsum solubility because calcium exchange reactions and lime solubility made calcium an unreliable index. Sulfate in the effluent samples was determined turbidimetrically as barium sulfate

(Bardsley and Lancaster, 1965) with a Coleman spectrophotometer. Duplicate analyses of each effluent sample were run as a minimum. The time to collect each 50-ml volume of effluent was recorded to calculate infiltration rates.

Results and Discussion

Shaking Experiment

The effects of particle size on gypsum solubility in the shaking experiment are shown in Figure 2. The 5-minute time to suspend, withdraw, centrifuge, and decant the sample was considered as the initial "contact time". The solubility differences of the particle size of gypsum are clearly shown in the first 5 minutes contact time before mechanical shaking was started. The Ca concentration of the <0.05 mm material was near (28.3 me/l) saturation for gypsum whereas little dissolution took place in the 1-2 mm material (0.9 me/l). All sizes <0.5 mm were nearly saturated (30.6 me/l) after 10 minutes shaking time. This indicates that in turbulent flow relatively rapid dissolution of <0.5 mm gypsum will take place if it remains in suspension. Quite precise control of calcium concentrations necessary to lower SAR levels to specific values should be obtained with <0.25 mm (<60 mesh) gypsum metered into flowing water. The 1-2 mm size dissolved at a much slower rate and required about 75 minutes to reach a saturated solution. However, less than 15 minutes were required to reach one-half saturation (about 15 me/l). Thus, the coarser sizes which could be placed in cross sections of ditches exhibit sufficient solubility to be useful in altering water quality.

Soil Dissolution Experiment

The effects of particle size on gypsum solubility in soil as measured by sulfate concentration of the effluent is shown in Figure 3. The smaller

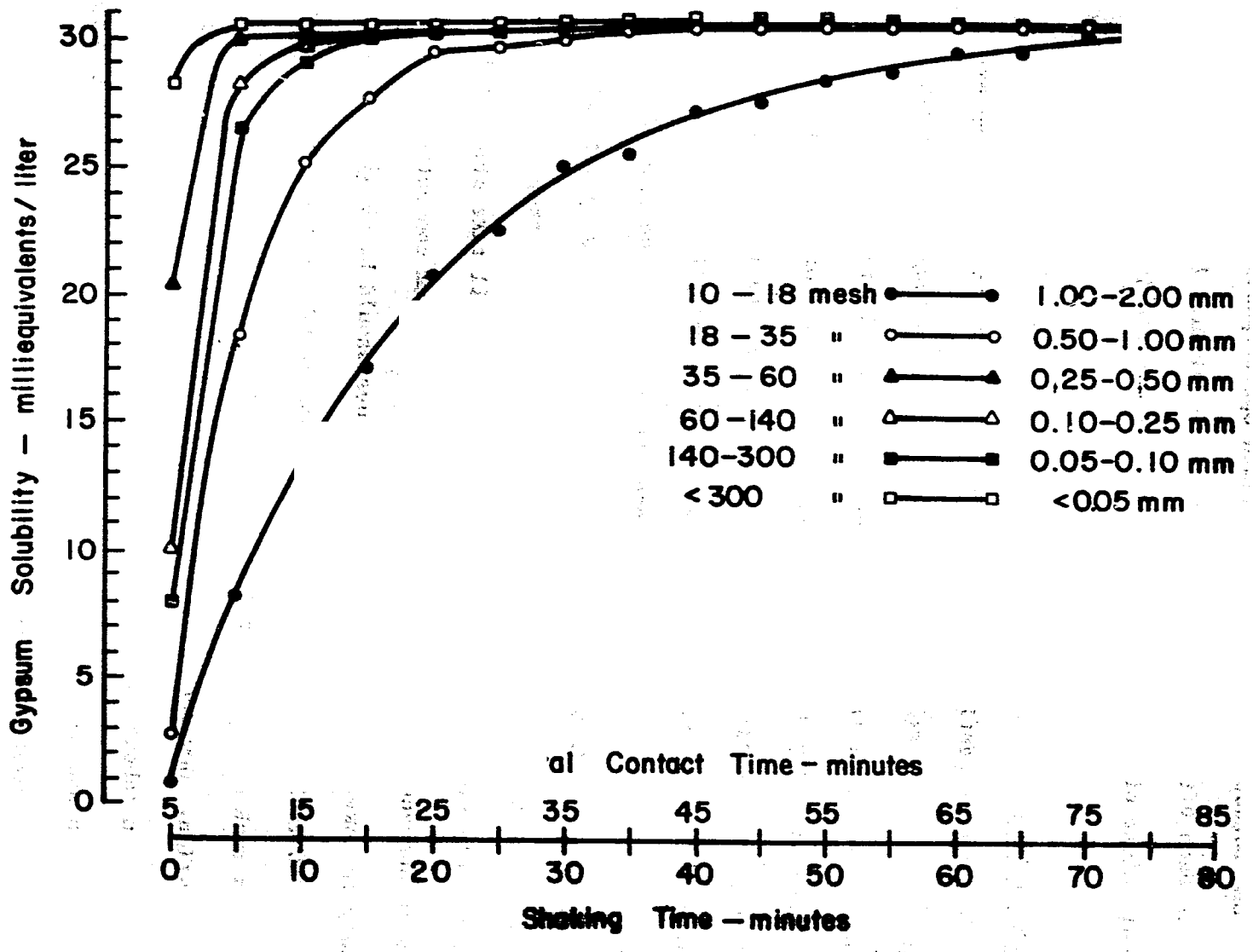
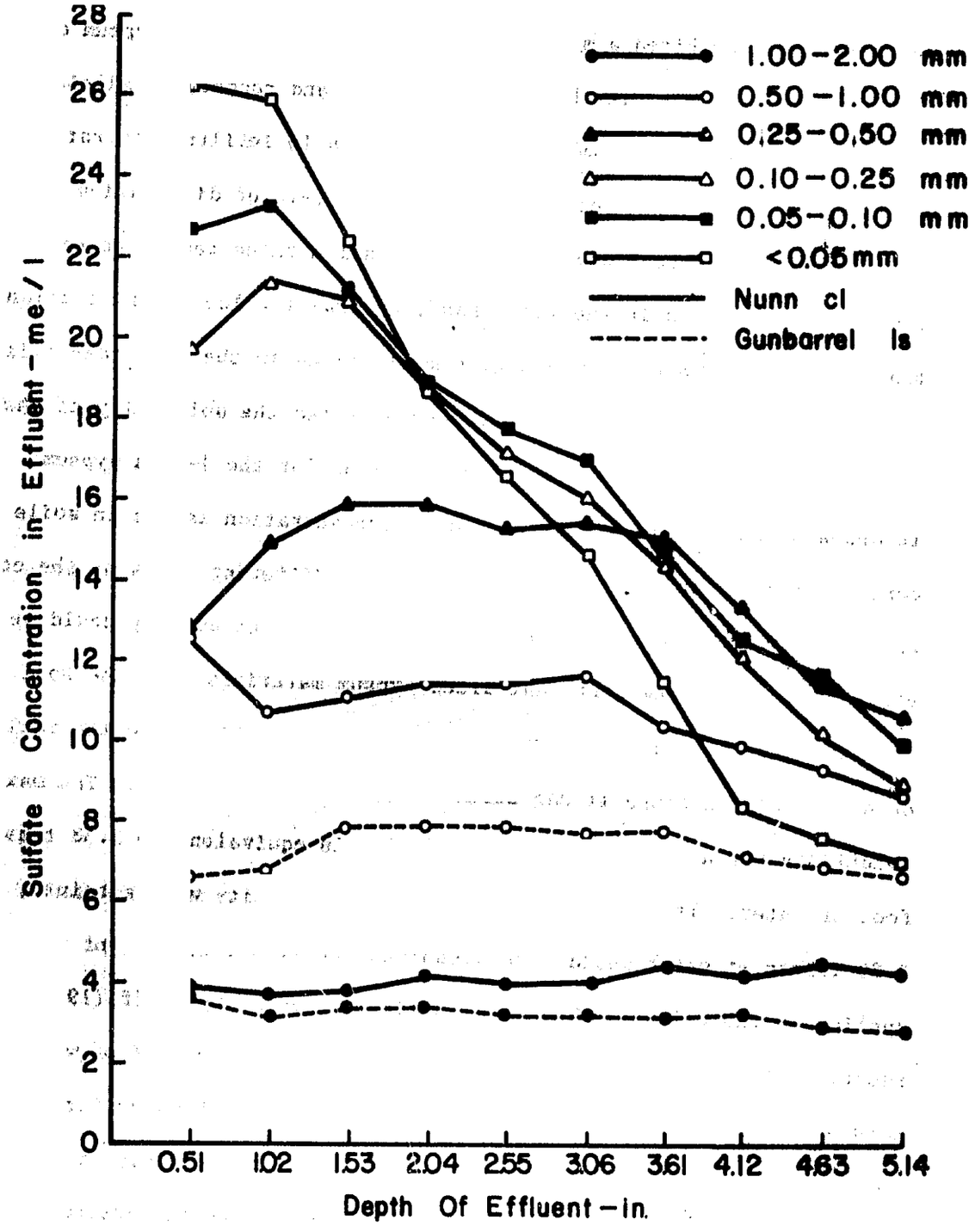


Figure 2. The effects of particle size, contact time, and shaking time on gypsum solubility.

gypsum sizes showed a higher average solubility in the wetting front but steadily decreased in concentration due to the limited amount applied. The coarser sizes exhibited a more constant dissolution rate. Gypsum dissolution was consistently lower in the loamy sand soil and roughly paralleled the concentration in the clay loam soil. Differences in infiltration rates occurring between the three different runs affected the rate of dissolution but not in a completely consistent way. High infiltration rates tended to reduce gypsum content of solutions in the loamy sand, whereas the lower infiltration rates tended to reduce rates at which gypsum dissolved in the clay loam soil. Infiltration rate and texture differences affected the solubility of the finer particle size gypsum to a greater degree than for the 1-2 mm gypsum. Thus, it appears that solubility rates and Ca concentration levels in soils could be controlled to a considerable degree by using different sizes of the coarser grade gypsum materials. Therefore, irrigation water quality could be altered efficiently by mixing different-sized gypsum materials into the soil.

The effect of gypsum size on solubility is pertinent to the reclamation of sodic soils because it can affect reclamation efficiency. The maximum solubility for a saturated gypsum solution is equivalent to 3.58 tons per acre-foot of water. If the theoretical maximum solubility were attained, only 3.89 inches of water would have dissolved the 1.16 tons/acre of gypsum applied in the columns. The U. S. Salinity Laboratory Staff (1954, p. 50) report that in the field about 1.3 tons/acre of gypsum, 85% of which will pass a 100-mesh screen, are dissolved per acre-foot of water for a 4-5 ton application rate. The percent solubility of the various gypsum particle sizes related to the theoretically maximum solubility (saturated solution) is shown in Table 3.



3. The effect of particle size and soil texture on gypsum solubility in soils.

Table 3. Average[1/] gypsum concentration of solutions passing through soils treated with gypsum of the indicated particle size as percentage of theoretical maximum soubility (per 3.89 in. of water) and average infiltration rates.

Gypsum Particle Size	Loamy Sand		Clay Loam	
	Solubility*	Infiltration	Solubility*	Infiltration
mm	%	in/h	%	in/hr
1-2	10.7	1.9	13.2	1.0
.5-1	24.3	2.2	36.9	1.1
.25-.5	36.7	2.0	48.8	1.2
.1-.25	45.4	2.0	58.4	1.2
.05-.1	52.1	2.0	61.7	1.2
<.05	52.8	2.0	60.8	1.2
Average	37.0	2.0	46.6	1.2

1/ Average of 3 runs.

* Standard error of means of particle size solubility = 6.2%

The gypsum concentrations of solutions coming through soils increased progressively as the gypsum particle sizes decreased down to 0.1 mm material. There was no statiscally significant difference between the gypsum concentrations when gypsum particle sizes were ≤0.1 mm in either soil. There was a highly significant difference between the average gypsum concentrations coming out of the two soils. The reason for this difference is interpreted as being due primarily to difference in infiltration rates. The average infiltration rate of the loamy sand and soil was almost double that of the clay loam soil. Less contact time of water with gypsum particles under high infiltration rates probably produced this difference. There is a possibility that "boundary flow" along the edge of the lucite tube may have been greater

for the loamy sand soil and could account for some of the difference. However, the small difference (about 2%) in solubility percentages for the 1-2 mm size would indicate that possible boundary flow differences were not important or absent.

The results in Table 3, which pertain to the solubility efficiency of the first 3.89 acre-inches of effluent solution, are not completely comparable to soil reclamation treatments where total dissolution is the main criteria. Complete recovery was attained for the <0.05 mm gypsum in only two of the separate runs and in only one of the separate runs for the 0.05-0.1 mm gypsum. The dissolution efficiency was highest for the powdered reagent grade gypsum. This was calculated to be 1.81 and 1.66 tons/acre-foot of water for the clay loam and loamy sand soils, respectively. Dissolution of the <0.05 mm gypsum was 1.58 and 1.31 tons/acre-foot and dissolution of the 0.1-0.05 mm gypsum was 1.45 and 1.16 tons/acre-foot for the clay loam and loamy sand soil, respectively. The dissolution of the latter two gypsum sizes is comparable to the average 1.3 tons/acre-foot for the 4-5 ton/acre application rate reported by the U. S. Salinity Laboratory Staff (1954). However, dissolution of the 1-2 mm gypsum in soil is estimated by extrapolation of average sulfate concentrations in the effluent samples, to be about 0.3-0.4 tons per acre-foot of water. Thus, it is concluded that large particle sizes (>100 mesh) would significantly reduce gypsum dissolution efficiency in soil applications for reclamation purposes.

