ESSAY 1

TRADITIONAL AGRICULTURE IN THE PAKISTAN PUNJAB: THE BASIC MODEL

CARL H. GOTSCH

Farmers in the Punjab, like farmers in most irrigated areas of the arid tropics, have a sizeable number of crop and livestock alternatives from which to choose as they allocate their land, water, labor and capital resources. Although seasonal temperatures exhibit wide variation, vegetative growth continues throughout the year, making double-cropping possible. Typically, cereals, food legumes, and oilseeds compete with one another during the winter months (November–April) while cash crops like cotton, rice, and vegetables are potential alternatives during the summer. Under these conditions, perennials (e.g. citrus, nuts, mangos, and bananas) and long-season crops like sugarcane are also common claimants of the farmer's scarce resources.

Irrigation water, in addition to making possible a variety of enterprise combinations, also affects the environment within which farmers make their decisions by altering markedly the degree of technical uncertainty associated with input-output relationships. Year-to-year weather variations that affect canal flows and critical growth periods do exist, of course, but they tend to have much less impact on production than do weather variables in the dryland areas.[1]

These two characteristics of arid-zone irrigated agriculture, i.e., the presence of a number of enterprise alternatives and of relatively deterministic outcomes, favor the use of refined analytical techniques like linear programming to investigate the optimal allocation of farm resources. This essay represents an attempt to capture, in such a model, the intricacies of the allocation problem as it existed prior to the rapid introduction of improved agricultural technology that characterized the Punjab during the 1960s. It is referred to as the "basic" model because large parts of its structure, such as the types of resources that have been assumed to limit output, the disaggregation of seasonal phenomena into monthly time periods, and the choice of crop enterprises, are common to each of the models in this volume.

The data used to estimate the parameters of the different modeling exercises, on the other hand, were drawn from several sources. In the present essay, the numbers came largely from surveys done in the central part of the Province

---

[1] Flows in the Central Punjab canals show considerably less annual variation than do canals elsewhere in Pakistan or in the Indian Punjab. Sometimes a combination of climatologically induced shortages plus a fixed canal rotation system may produce several weeks during peak-demand periods when no water at all is available.

(Lyallpur and Gujranwala Districts) by consultants of the International Bank for Reconstruction and Development (IBRD)-financed Industrial Basin Special Study.[2] The same institutional sources provided the materials for the "traditional" model in the second essay, although the geographical origin of the material differs; i.e., it refers to the Districts of Sahiwal and Multan located in the southern part of the Punjab. Subsequently, independent data sets were developed by Naseem and Ahmed for their respective studies. The results of the latter field surveys were incorporated by the authors into their studies at the same time that certain aspects of the basic model's specifications were being adapted to their special problems.

The common structure referred to above is largely a product of the agroclimatic environment of the Punjab. Those elements that are among the most relevant for resource allocation decisions: temperatures, precipitation, canal flows, and land utilization, are described briefly in the following section. On the basis of this general description, the activities and constraints of the model are spelled out in detail. An optimal solution to the model is then reported and compared with the results of several field studies, particularly as regards cropping patterns and cropping intensity.

In the final portion of the essay, the model is used to explore T. W. Schultz's hypothesis that "traditional" farmers allocate resources in order to maximize profits and that the low level of investment in water producing activities is the result of a low rate of return on capital.[3] The "dual" solution, showing the scarcity values of the model's constraints, is also examined for clues as to how research might contribute most effectively to increasing agricultural output.

CHARACTERISTICS OF PUNJAB AGRICULTURE

Of the 40 million acres that make up the Pakistan Punjab, approximately 40 percent lie in the vast plain that is commonly referred to as the Indus Basin. (The remainder consists of rainfed uplands that ultimately become the foothills of the Himalayas.)

The soils of the plain are alluvial in origin and are, at some points, over 1,000 feet deep. Cross sections taken from test borings show a fine topsoil that gradually gives way to coarser particles of sand and gravel laid down during the early stages of the delta's formation. The coarse strata form one of the largest unconfined acquifers in the world and represent a groundwater reservoir that is one of Pakistan's great natural resources.

The area lies between 30° and 32° north latitude at an elevation of approximately 500 feet above sea level. The lowest maximum monthly mean (65°F) occurs during the pleasantly cool winter in January. In the summer, the Plains become uncomfortably warm with a maximum monthly mean in June that reaches 110 to 115°F.

---

[2] In addition to materials drawn from the International Agricultural Consultants (*3*), supplementary data were obtained from Tipton and Kalmbach (*8*), Ghulam Mohammad (*4*), and Harza Engineering Company (*2*).

[3] "Traditional" is used here in the conventionally vague way, i.e., to describe cultivators in an agriculture that has exhibited relatively little change over a rather extended period of time. For a discussion of the hypothesis that such stagnation results from a lack of profitable investment opportunities, see T. W. Schultz (*7*).

Lahore, the capital of the Province, lies at the edge of the Indian monsoon belt and receives 15 to 20 inches of rainfall annually, most of which falls in the period June to September. The districts of Gujranwala and Lyallpur, from which many of the data for this essay were drawn, show a similar pattern. The summer temperatures are cooler and the humidity higher than the south-central region, a condition that in part accounts for the predominance of rice over cotton in the area.

Precipitation declines rapidly from north to south. Sahiwal and Multan, the areas in which data collection for the other essays in this volume was centered, receive only 6 to 8 inches of rainfall annually. Consequently, these districts are entirely dependent on irrigation; before the canals were built, they consisted of vast tracts of desert sparsely populated by nomads who lived on the active flood plains of the rivers that crossed the region.

Irrigation is the lifeblood of the area. Nearly 13 million acres are served by a vast network of perennial and non-perennial canals that direct approximately 30 million acre-feet of water from the four rivers that have remained under Pakistan's administration.[4] Development of the system was begun by the British in the late nineteenth century in order to help stabilize the uncertain food supply of the Indian sub-continent; the design criteria were therefore more closely related to crop insurance than to intensive agriculture. As a result, the areas commanded by the canals are large relative to the water they are able to deliver. This in turn led to historical cropping systems in which the land was cultivated approximately once a year, i.e., to cropping intensities of 100 percent, even where some water was available throughout the year.[5] The seasonal rotation on given fields was approximately fallow-crop-fallow-crop, but only about 40 percent of the land was idle during the winter while 60 percent was left fallow during the summer. The higher winter-cropping intensities were obtained despite low river flows because the diminished water supplies were more than compensated for by the lower water requirements of winter crops and the smaller evaporation losses from November to April. The canals are fed directly from the river by barrage divisions and the amount of water they carry varies with river runoff as determined by the characteristics of the monsoon and the snowmelt in the Himalayas (Chart 1.1).

An example of a typical cropping pattern in the Central Punjab, where the irrigation water supply is limited to perennial (year-round) canal deliveries is shown in Chart 1.2. An examination of planting and harvesting dates reveals several facts on which subsequent model results are heavily dependent. Because of the time required for cotton picking, cotton and wheat compete for land. Rice and maize, on the other hand, are summer crops that can be grown—at least in terms of land use—before late-sown wheat. Fodder for the farm's animals requires land the entire year and diverts a substantial portion of the total cropped area (10 percent) from crops that contribute directly to farm revenue. Sugarcane and fruit also occupy the land throughout the year and contribute to a high cropping intensity.