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EVAPOTRANSPIRATION AND IRRIGATION WATER REQUIREMENTS FOR PAKISTAN 1/

Wayne Clyma 2/

Estimation of evapotranspiration 3/ is of interest for several applications in Pakistan. Primary among these are to estimate the irrigation water requirements of growing crops to know when to irrigate and to provide comparative data in water management research between measured soil moisture use and estimated soil moisture use. Proper On-farm water management in Pakistan requires careful consideration of the rate at which crops use water and the levels of soil moisture depletion that develop in the soil.

Many of the methods for estimating evapotranspiration are considered unacceptable for short term estimates and relatively inaccurate for periods up to one month. Experience with the Jensen-Haise (Jensen and Haise, 1963) method of estimating evapotranspiration suggests an accuracy which approaches the accuracy of soil moisture measurements for periods of seven to ten days or more [Jensen (1966), Jensen et al (1971)].

The primary data requirements for estimation of evapotranspiration using the Jensen-Haise method are long term mean maximum and minimum temperatures and for each daily estimate the daily solar radiation, daily mean temperature and the crop coefficient curves for each particular crop. These data are available for Pakistan and equations applicable for Lahore, Lyallpur, Sargodha, Peshawar, and Multan are presented with illustrations of the use of the equation at Sargodha.

1/ Prepared for publication in Indus, a monthly publication of the Water and Power Development Authority, Lahore, Pakistan. This research is supported by USAID contract csd-2162.

2/ Agricultural Engineer, Agricultural Engineering Department, Colorado State University, Water Management Research Contract, Islamabad, Pakistan.

3/ A glossary of words are defined at the end of the paper.

Data on long-term mean temperatures are difficult to obtain for most locations in Pakistan. A report by Asghar and Nur-ud-Din (1962) gave long-term mean maximum and minimum temperatures for Lahore, Lyallpur, Sargodha located near the Mona Reclamation Project, Multan, and Peshawar and these are presented in Table 1. The maximum and minimum temperatures for June and August are presented because Jensen et al (1970) recommends that in a climate where there is a definite wet and dry season that coefficients for the evapotranspiration equation should be derived for the two definite climatic periods. June has the highest maximum temperature for the arid climate and August was selected to represent the monsoon climate. The maximum temperatures for July are higher than August but it was assumed that August was more appropriate for calibrating the evapotranspiration equation since the monsoon climate has the greatest effect during August. The evapotranspiration equation for the monsoon climate will be used for both July and August.

The relationship given by Jensen et al (1970) for potential evapotranspiration is

$$Et_p = C_T(T-T_x)R_S \quad [1]$$

where

Et_p is potential evapotranspiration

C_T is the air temperature coefficient, constant for a given area, and derived from long-term mean maximum and minimum temperatures.

T is mean daily temperature

T_x linear equation intercept for the temperature axis and constant for a given area.

R_S daily solar radiation in inches of water.

The necessary data for calibration of C_T and T_x are given in Table 1 for the stations listed.

Table 1. Summary of data for calibration of Jensen Haize evapotranspiration equation.

Location	Elevation (ft)	Long Term Average Temperature (°F)1/ Maximum June	Maximum August	Minimum June	Minimum August
Lahore	702	106	96	81	80
Lyallpur	600	106	97	82	81
Sargodha	600	107	98	80	79 2/
Multan	404	109	101	85	84
Peshawar	1175	104	96	79	78

1/ Temperature data from Asghar and Nur-ud-Din (1962)

2/ See West Pakistan Water and Power Development Authority

Table 2 presents the coefficients for the Jensen-Haise evapotranspiration equation for several locations for the arid and monsoon climates. C_T and T_X are the appropriate coefficients in computing evapotranspiration. No significant difference except in the third decimal place for C_T was obtained for any of the locations or for the arid or the monsoon climate. Thus, C_T for any location and for the arid and the monsoon climate are essentially equal. The maximum difference in T_X between locations is 1.1 for an arid or a monsoon climate. This suggests that location in Pakistan has a relatively small effect on evapotranspiration estimates. T_X, however, for an arid as compared to a monsoon climate has a difference approaching 5 degrees for some locations and could be significant in computi evapotranspiration. Details of the procedures for computing the various coefficient are given by Jensen et al (1970) and are reviewed by Clyma and Chaudhry (1974).

Table 2. Coefficients for Jensen-Haise evapotranspiration equation for several locations for arid climate and monsoon climate 1/

Location	C_H		C_T		T_X	
	Arid	Monsoon	Arid	Monsoon	Arid	Monsoon
Lahore	1.185	2.161	0.0124	0.0107	16.27	21.02
Lyallpur	1.224	2.110	0.0122	0.0107	16.68	20.98
Sargodha	1.093	1.79	0.0125	0.0112	15.47	19.92
Multan	1.129	1.816	0.0123	0.0111	16.01	20.22
Peshawar	1.292	1.565	0.0124	0.0129	16.62	20.08

1/ Arid climate applies to September thru June and monsoon is for July and August.

Potential evapotranspiration is of interest because it is a measure of the expected peak water use rates and, therefore, the consumptive use for given cropping patterns and intensities for irrigation projects. A fact that is frequently ignored when using potential evapotranspiration data is that consumptive use may be as little as 50% of the potential evapotranspiration. Evapotranspiration is reduced because of crop limiting factors. That is, a young crop growing in a field limits evapotranspiration because the young crop cannot transpire at the potential rate.

Table 3 presents the monthly potential evapotranspiration for Sargodha using mean monthly temperatures and mean monthly solar radiation for Sargodha and the Jensen-Haise equation. The maximum rate of potential evapotranspiration is 0.32 inches per day. This is a mean maximum rate and individual days and intervals of time of 7 to 10 days will exceed this rate by as much as 25 percent. Thus for a given climatic regime 0.4 of an inch per day can be expected for relatively short intervals of time of one to two weeks.

Table 3. Monthly potential evapotranspiration for Mona using mean monthly temperatures and mean monthly solar radiation from Sargodha and Jensen-Haise equation.

Month	Mean Monthly Temp. (°F)	Solar Radiation (in/day)	Evapotranspiration (in/day)	Mean Monthly Evapotranspiration (in)	(Accum/in.
January	53.0	0.17	0.08	2.48	2.48
February	58.5	0.21	0.1[illegible]	3.08	5.56
March	68.0	0.27	0.1[illegible]	5.58	11.14
April	77.5	0.32	0.2[illegible]	7.50	18.64
May	85.5	0.35	0.3[illegible]	9.61	28.25
June	93.5	0.33	0.3[illegible]	9.60	37.85
July*	91.5	0.30	0.2[illegible]	7.44	45.29
August*	88.5	0.29	0.2[illegible]	7.82	52.11
September	85.0	0.28	0.2[illegible]	7.20	59.31
October	77.5	0.24	0.1[illegible]	5.89	65.20
November	66.0	0.19	0.1[illegible]	3.60	68.80
December	56.5	0.16	0.0[illegible]	2.48	71.28

*Estimate based on using coefficients for monsoon climate.

1/ $E_{t_p} = C_T(T - T_x) R_s$

Arid: $E_{t_p} = 0.012 (T - 15.5) R_s$

Monsoon: $E_{t_p} = 0.011 (T - 19.9) R_s$

Table 3 also presents the mean monthly evapotranspiration and the accumulated annual potential evapotranspiration based on a period of 10 years of record for temperature and 5 years for solar radiation. Mean potential evapotranspiration for the Mona area is 6 feet per year. Net irrigation water

requirements for this location should be considerably less because of the mean annual precipitation of approximately 15 inches and reduced evapotranspiration due to crop limiting factors. Clyma and Chaudhry (1974) have presented detailed procedures described by Jensen et al (1970) and Jensen (1972) that may be used for estimating evapotranspiration for many different crops by using a crop coefficient that is based on the stage of growth of the crop. The relationship:

$$E_t = K_c E_{t_p}$$

where

E_t is evapotranspiration for a particular crop

K_c is the mean crop coefficient based on experimental data where soil moisture is not limiting

E_{t_p} is potential evapotranspiration

A realistic estimate of evapotranspiration can be obtained by computing evapotranspiration for a given cropping sequence for a particular year.

With this concept in mind, a cropping pattern of wheat for the rabi season and cotton for the kharif season was selected. Mean climatic data over estimate the minimum water requirements during wet years and underestimate the maximum water requirements for dry seasons. Thus, two wet seasons, one for the rabi and one for kharif, and similarly two dry seasons were selected. A planting date for wheat of November 1 and a harvest date of April 15 were selected. For cotton the planting date was assumed to be May 1 and the harvest date October 15. Actual cropping practices deviate from these sequences to some extent because it has been observed that wheat is commonly planted on land that was fallow for the rabi season. However, some overlapping or continuous cropping does occur. A planting and harvest date for wheat and cotton that would permit continuous cropping and a 200 percent cropping intensity is of considerable interest.

The general criteria for selecting the wet and dry seasons for rabi and kharif were to select out of ten years of record the seasons with the highest and lowest rainfall. Radiation will be reduced during rainfall periods, but periods of peak radiation may not occur during the dry year. Thus, the dry year may be an indication of peak seasonal net evapotranspiration, but it may not identify the design peak water requirements for adequate water supply for maximum crop yields.

Kharif water requirements for cotton are based on a normal planting date, but the harvest date is probably early. The amount of water used will not be appreciably greater because of maturation of the crop and low potential evapotranspiration. Other crops could be considered as representative of the kharif season such as sugar cane, rice or a fodder. Each of these crops have low actual evapotranspiration rates during April, May and June because of early stages of growth or because the soil is fallow. Sugar cane rauni irrigations do conflict with water required for wheat. This may be a serious problem because the author feels that demand for water is greatest at planting time for most crops because of the excessive amounts of water applied. This peak period would occur February thru April during the period of peak water demand for wheat. There would thus be a conflict for water.

Table 4 presents data on seasonal (rabi and kharif) and seasonal total potential evapotranspiration, and evapotranspiration and net irrigation water requirements for cotton and wheat for wet and dry seasons for Sargodha. Table 5 gives the ratios as percent of evapotranspiration and net irrigation water requirements to potential evapotranspiration for the wet and dry seasons and the seasonal totals. The ratio as percent of rabi, kharif and seasonal total potential evapotranspiration, evapotranspiration and net irrigation water

requirements are also given in Table 5. Evapotranspiration is approximately 85 percent of potential evapotranspiration during rabi for either the wet or dry year. Similarly, evapotranspiration during kharif is 70 percent of potential evapotranspiration whether during a wet or a dry season. Because of greater potential evapotranspiration during kharif, the seasonal totals tend to follow the pattern established for kharif.

Table 4. Potential evapotranspiration (E_{tp}), evapotranspiration (E_t), and net irrigation water requirements (net E_t) for Sargodha for season (wheat during Rabi and cotton during Kharif) and seasonal totals for a wet and dry season.

Type of Season	Rabi			Kharif			Seasonal Totals 3/		
	E_{tp}	E_t	Net E_t	E_{tp}	E_t	Net E_t	E_{tp}	E_t	Net E_t
Wet 1/	18.4	15.5	6.8	39.8	28.1	16.8	58.1	43.6	23.6
Dry 2/	20.9	17.3	16.3	45.8	31.1	25.8	66.7	48.4	41.5

1/ Wet season for Rabi was 1967-68 and for Kharif was 1969.

2/ Dry season for Rabi was 1970-71 and for Kharif was 1966.

3/ Mean annual potential evapotranspiration was 71 inches (from Table 3).

Table 5. Comparison of seasonal totals, rabi and kharif evapotranspiration (E_t) and net irrigation water requirements (net E_t) to potential evapotranspiration (E_{tp}) and the ratios of wet season to dry season potential evapotranspiration, evapotranspiration and net irrigation water requirements.

Type of Season	Rabi			Kharif			Seasonal Totals		
	E_t/E_{tp}		Net E_t/E_{tp}	E_t/E_{tp}		Net E_t/E_{tp}	E_t/E_{tp}		Net E_t/E_{tp}
Wet	84		37	71		42	74		41
Dry	83		78	68		56	73		62
	E_{tp}	E_t	Net E_t	E_{tp}	E_t	Net E_t	E_{tp}	E_t	Net E_t
Wet/Dry	88	90	42	87	90	65	87	90	57

The cropping pattern that results in low water use during the periods of high potential evapotranspiration is an important method for reducing water requirements in Pakistan. Potential evapotranspiration for April through June approaches 30 inches and rainfall is zero during many years. The current pattern of cropping suggests actual water requirements are as low as ten inches or one-third of the potential. A careful study may show that these practices are primarily to reduce water use as other cropping practices may produce higher yields. For example, studies at Mona have shown that plantings of cotton as early as April produced the highest yields, and this was the earliest date of planting in the experiment (West Pakistan Water and Power Development Authority, undated).

Net evapotranspiration is the water that must be supplied by irrigation and is the remainder after subtracting effective rainfall. The amount that rainfall exceeds the soil moisture depletion during an interval goes to deep percolation. The remainder is effective rainfall. The net irrigation water requirements during a wet season is near 35 percent of potential evapotranspiration, but during a dry season this requirement more than doubles to near 80 percent (Table 5). This is nearly the same as the change in rainfall from a wet to a dry season. Rainfall is generally low during the rabi season and any rainfall that occurs may be effective unless occurring just subsequent to an irrigation. There is a smaller range in the ratio of Net E_t to E_{tp} for the kharif in Table 5. Since in even dry years some rainfall events will exceed the soil moisture storage capacity, a smaller amount of the monsoon rainfall is effective and there is less of a difference between wet and dry seasons. Still, net irrigation water requirements during kharif average only 50 percent of potential evapotranspiration.

Another factor significantly affecting water demand in Pakistan is the increased humidity, decreased temperatures and radiation and significant amounts of rainfall during the monsoon. The potential evapotranspiration in August is 25 percent less than the potential evapotranspiration in June.

The relative effects of a wet season as compared to a dry season on each of the components of evapotranspiration are shown in Table 5 where the wet season to dry season ratios are given. The greatest effect is on net irrigation water requirements and is greatest during rabi.

Seasonal total potential evapotranspiration for Pakistan is quite large - approaching six feet (Tables 3 and 4). Evapotranspiration for a continuous cropping sequence and a 200 percent cropping intensity ranges from 3.2 to 4.0 feet (Table 4). This is a significant reduction in water requirements because of the particular cropping patterns in Pakistan.

Table 6 is a compilation of estimates of crop evapotranspiration as published by Sir Alexander Gib and Partners et al (1966) and the average of the wet and dry years as estimated using the Jensen-Haise procedure. The results are quite comparable and while great precision is not assured acceptable accuracy should be expected.

Table 6. Comparison of wheat and cotton evapotranspiration amounts as calculated using Jensen-Haise and those previously published.

Source	Wheat	Cotton
Jensen-Haise (Aug.)	16.1	29.6
World Bank	15	32
Harza	15	29
Blaney-Criddle	16	37
Asghar	13	28
White House Panel	14	38
Risalewala[1/]	14	29

1/ See also Harza Engineering Co. International (1965). Experimentally determined values.

Volume of water supplied appears to range from near 2 acre-feet per acre (AF/A) in non-SCARP (Salinity Control and Reclamation Projects) to near, 4AF/A in SCARP and private tubewell areas. As a volume required, the 2 AF/A would support even in dry years the approximately 80 percent cropping intensity frequently found in non SCARP areas in Pakistan assuming the water is available during a single cropping season. This assumes minimal losses in delivery and application of water to farmers' fields. The 2 AF/A is short if compared to potential evapotranspiration. Four acre feet could supply the requirements for two crops in dry years if minimal losses in delivery and application occur and there would be a surplus during wet years. Thus, the fact that SCARP areas average only 125 percent cropping intensity implies a considerable loss of water. That some watercourses exceed the 125 percent intensity implies that farmers on some watercourses are more effective.

The difference between what water is used affectively as implied by cropping intensity and how the water is actually used are two different conditions. If water is used ineffectively the cropping intensity can still be relatively higher by stressing the crop during the periods of rapid water use. Thus, because a cropping intensity of 80 percent can theoretically be supplied by 2 AF/A in a dry year does not mean that water is used effectively or that little water is lost through the delivery and application of the water. Instead, crops can be stressed during peak periods of water use and yields of the crops would be low. Crop yields in Pakistan are low. A double effect can be achieved through improved on-farm water management in Pakistan. Water can be saved and yields can be increased. The water saved can be used to crop more area and higher yields for all the crops can be achieved by properly managing water.

Peak water use rates are another criterion to judge the adequacy of an irrigation system. Standard water supply rates in Pakistan appear to average one cusec per 350 acres in non SCARP areas and one cusec per 150 acres in SCARP areas. Using the Jensen-Haise procedure for estimating daily rates of E_t, wheat and cotton have average daily rates for ten day intervals of 0.22 and 0.26 in/day, respectively. Using this criterion one cusec fpr 75 acres would be a more realistic supply for meeting the peak water requirements for maximum production. This also may suggest why SCARP areas have not achieved the cropping intensities planned, especially when much of the water available in a SCARP watercourse is not stored in the farmers fields for crop use.

GLOSSARY

Potential Evapotranspiration - the amount of water transpired from a unit area in a unit of time by a short green crop such as alfalfa, completely shading the ground, of uniform height and where water is not limiting.

Evapotranspiration or consumptive use - the amount of water transpired or used in building plant tissue and evaporated from the soil, or from intercepted precipitation from a unit area in a unit of time.

Deep Percolation - the amount of water which passes below the root zone of a crop and is not used by the crop by evapotranspiration.

Effective Precipitation - the amount of rainfall evaporated from plant or soil surfaces or stored in the root zone of the crop.

Net Irrigation Requirement - water that must be supplied by irrigation to satisfy evapotranspiration, leaching requirements and other miscellaneous water requirements minus the effective precipitation.

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Appendix H

GROUNDWATER QUALITY DISTRIBUTION NEAR THE RATTOKALA DISTRIBUTARY-MONA AREA

Report to

DIRECTORATE OF MONA RECLAMATION EXPERIMENTAL PROJECT

RECLAMATION DIVISION

MONA COLONY

BHALWAL

by

David B. McWhorter

Colorado State Universit

March, 19

BACKGROUND AND PURPOSE

The author of this informal report was on temporary duty in Pakistan from February 1 to March 15, 1973. The major purpose of the visit to Pakistan was to investigate the possibilities of conducting field research into methods by which sweet water can be recovered from saline groundwater aquifers. This objective led to the review of existing data at MONA plus the collection of limited additional data in an attempt to ascertain the suitability of the MONA Project Area as a site for the research.

Mr. Muhammad Ashraf, MONA Project Director, expressed interest in making an attempt to recover sweet water in a particular area where the existing deep wells are presently discharging water of unsuitable quality. The purpose of this report, prepared at Mr. Ashraf's request, is to document the data collected and to provide recommendations on what additional data is required and how the "skimming" facility should be constructed.

OBSERVATIONS

The MONA Project Area is bounded on three sides by canals; the Lower Jhelum Canal on the east, the Northern Branch of the Lower Jhelum Canal on the south, and the Shan Pur Branch on the north. Evidently seepage from these three main water channels keeps the water table sufficiently high on the north, south and east sides of the project area so that the direction of flow on these boundaries is inward, toward the center of the project area. The regional pattern of flow is toward the west end of the project area which is not bounded by a major water channel (1). A north-south cross-section through the project area at almost any point will show that the water table elevation decreases toward the center.

Contour maps, showing the areal distribution of total dissolved solids in tubewell water, clearly indicate that the best quality ground

water is located adjacent to the major water channels which form the boundaries of the project area. The groundwater quality deteriorates toward the center and toward the west side. Comparison of the water table and total dissolved solids maps, indicates that total dissolved solids increase in the direction of flow.

The public tubewells from which the water quality data was obtained are usually 200 feet or more deep. Typically, the top of the well screen (strainer) is 50-80 feet below the water table and extends to the bottom of the well. Thus the dissolved solids concentration in the discharge does not reflect the water quality in the first 100 feet below the water table to any significant degree.

One of the areas in which tubewell water is of particularly poor quality is along the Rattokala Distributary including tubewells numbered 33, 34, 36, 37, 39, 40, 41, 44, 45, 46, 48, 49 and 50. It is in this area, that tests were conducted to determine if any significant quantities of sweet water exist above the depth at which these wells pump. The pumping equipment was removed from tubewell 39 so that the pump could be inspected and to provide access for a device designed to collect water samples at various depths. Tubewell 39 had not been in use for several months prior to the time the samples were collected. The following data were taken.

TUBEWELL NO 39 - February 27, 1973.

Electrical Conductivity mmhos/cm	Depth Below Water Table - ft
0.75	1.5
0.74	10
0.72	20
0.70	30

Electrical Conductivity mmhos/cm	Depth Below Water Table - ft
0.70	40
0.70	50
0.70	60
0.70	62.5
0.70	70
0.70	80
0.72	90
1.55	106

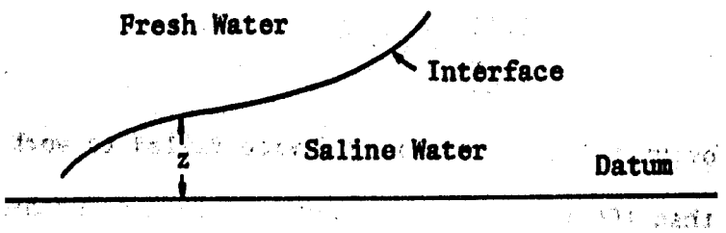
Unfortunately, the sampling device failed to work properly at depths greater than 106 feet below the water table and further sampling could not be accomplished. Nevertheless, the above data indicate a total dissolved solids concentration of approximately 500 ppm down to about 100 feet below the water table.

Water samples were also collected from six hand pumps in the immediate vicinity of tubewell 39. The electrical conductivity of the three samples collected on the north side of Rattokala Distributary ranged from 2.1 mmhos/cm for the pump nearest the canal to 2.9 mmhos/cm for the pump furtherst from the canal. The hand pump nearest the canal on the north side was estimated to be 750-1000 feet from the canal.

A hand pump about 500 feet from the canal on the south side produced water with a conductivity of 0.45 mmhos/cm. The conductivities of the remaining two samples were 1.3 and 2.4 mmhos/cm and were collected at a distance of some 1000 feet from the canal.

AN EXPLANATION

Some simple concepts which describe the behavior of idealized fresh-saline groundwater flow systems can be used to explain the observations described above. The system is idealized somewhat by assuming that the relatively gradual change between the saline water and the fresh water is replaced by an abrupt change. Thus, it is assumed that an interface exists between the fresh water and the saline water as shown below.



In reference 2, it is shown that the elevation z of the interface above some datum is expressed by

$$z = \frac{\rho_s}{\Delta\rho} H_s^i - \frac{\rho_f}{\Delta\rho} H_f^i \qquad (1)$$

where

ρ_s = density of the saline water

ρ_f = density of the fresh water

$\Delta\rho = \rho_s - \rho_f$

H^i = hydraulic head on the interface.

is also shown that the slope of the interface is given b

$$\text{slope} = \frac{\rho_f}{\Delta\rho} \frac{q_f^i}{K} - \frac{\rho_s}{\Delta\rho} \frac{q_s^i}{K} \qquad (2)$$

= velocity of fresh water on the interface.

= velocity of saline water on the interface.

= hydraulic conductivity (permeability).

Precise values of q_f^i and q_s^i are difficult to measure, but qualitative estimates of the direction and magnitude of flow are often sufficient. In the case of interest in this report, it is assumed that $q_s^i = 0$ and that the direction of q_f^i can be estimated from the water table contour map.

Equation 2, with the second term on the right equal to zero, predict that the interface will slope upward in the direction of flow. Furthermore, the magnitude of the slope of the interface is much, much greater than the slope of the water table. This is true because the numerical value of $\rho_f/\Delta\rho$ is large (40 or more).

It has already been pointed out that, in the Mona Project Area, the flow on the north, east, and south boundaries is toward the center of the area. Equation 2 predicts that the interface should slope upward toward the center of the project, therefore. In other words, poor quality groundwater would be expected to be nearest the surface toward the center and west end of the project area. Maps of the distribution of total dissolved solids (ref. 1) show that this is indeed the case.

Equation 1 can be used to estimate the change in depth of the fresh water zone in local areas in response to a change in water table elevation. The equation predicts that a unit increase in H_f^i will produce a decrease of $\rho_f/\Delta\rho$ in the elevation of the interface. From a practical standpoint, this means that small increases in water table elevation produce large depressions in the interface elevation.

The above rationale can be used to estimate the consequences of seepage from Rattokala Distributary. Even small quantities of percolation through the bottom and sides of the canal tend to create a groundwater mound beneath, which in turn, tends to depress the saline water. A short distance away from the distributary, the mound is probably insignificant and the saline water will not be depressed. Therefore, a narrow "trench" of sweet groundwater can be expected beneath the distributary in those areas where pumping has been terminated for several months. It is believed that this is the reason why sweet water was found in tubewell 39 (immediately adjacent to the canal) to a depth of 110 feet below the water table and why saline water was found to exist near the water table several hundred feet away from the channel. A schematic cross-section showing the conditions that are believed to exist in the vicinity of tubewell 39 is shown in Figure 1.

RECOMMENDATIONS

The quantity of data upon which the above interpretations are based is quite limited. It is recommended, therefore, that additional data be collected. Samples at various depths in several more wells along Rattokala Distributary should be taken in a manner similar to that used at tubewell 39. Samples should be taken in only those wells which have not been pumped for several months. Samples of water from hand pumped wells should be collected as well. The vertical and lateral distribution of sweet water along the canal can be mapped from the analysis of the samples.

A simple device for collecting samples at various depths can be constructed from a flexible, plastic bottle. Obtain a rubber or cork plug which will seal the top of the bottle. Attach a cotton rope (or something similar) securely to plug and another rope to the bottle.

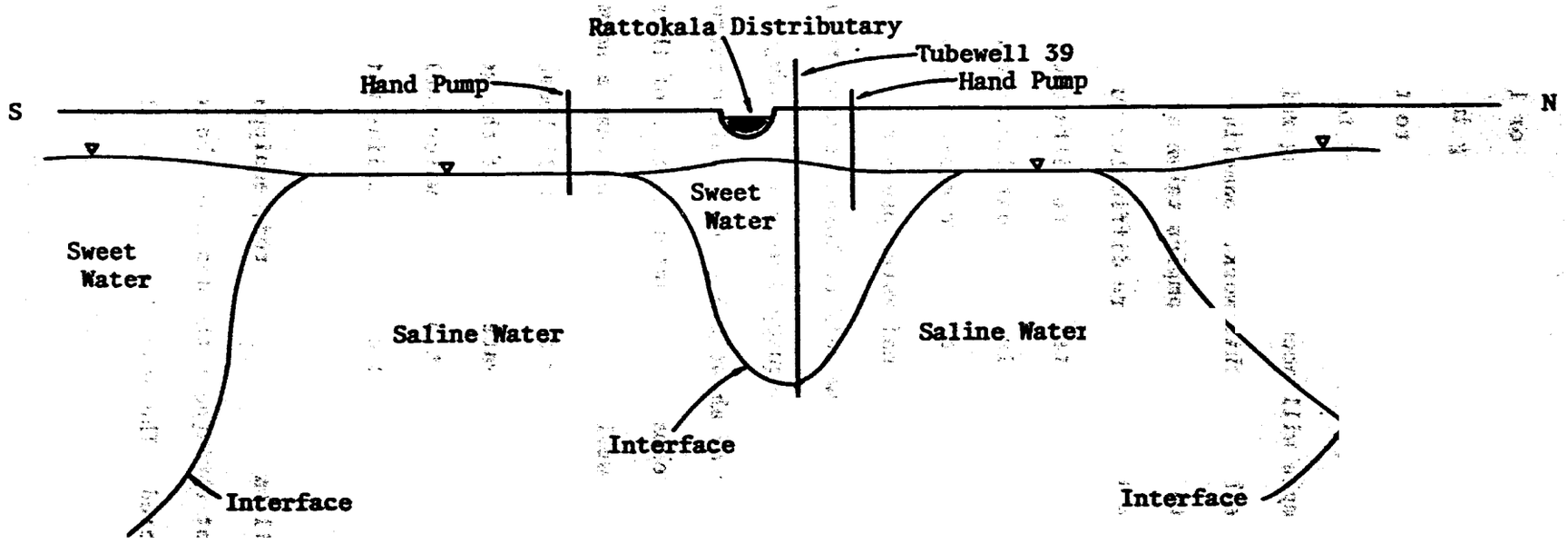


Figure 1. Schematic North-South Cross-section at Tubewell MN #39.

Weight the bottle by placing stones, scrap steel, or lead on the inside so that the bottle will sink readily with the plug in place.

The procedure is to allow the bottle to sink to the desired depth and then pull the plug. The bottle is then lifted to the surface. Some contamination of the sample will occur while being raised to the surface, but the data will be useable for this work. Sampling should be begun near the water table with subsequent samples taken at greater and greater depths. As the depth is increased, more difficulty pulling the plug will be experienced because of the greater pressure difference between the outside and the inside of the bottle. This difficulty can be minimized by using a small diameter plug and a flexible plastic bottle which will partially collapse under the external water pressure.

It is recommended that a new well be bored as near tubewell 39 as practical. This well should be equipped with a centrifugal pump with a maximum discharge capacity of about 0.5 cusec. Well construction and pump specifications are presented in a later section of this report. Note that the recommended well is much shallower than a normal tube well. Tubewell 39 is not appropriate for a skimming well because the top of the screen is some 70 feet below the water table. If the well were simply plugged back to a depth of 100 feet below the water table, the remaining open area of the screen would be too near the saline water to operate effectively.

After the new well has been constructed, equipped, and samples collected every 10 feet throughout the depth of the well, the following tests should be conducted. The well should be pumped at a very low discharge (say 25 gpm) for about two weeks. The actual discharge should be measured. A valve in the discharge line can be used to control the discharge. Throughout the two week period, samples of the discharge should

be collected daily and the water level and drawdown in the well noted. The water level in tubewell 39 should also be recorded daily. Near the end of the two-week period, the vertical distribution of total dissolved solids in tubewell 39 should be determined.

The next step is to increase the discharge to about 50 gpm and repeat all of the above procedures. Again the time period should be two weeks. The above processes are repeated in steps of 25 gpm discharge until a discharge of 125 gpm is reached. The discharge is then increased in increments of 50 gpm until the pump capacity is reached.

The data collected from these tests, coupled with maps showing the vertical and lateral distribution of sweet water along the distributary will form the basis for analyzing the feasibility of installing more "skimming wells" along the canal, provide data on the maximum safe discharge of skimming wells and other data required for a rational design of future skimming wells.

The importance of determining the relationship between discharge and dissolved solids concentration in the discharge cannot be over emphasized. There is a great deal of laboratory data and theoretical research which indicate that the quantity of dissolved solids pumped from a skimming well depends strongly on the pumping rate. It is quite likely that the optimum discharge of the skimming well will be found to be on the order of 0.2 cusecs. In this case, since the wells are shallow and relatively inexpensive, several skimming wells can be bored in an area, connected through a manifold, and pumped in battery by a single pump. In this way, discharges of 1 cusec or more might be attained without serious contamination from salt. The feasibility of these ideas depends upon the results of the test outlined above.

SKIMMING WELL DESIGN

The data collected at tubewell 39 show that the groundwater begins to get salty about 90 feet below the water table (Figure 2). Laboratory and theoretical research indicate that the optimum penetration of skimming wells is 30% or less of the thickness of the sweet water zone. From Figure 2, it is observed that the thickness of the sweet water zone is nearly 100 feet. Therefore, the skimming well should be constructed to a depth of 30 feet below the water table. A diagram of the well construction is shown in Figure 3.

The maximum water horsepower that will be required is 2.5 HP. Without knowledge of the efficiency of the particular pump selected, the required brake horsepower of the motor cannot be calculated accurately. Certainly a motor which will develop a brake horsepower of 5 HP should be adequate to drive the pump.

REFERENCES

1. Annual Report of MONA Reclamation Experimental Project, July 1971-June 1972. WAPDA.
2. McWhorter, D. B., Steady and Unsteady Flow of Fresh Water in Saline Aquifers, WMR Tech. Report #20, Colorado State University, Fort Collins, Colorado.

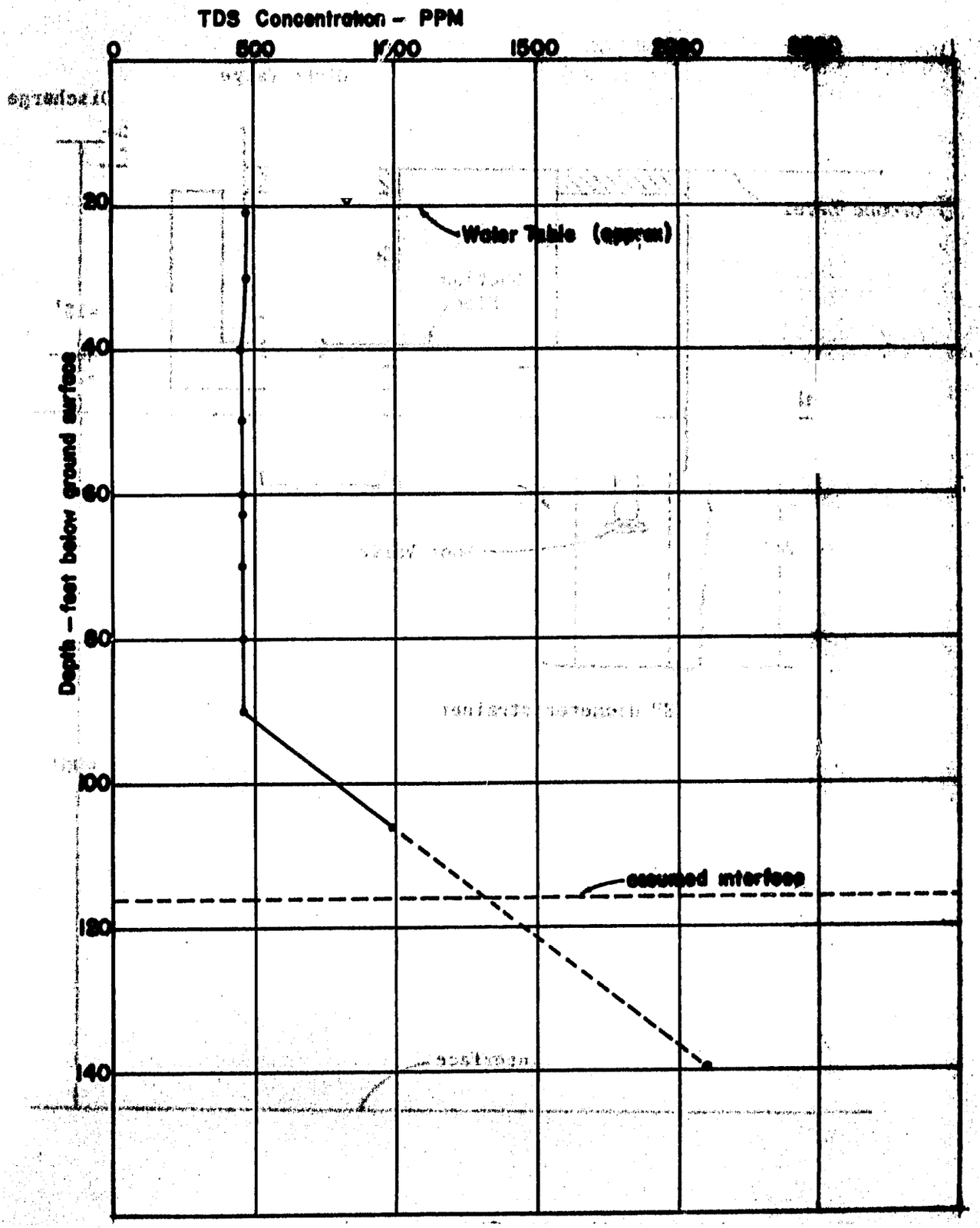


Figure 2. Salt concentration profile tubewell MN 39.

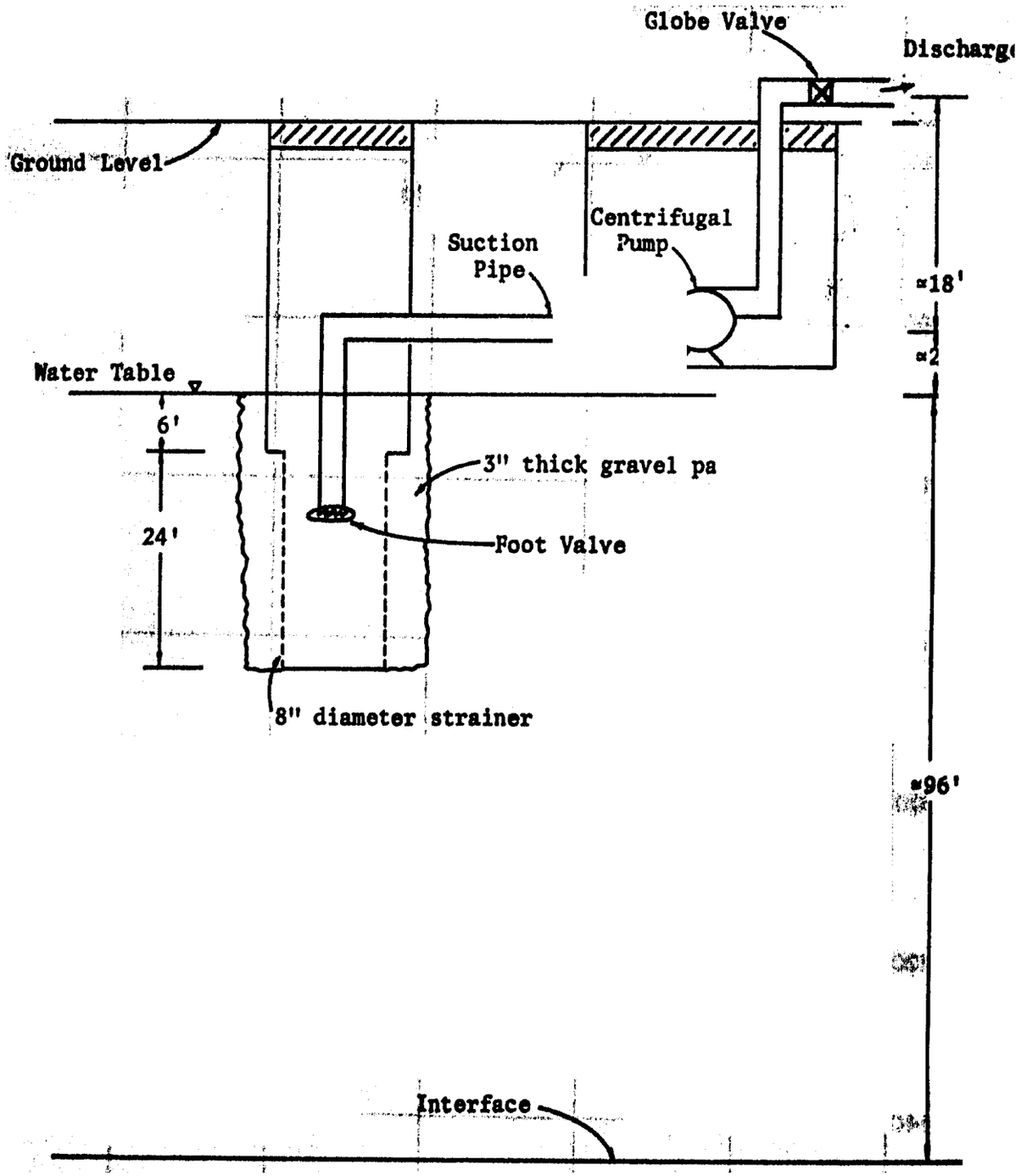


Figure 3. Schematic diagram of skimming well.

Appendix I

I-1

Progress Report Water Quality Experiments, Lyallpur [1]

J.J. deMooy, H.M. Bhatti, and A.A. Cheema

Infiltration rates of irrigation water were measured on all plots of the experimental area at Lyallpur on April 24 through 27. Three crops, wheat sorghum fodder, and berseem, were grown in succession using various water qualities (175, 1000, 2000 and 2700 ppm soluble salts). After harvesting the third crop, a special irrigation was applied using the four water qualities each with three leaching fractions and three replications (36 plots). The entire plots were irrigated and the rate of recession of the water level measured. The results are summarized in six graphs and five tables.

Considerable difference in infiltration rate was found between the water qualities Q_1, Q_2, and Q_3. Use of the poorest quality water, Q_4, led to an intermediate infiltration rate (Figure 1). The graphs represent means of 3 leaching fractions and 3 replications. The mean rates of infiltration for absorption of 1, 2, and 3 inches of water are summarized in Table 1. The main distinction is between canal water (Q_1) and the other qualities. The time required for absorption of 1.5 and 3 inches of water is shown in Table 2. It appears that 1.5 inches of water enter the soil in less than 10 hours. Only the soil irrigated with canal water had the capacity to absorb 3 inches of water in a relatively short time. The period of inundation exceeded 24 hours using the other water qualities.

nternal report only, not for publication

The variation in infiltration rates associated with leaching fractions was small for Q_1 and Q_3, but rather substantial for the qualities Q_2 and Q_4 (Figure 2, 3, 4, 5). It is likely that the differences reflected random variation whic will be tested later by statistical analysis of the data.

Twelve-inch diameter rings were used to evaluate the initial rates of infiltration. Three rings were placed in a plot irrigated with canal water and three in a plot receiving tubewell water (Q_4). The location of the rings repre sented a high spot, a shelf area, and a depression in each plot. The maximum difference in elevation was of the order of 3 inches. The water level in the rings was maintained at approximately one inch. Observations were made simultaneously with the irrigation of the entire plots.

The initial rate of infiltration exceeded 2 inches per hour on all plots, but was maintained only for a few minutes (Table 3). There was little differenc among the three rings in the canal water plot, but large differences occurred within the tubewell water plot. Water entered the soil three times as fast in depressional areas compared with the high spots. After 22 minutes the average rate of brackish water entry in the depressions still exceeded that of canal water, but shelf areas and high spot fell behind. Brackish water entry in depressions kept pace with that on canal water plots for a period of one to two hours, then fell behind. Table 4 shows mean infiltration rates for one, two or more inches of water under the various conditions. The data in Table 5 indicate that the time required for absorption of 3 inches of tubewell water was rather long regardless of the microtopography owing to very low final infiltration rates in both depressions and high spots. When the required time for entry of 1.5 inches of water is short and the time required for 3 inches is very long, the possibility exists that two irrigations of 1.5 inches each could prevent crop injury that might occur when the

land remains inundated for a long time after application of 3 inches of wate Assuming the occurrence of extensive areas of land resembling the conditions described under "depressions", the practice of frequent but light irrigations could be beneficial to the farmer, especially during periods of hot weather. On the other hand, very few fields in Pakistan are sufficiently level to permit 1.5 inch irrigations. Furthermore, such practices are not practicable for farmers operating under fixed irrigation schedules and could lead to salt accumulation if continued too long.

The observed differences in rate of water entry between depressions and high spots may partly explain the renewed upward trend in infiltration rates which is noticeable after 24 hours using brackish water on entire plots (Figures 1, 3, 4, 5). One day after water application the high spots are exposed and the rate of infiltration is entirely that of the depressional areas. Rising temperatures after sunrise of the second day presumably had an effect also. This effect could explain slightly upward trends in Figure 6.

TABLE 1 Mean rates of infiltration (inches/hour) of various amounts of water as affected by water quality, Lyallpur, April 1973.

Amount of water (inches)	Rate of infiltration (inches/hour)1/			
	175 ppm	1000 ppm	2000 ppm	2700 ppm
1	0.75	0.27	0.19	0.23
2	0.57	0.17	0.11	0.13
3	0.47	0.12	0.10	0.10

1/ Means of 9 observations

TABLE 2

Time required for absorption of water by the soil as affected by water quality, Lyallpur, April 1973.

Amount of water (inches)	Absorption time (hours/minutes)			
	175 ppm	1000 ppm	2000 ppm	2700 ppm
1.5	2.25	7.35	9.45	8.35
3.0	6.30	25.35	31	30

TABLE 3

Mean rates of infiltration (inches/hour) in 12-inch diameter rings as affected by water quality and micro-relief of the field, Lyallpur, April 1973.

Period of time	Rate of infiltration (inches/hour)			
	175 ppm 1/	2700 ppm		
		Depression	Shelf area	High spot
4 mins.	2.25	6.56	3.75	2.34
22 mins.	1.38	1.68	0.89	0.77
1 hour	0.94	0.94	0.56	0.34
2 hours	0.63	0.58	0.38	0.23
10 hours	0.29	0.19	0.15	0.11

1/ Means of observations for depression, high spot, and shelf area.

TABLE 4

Mean rates of infiltration (inches/hour) of various amounts of water measured by means of the ring method as affected by water quality and microrelief of the field, Lyallpur, April 1973.

Amount of water inches	Rate of infiltration (inches/hour)			
	175 ppm 1/	2700 ppm		
		Depression	Shelf Area	High Spot
1	0.83	0.83	0.24	0.12
2	0.38	0.19	0.08	0.07
3	0.29	0.10	0.08	0.07
4	0.22			
5	0.19			

1/ Means of observations for depression, high spot, and shelf area.

TABLE 5

Time required for absorption of water by the soil as affected by water quality and microrelief of the field, Lyallpur, April 1973.

Amount o of water (inches)	Absorption time (hours/minutes)			
	175 ppm 1/	2700 ppm		
		Depression	Shelf Area	High Spot
1.5	3	4.45	10.25	19.10
3.0	10.20	30	34.10	40.50

1/ Means of observations for depression, high spot, and shelf area.

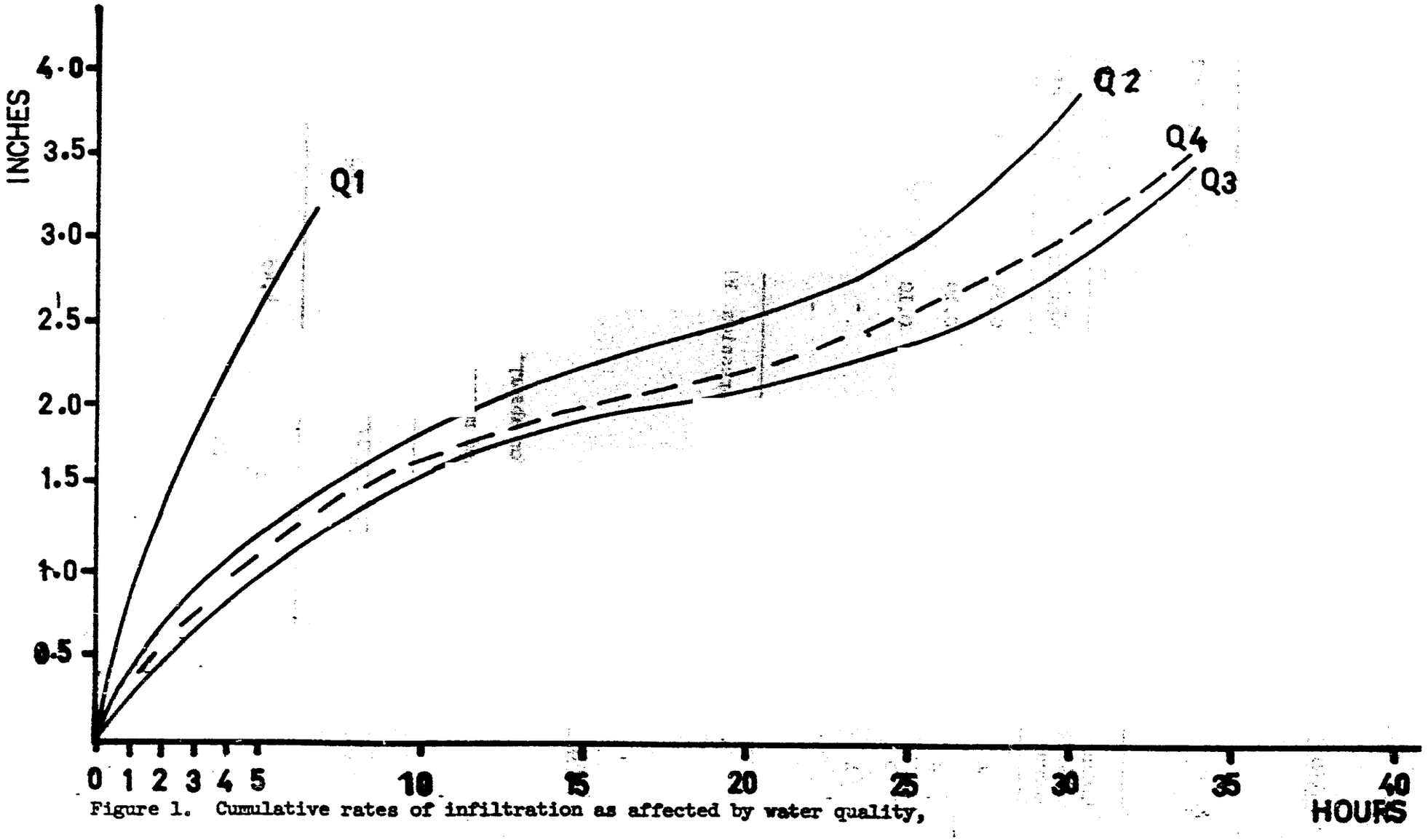


Figure 1. Cumulative rates of infiltration as affected by water quality, PARI, Lyallpur.

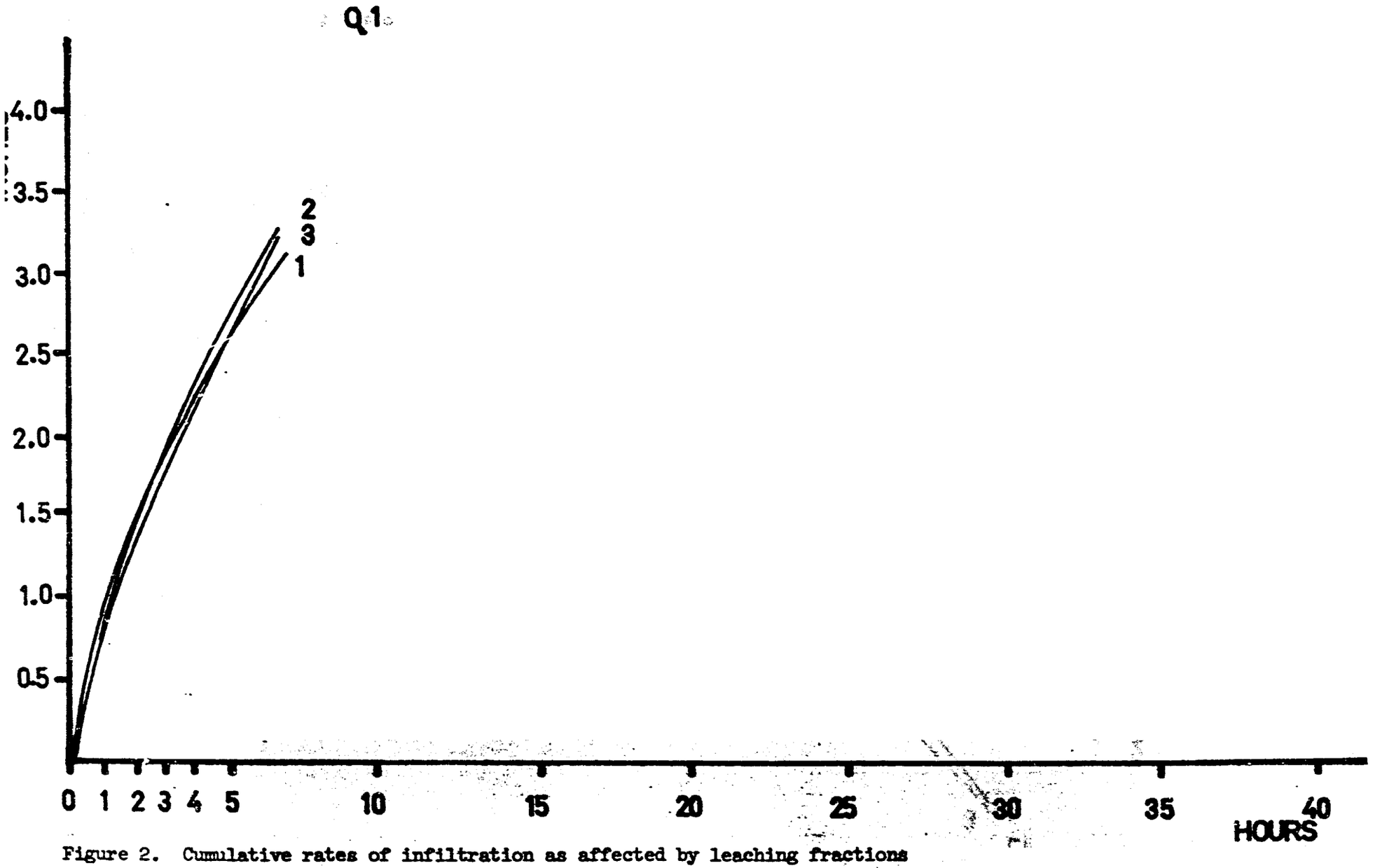


Figure 2. Cumulative rates of infiltration as affected by leaching fractions of 0, 10, and 20% on plots irrigated with canal water (175 ppm TDS), PARI, Lyallpur.

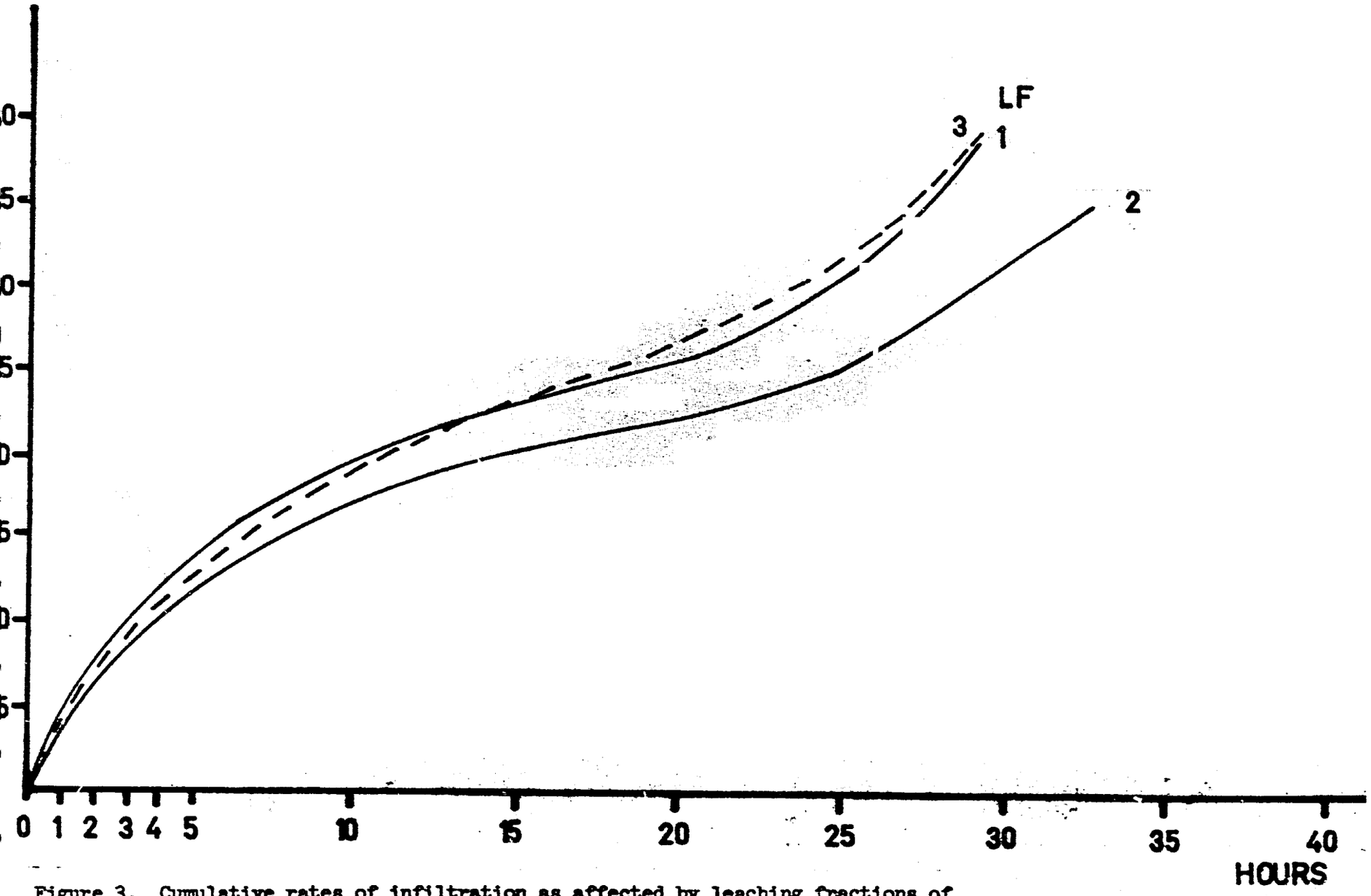


Figure 3. Cumulative rates of infiltration as affected by leaching fractions of 10, 20 and 30% on plots irrigated with water containing 1000 ppm TDS, PARI, Lyallpur

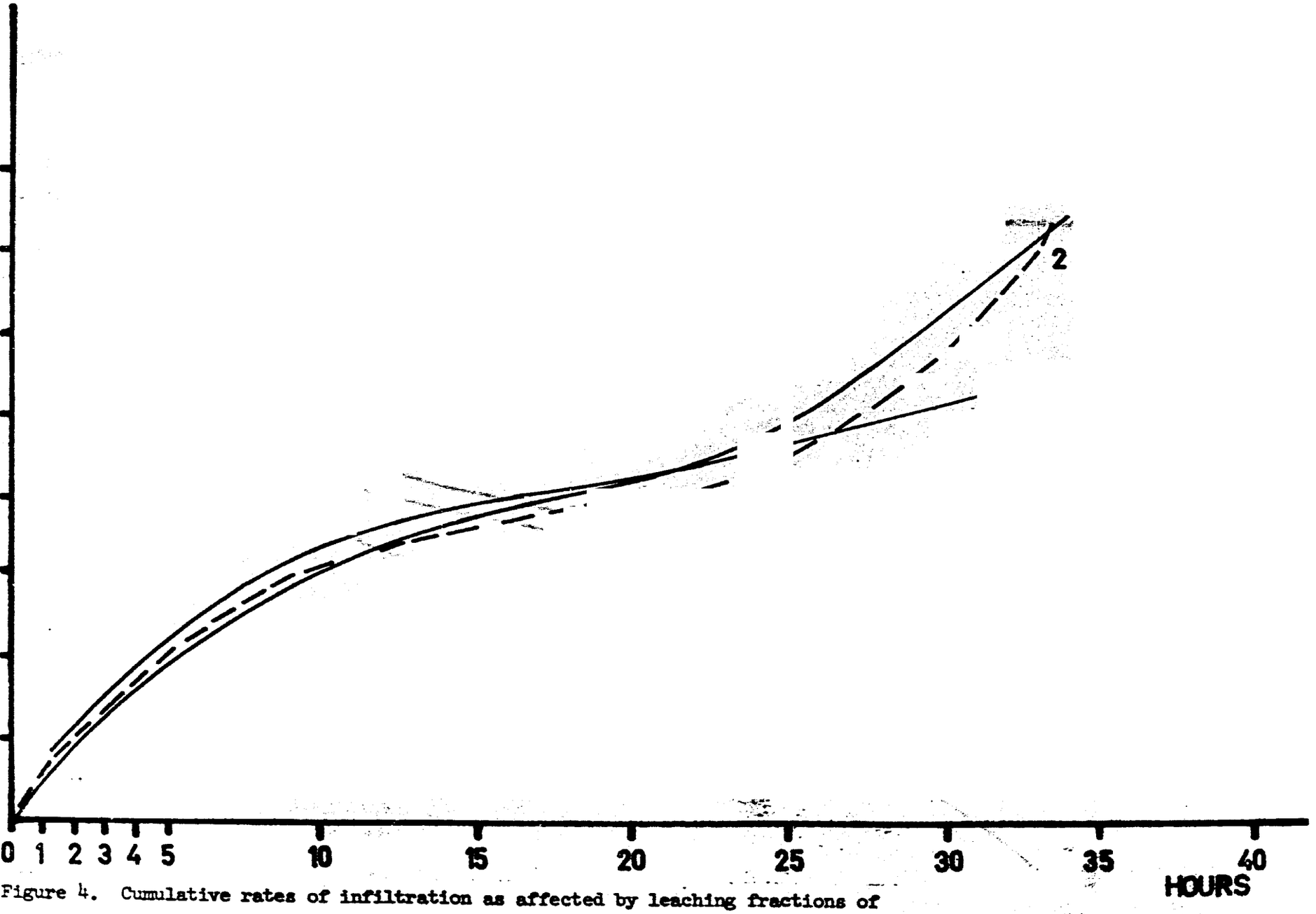
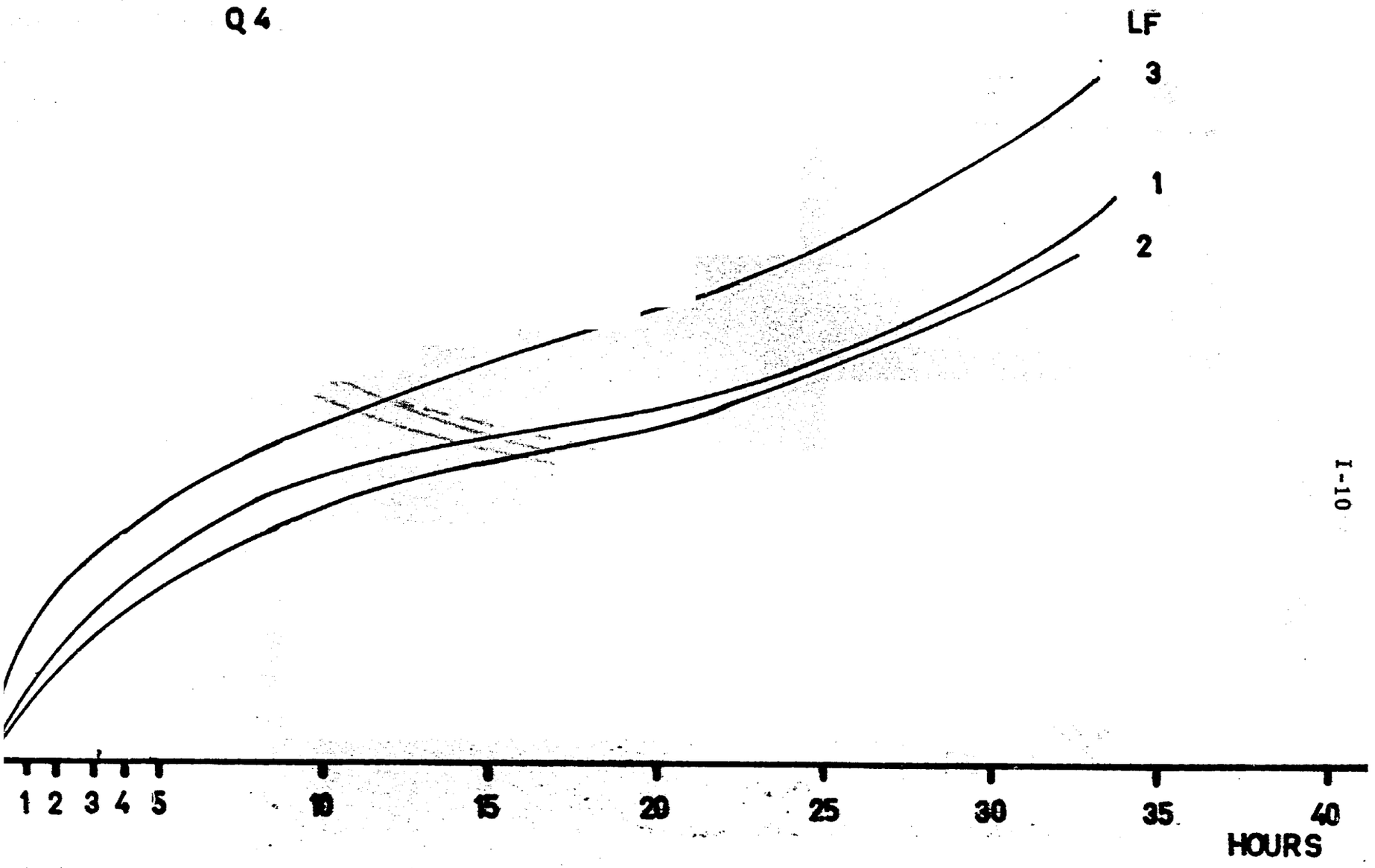
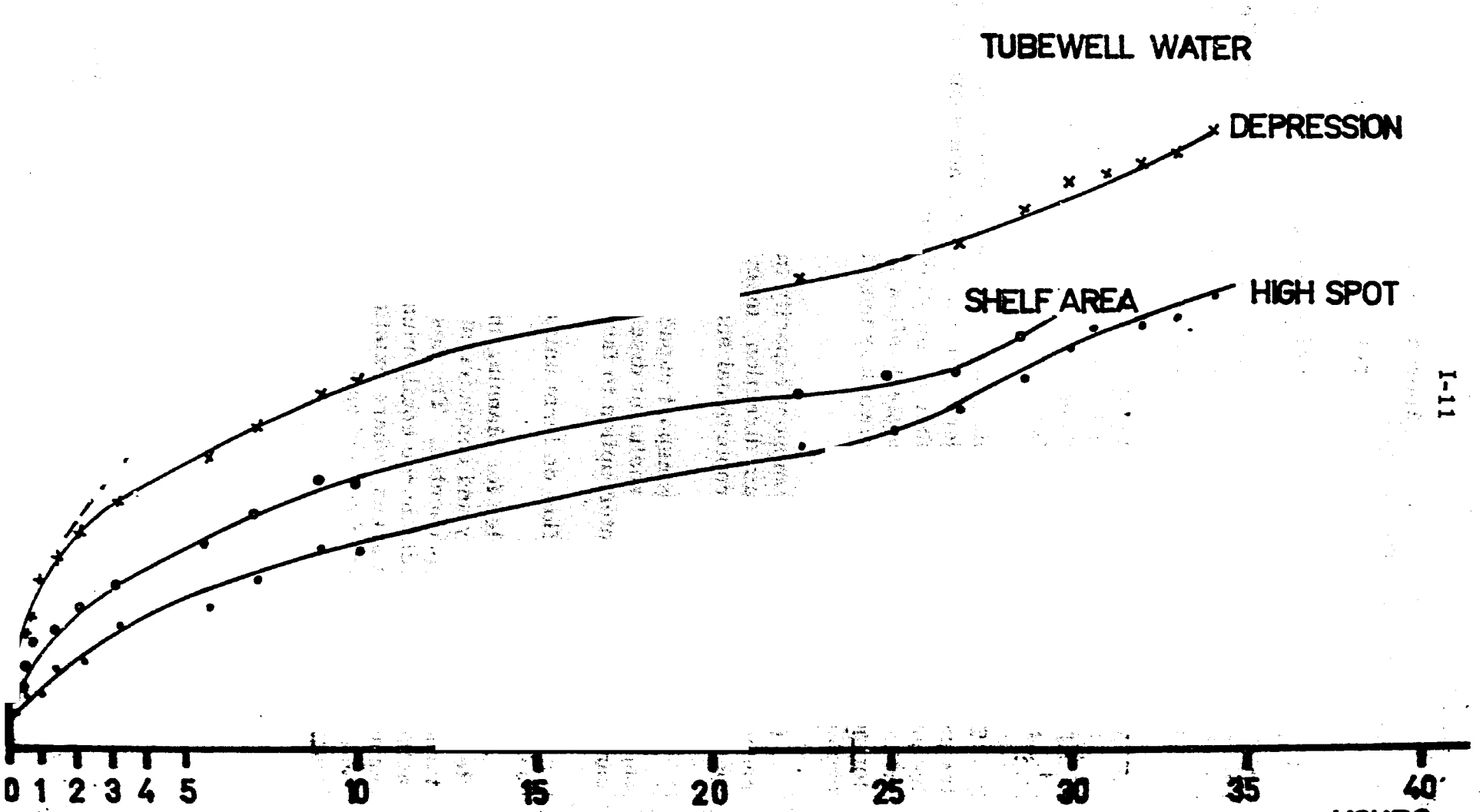


Figure 4. Cumulative rates of infiltration as affected by leaching fractions of 15, 30, and 45% on plots irrigated with water containing 2000 ppm TDS, PARI, Lyallpur.



igure 5. Cumulative rates of infiltration as affected by leaching fractions of 30, 45, and 60% on plots irrigated with water containing 2700 ppm TDS, PARI, Lyallpur.


TUBEWELL WATER
DEPRESSION
SHELF AREA
HIGH SPOT
0 1 2 3 4 5
10
15
20
25
30
35
40

Appendix J

J-1

Publications, Reports, Papers and Manuscripts

A. Publications - Council of U.S. Universities for Soil and Water Development in Arid and Sub-Humid Areas. Water Management Technical Reports not included in Appendices A-I.

1. Mahmood, Khalid. Planning Sediment Distribution in Surface Irrigation Systems. Council of U.S. Universities for Soil and Water Development in Arid and Sub-Humid Areas. Technical Report No. 26. Fort Collins: Colorado State University, 3 December 1973.

This report deals with planning sediment load distribution in surface irrigation systems. The object is to route water and sediment through an irrigation canal network so that sediment discharge equilibrium is achieved by diverting the sediment inflow with the farm supplies. A computer-simulated canal network is used for the routing, and following problems are identified:

(1) The sediment transport capacity in a branching canal network reduces in the downstream direction, mainly because smaller channels cannot transport their proportional share of the sediment load in the system.

(2) The sediment transport capacity of farm watercourse channels is especially limited, and sediment discharge nonequilibrium in these channels can cause frequent interruption to farm water deliveries.

(3) Sediment inflow on farm units necessitates recurrent land levelling.

General principles for planning the sediment routing are derived. Results of laboratory and computer studies of sediment withdrawal in farm turnouts are also presented. The design of system components, so as to achieve sediment discharge equilibrium, is illustrated by a numerical example. Subject areas, where existing knowledge is deficient or unavailable, are also identified; and specific topics for field research are suggested.

2. Zuberi, F. A. and D. B. McWhorter. Practical Skimming Well Design. CUSUSWASH Water Management Technical Paper No. 27. Fort Collins: Colorado State University, 4 December 1973.

Well patterns and designs have been investigated in order to compare the technical performance and costs of several possible skimming facilities. It was established that, for aquifer properties typical in Pakistan, individual skimming wells can be expected to discharge in the range of 0.1 to 0.2 cfs. It is shown that several closely spaced wells can be

pumped at a higher total discharge than a single isolated well, even though the individual wells in the battery are discharging at less than capacity. This results from the fact that distributed pumping produces a smaller maximum drawdown than does a single well pumping at the same rate. The discharge obtained by pumping in battery from closely spaced wells (i.e. 10 to 15 feet apart) is approximately 60 percent greater than for a single isolated well. The increased investment for the battery of wells is more than 60 percent higher than for a single well, however.

Cost estimates are contained in the report that indicate a single skimming well will cost approximately Rs. 2200. A typical private tubewell costs approximately Rs. 7000 for comparison. On a per unit discharge basis, the investment in a private tubewell is about Rs. 7000 per cfs and for a skimming well about Rs. 18,000 per cfs. Operating costs for electrically powered skimming wells is estimated to be about 15 percent of the operating cost for a typical private tubewell. On a per acre foot of water pumped, a skimming well will provide water at about Rs. 20 per acre foot compared with a cost of about Rs. 13 per acre foot for a private tubewell.

3. Franklin, W. T. and W. R. Schmehl. Physical, Salinity and Fertility Analyses of Selected Pakistan Soils. CUSUSWASH Water Management Technical Report No. 28. Fort Collins: Colorado State University, November, 1973.

This report presents basic data of physical, salinity, and fertility analyses of soil samples from Pakistan. Textural analyses and moisture retention properties are given for 58 samples from the Punjab. Soils in the Indus Plain are generally high in silt and low in organic matter, which results in little or no water stable aggregate formation. Empirical relations between moisture retention and textural analyses were developed from the data. Salinity problems are widespread in Pakistan but only a few of the soil samples analyzed contained saline and sodic layers. Sodium-adsorption ratios of saturated paste extracts were correlated with exchangeable sodium percentage and exchangeable-sodium ratios. Correlation coefficients of about 0.96 were found for these correlations. The Pakistan soils generally show less exchangeable sodium percentages in the higher SAR range than do western U.S. soils.

4. Rai, Dhanpat and W. T. Franklin. Program for Computing Equilibrium Solution Composition in $CaCO_3$ and $CaSO_4$ Systems from Irrigation Water Compositions. Water Management Technical Report No. 29. Fort Collins: Colorado State University, October, 1973.

This study develops a computer program to calculate equilibrium solution compositions in calcareous and gypsiferous systems. The

calculations in the program are based upon published solubility products of calcite and gypsum and take into account ion-pair formation and the solubility enhancement of calcite resulting from the presence of Mg^{++} and $SO_4^{=}$ in the solution. For a given pre-equilibrium solution, the program predicts equilibrium ionic strength, ionic activity coefficients, dissociated (free) ions, ion-pairs, and total concentration of solute species, amount of $CaCO_3$ precipitated or dissolved at a specified partial CO_2 pressure, and the amount of gypsum precipitated. Lime and gypsum solubility results predicted with the computer closely agree with published experimental results. The program is suitable for assessing the sodium and salinity hazards of marginal quality waters using other independently developed parameters, such as the concentrating effects taking place in the soil solution due to evapotranspiration during the cropping cycle and partial CO_2 pressures developed under particular soil and cropping conditions.

5. Chaudhry, Mohammad Talib. Conjunctive Use of Indus Basin Waters - Pakistan. (Summary of Ph.D. Dissertation) Water Management Technical Report No. 30. Colorado State University, Fort Collins, October 1973.

This study is a part of the "Grow More Food" campaign of our civilization for world peace and prosperity. It provides a working mathematical model for analyzing and optimizing the conjunctive use of surface and ground water resources of West Pakistan. In specific terms, the objective of the study is to determine the size of the canal system, the surface reservoir, and the ground water pumping facilities, such that, when the system is operated optimally, the capital and operation and maintenance costs of meeting the given irrigation water requirements are minimized.

The results of this research indicate that by optimal conjunctive use management of the Indus Basin Irrigation System in Pakistan, the available water resources can be used more efficiently and at a lesser cost; the ground water aquifer can serve as a functional reservoir and a recycling facility, considerably increasing the usable water resources; and the present "use-when-available" supply system could be developed into a "supply-on-demand" system. This will make other technological, social, and economic inputs more effective and meaningful. As a result, the agricultural produce in the country could potentially be increased by 5 to 6 times. Continued research extension and development are necessary to explore this potential and determine its attainability.

The scope of this study is limited to only a relatively small subset of the overall conjunctive use problem in West Pakistan. Some other problems, however, are identified and suggested for future research.

B. Reports and Papers Included in Appendices A-I

6. Improving Farm Water Management - G. L. Corey and W. Clyma

7. Watercourse Losses - Case Study No. 1 - Wayne Clyma and Arshad Ali

8. Irrigation Method as a Determinant of Pore Space and Crust Strength of Cultivated Soils - W. D. Kemper, John S. Olson and Alan Hodgdon

9. Dissolution Rate of Gypsum in Flowing Water - W. D. Kemper, John S. Olson and C. J. deMocy

10. Fertilizer or Salt Leaching as Affected by Surface Shaping and Placement of Fertilizer and Irrigation Water - W. D. Kemper, John S. Olson and Alan Hodgdon

11. Water Quality Improvement and Gypsum Solubility - W. T. Franklin

12. Evapotranspiration and Irrigation Water Requirements for Pakistan - Wayne Clyma

13. Groundwater Quality Distribution Near the Rattokala Distributary - Mona Area - D. B. McWhorter

14. Progress Report, Water Quality Experiments, Lyallpur - C. J. deMooy, H. M. Bhatti, and A. A. Cheema

15. Water Management Research in a Developing Nation - G. L. Corey

C. Manuscripts Not Published But Available Upon Request

16. Salt Water Coning in Anisotropic Media - R. L. Chandler

17. Economics of Saline Water Management in Indus River Basin of Pakistan - Ahmad S. Khan

18. Crop Yield Models With Limited Soil Water - H. M. Neghassi, Dale F. Heermann, Darryl E. Smika

19. Water-Fertilizer Response Trials, Wheat: 1972-73 - J. B. Eckert

20. Institutional Alternatives for Local Water Management in Pakistan - G. E. Radosevich

D. Submitted for Journal Publication

21. Effect of Hygroscopic Moisture on Ethylene Glycol Retention by Clay Minerals - Dhanpat Rai and William T. Franklin. Submitted to Soil Sci. Soc. Amer. Proc.

22. Sediment Routing In Irrigation Canal Systems - Khalid Mahmood. Proceedings ASCE, Irrigation and Drainage Div. Vol. 100, March, 1974.

Appendix K

K-1

Known Uses During the Report Period of Materials Produced by the Project for Seminars, Speeches, etc.

The following seminars based on Water Management Project Studies were presented at the International Interdisciplinary Seminar on Water Resources Management conducted at CSU and attended by nationals of over a dozen foreign countries:

1. "Problems and opportunities in water management in Pakistan," Gilbert Corey and Jerry Eckert

2. "Water management technology variants needed to accommodate farmers with small as well as large holdings."

The following seminars, papers and reports were given at various locations:

1. "Water management research in a developing nation--concepts and constraints." A paper presented by Gilbert Corey at the International Seminar on "On-Farm Water Management." This will be published in the proceedings of that seminar.

2. "Adequacies and deficiencies of water management knowledge in South Asia." A presentation to the International Seminar on "On-Farm Water Management," by Jerry Eckert.

3. "Role of CSU in water management in Pakistan." A paper presented by Gilbert Corey at the first national "Seminar on Water Management." Printed in the proceedings of that seminar.

4. "Principles and procedures for evaluation of irrigation procedures." Seminar given by Wayne Clyma and Gilbert Corey to 26 agricultural engineering students at the University of Agriculture, Lyallpur

5. "Evaluation of farmer irrigation practices and specific deficiencies of traditional methods of irrigation in comparison to modern irrigation methods." Training session by Gilbert Corey and Wayne Clyma for technicians at the technical training and extension center at Mian Channu.

6. "Crop response to fertilizer and water." Presentation and discussion led on this subject at Pakistan Seminar on Water Management, by J. C. deMooy.

7. "Soil and Soil Moisture Management" - presentation and discussion

8. "Alleviating rural underemployment through integrated rural development," by Jerry Eckert. Written at the request of Col. Malik Shoaib Sultan for presentation and distribution to 50 staff members of the Integrated Rural Development Program.

9. "Nitrate and chloride movement in soils irrigated by furrows compared to basin flooding." Presented at the 1973 American Society of Agronomy Meetings by W. D. Kemper.

10. "Effect of irrigation method on pore size distribution and crusting of soils." Presented at CSU Agronomy Department Seminar by W. D. Kemper.

11. "Proposal for research on the heavy clay soils of the Mekong delta." Presented at the annual meeting of the directors of the Heavy Clay Soils Study by S. A. Bowers.

Appendix L

L-1

BRIEF UTILIZATION REPORT - PAKISTAN (BURP)

Utilization of project production in an LDC is difficult to farily evaluate. There are generally many secondary benefits which tend to go unnoticed and not enumerated as utilization. To consider only transfer of technologies resulting from research per se would be to omit a great portion of a successful program in a developing nation. This project is undoubtedly not unique in the slowness with which a full scale coordinated research program was developed in the participating country. To be successful such programs must be developed gradually with country support. A program transplanted with immediacy but without local support will not succeed regardless of its completeness or sophistication.

This brief narrative report is presented to bring together the project history and development in a manner which emphasizes its utility to Pakistan's agriculture.

Historical

The project, initiated in mid-1968, was actually not started in Pakistan until September 1970 with the arrival of the first member of the field party. Prior to that time a small program of research was planned with two agencies. Discussions were held and plans were developed by correspondence and through short visits to Pakistan by CSU scientists. As a result, no coordinated, country-wide acceptable program for Pakistan was even in the planning stage before 1 January 1971.

The resident CSU engineer began discussions with USAID personnel and Pakistani officials to create such an endeavor. To develop a worthwhile program,

it was first necessary to inculcate a genuine respect for and belief in the fact that water management research was good for and needed by the country. Much time and effort was devoted to this aspect.

There are presently four field party memebers working with most research agencies in Pakistan as advisors and cooperating directly on four documented research programs which have been accepted and wholeheartedly endorsed by the Government of Pakistan. Two of these are suitably financed by USAID grants while the others receive Government of Pakistan financing.

Country Development Climate

The economic and political situation in Pakistan has not been favorable for launching new programs during the past two years. A nine-month civil war terminating only after a major conflict with India on two widely separated fronts left the economy in shambles. Until the termination of this national and international crisis it was virtually impossible to discuss program development on anything other than an informal basis. With the Government of Pakistan's integrity being freely and openly questioned in many quarters around the world, responsible officials were understandably non-committal regarding new foreign aid programs.

The cease fire brought a split in the country and an entirely new regime to power. The usual period of instability and anxiety followed with transfers of positions, policies and programs. To the credit of the new government, this period of insecurity was short lived. There was an openness regarding overall policy and a definite desire to launch rural uplift programs. This favorable atmosphere has existed during the past one year.

Program Promotion

With research progressing on the campus, it was important to develop a

healthy and friendly atmosphere for testing and development in the field. It was apparent that to meet the objectives of the contract it was desirable to promote a change in emphasis in irrigation water management research in Pakistan. Water management seemed to mean production of new water sources or improving the canal system. The strict engineering phases were emphasized at the expense of the agronomic ones. Little attention was being paid to on-farm water management except for the growing concern over salinization which affects large acreages.

Consultation with USAID Agricultural Specialists and knowledgeable Pakistani researchers led to the development of a research promotion campaign centered around efficient use of water through proper land preparation and watercourse rehabilitation. Even the casual observer notes that these two areas have been neglected even though there may be good reasons for the negligence. This is true in most areas of the world where irrigation is practiced. The Pakistan irrigation system is unique in that there is insufficient water supplied for full production. Therefore it is doubly important to use water efficiently since water saved can be used directly by the one who saves it to irrigate more acres or irrigate existing acres more effectively. There is, then, increased production potential from increased acreage as well as increased yields per acre.

The promotional campaign was carried out by developing contacts with key governmental people and discussing in detail the on-farm water management program. The necessity for a viable research program was continually emphasized pointing out the importance of efficient and effective use of water especially where it is so scarce.

The water management film developed under the contract was used extensively. Government officials, students, engineers and farmers all were able to associate

A seminar was held and attended by practically all senior researchers dealing with water management in Pakistan. Several government officials were also in attendance as it was sponsored in cooperation with the Agricultural Research Council. This seminar could be considered the culmination of the on-farm water management research promotion campaign since the recommendations developed there reflect the desired results.

Recent Developments and Utilization

There has been a revolution in Pakistan relative to emphasis in improving on-farm water management. This has occured essentially during the past 15 months. Pakistan is moving fast and almost recklessly in adopting some of the concepts CSU has been promoting. This was unpredictable. A report prepared by the Chief of Party in January 1972 indicated that "the project (CSU/WMR) needs to expand slowly and deliberately since the merits of the program are not self-evident to local agencies". Yet one year later the actions listed below are taking place.

1. The President appointed a high level engineering team to study water management and make recommendations relative to important programs. The Chief of Party was consulted on an informal basis by committee members. High on the priorities was land leveling, watercourse rehabilitation and water management on the farm.

2. A tubewell promotion scheme has been inaugurated by the Government. Farmers are given incentives to drill private wells to increase their water supplies. The field party was consulted.

3. The Government has decided to promote small tubewells to lower water tables in saline affected areas.

4. A national effort is being promoted in precision land leveling. Two provinces are developing programs with USAID whereby Soil Conservation Service teams from the USA will develop training centers to teach precision land leveling techniques and promote the practice as a water management technology.

Watercourse lining is now being promoted by the Government of Pakistan. The Integrated Rural Development Program - Punjab has received funding for an experimental program to test the feasibility of such a program. It is proposed to line 150 miles of watercourses with a brick masonry type of lining in fifteen districts. These test sections will be used to demonstrate the benefits as well as determine farmer acceptance. The farmers are cooperating by furnishing all labor and in fact are acting as the contractors for construction. The Irrigation Department is providing engineering expertise for design and construction.

The plans and discussions which led to this program were definitely influenced by the CSU field team through development of the SHADAB research scheme and other contacts.

6. Practically all research agencies are now conscious of the necessity for better water and soil moisture measurements. The level of precision for these measurements has risen in Pakistan during the past year. There is a demand for weirs, measuring flumes, soil cans, ovens and infiltrometers. Small manufacturers are being assisted by the field party to enable them to fill these needs. Farmers themselves are requesting siphon tubes and manufacture of these is being promoted.

7. The Agricultural Research Council published the recommendations developed at the Water Management Seminar. These were printed in English and Urdu and distributed widely since they contained not only recommendations for priority research programs but also recommendations for the farmer on how to more efficiently utilize his water.

8. The Agricultural Research Council has recently, 15 June 1973, requested the field party to develop "a sound research programme for Baluchistan for optimizing available resources of water supply for use in crop production there".

9. In the interest of developing better methods of watercourse rehabilitation, the Director of the Mona Reclamation Project and the CSU Chief of Party visited Turkey recently to study methods used there. As a result, a brick tile type lining utilized successfully there will be tested in Pakistan. Pipe manufacturers are being helped and encouraged to make rubber gasket irrigation pipe in Pakistan. These will be field tested on the Mona project. Some of the techniques utilized by manufacturers in Pakistan have been adapted in Turkey as a result of this cooperative effort among the two countries. The benefits of such cross fertilization are not easily measured but could certainly prove to be very great.

10. The Director of the Mona Project presented a paper at the Water Management Research Seminar detailing the problems of on-farm management as problems of (a) excessive applications of water due to poor land leveling, and knowledge of crop needs; (b) loss of water from ditches thru spills and seepage. This information was also published as a Paper in INDUS, an engineering publication in Pakistan.

11. Personnel at eight research locations have requested assistance and made efforts at measuring water and soil moisture to make the research more quantitative:

    a. Agricultural Engineering Directorate, Lyallpur

    b. Punjab Agricultural Research Institute, Lyallpur

        (1) Cereals Section - three locations
        (2) Soil Chemist Section

    c. Rice Research Institute, Kala Shah Kaku

    d. Cotton Research Institute, Multan

    e. Maize Research Institute, Yousafwala

    f. Agricultural Engineering, Agricultural University, Lyallpur

    g. Mona Research Project, Bhalwal

    h. Department of Agronomy, Sind Agricultural College, Tandojam

12. Personnel at five locations have received training and practical experience on the evaluation of existing irrigation systems and practices needed to increase water use effectiveness.

    a. Agricultural Engineering Directorate, Lyallpur

    b. Agricultural Engineering, Agricultural University, Lyallpur

        (1) University Professor has used principles and procedures in teaching and in research programs.

        (2) Twenty-six students were given training in classroom and field on principles and procedures for evaluation of irrigation systems. These students have used these procedures to evaluate farmer irrigation systems at several locations in Pakistan.

        (3) Senior students are now required to do a field study as prerequisite to graduation. Before CSU involvement the students did a library thesis.

    c. USAID sponsored class on land leveling design was given to 20 graduate engineers. CSU field party taught and gave field experience in the evaluation and design of irrigation systems.

13. Personnel of the Farmers Technical Training and Extension Center, Mian Channu were given training on the valuation of farmer irrigation practices as well as the specific deficiencies of traditional methods of irrigation in comparison to modern irrigation methods.

14. There is a growing awareness of the need for increased efficiency of water utilization in terms of production. As a result of CSU input, research agencies at some 7 locations are preparing to look into the interaction of soil fertility and other agronomic factors with soil moisture variables. At two of these locations field trials have been initiated even before funds have been made available. It is realized that besides the possible savings in water application and an improved distribution of water on the land, it also is possible to greatly increase the agricultural production per unit of water applied by improvement of production management practices. Experiments with cotton are in progress during this season whereby more careful attention is being paid than ever before to moisture levels, soil fertility conditions, crop stand and plant spacing in comparisons of ridge planting with plantings in basins. No progress can be made unless all production factors are coordinated in this research. Crop breeders also should be involved in this work because new varieties are needed which can tolerate and utilize high levels of moisture, fertility, and management. So far, this kind of coordination has been lacking in Pakistan. The concept of a multiple discipline approach combined with greater precision in all research activities is rapidly being accepted.

15. Water quality research in Pakistan is headed for conclusions which are to some extent conflicting with the standards arrived at in the U.S. Permissible limits in TDS, SAR, and RSC of soils and water tend to be viewed more liberally in Pakistan than in the U.S. Possibly this is caused by insufficient precaution against soil deterioration. If this is true, production and soil resources could be affected in the long term. Most of the important research in this area is being conducted with CSU cooperation. Whether or not water quality standards will coincide ultimately with those of the USA is undecided and remains a most interesting problem.

Program for Increased Utilization

Certainly not all the above listed developments can be credited solely to the CSU project in Pakistan. The USAID Mission has cooperated closely with the program and fortunately the time was exactly correct to develop such endeavors. Adaption of our findings and opinions is so fast that a definite risk exists of our ideas and thoughts being accepted before the necessary research has been done. AID/TAB should be careful not to put excessive pressure on reporting and adaption of incomplete research findings for this reason.

The current emphasis and enthusiasm within the Government of Pakistan will wane unless research keeps pace and defines limits and quantifies costs/benefits on the various technologies being adopted. Two significant projects have been developed to field test any on-farm water management technology which results from research either on the CSU campus or among cooperating stations in Pakistan. Technologies which have proven successful elsewhere can also readily be tested. These are referred to as the Mona and Shadab Projects and involve entire watercourse areas as laboratories. In this manner, the socio-economic conditions become a part of the field test as research is carried out with the farmer under his constraints and utilizing his resources. Land leveling, watercourse linings of several types, improved methods of water delivery, tillage practices, irrigation methods and other agronomic practices can all be field tested and just as important promoted at these field sites. These projects have been financed by the USAID Mission to Pakistan and the Government of Pakistan anxiously awaits funding beginning 1 July 1973.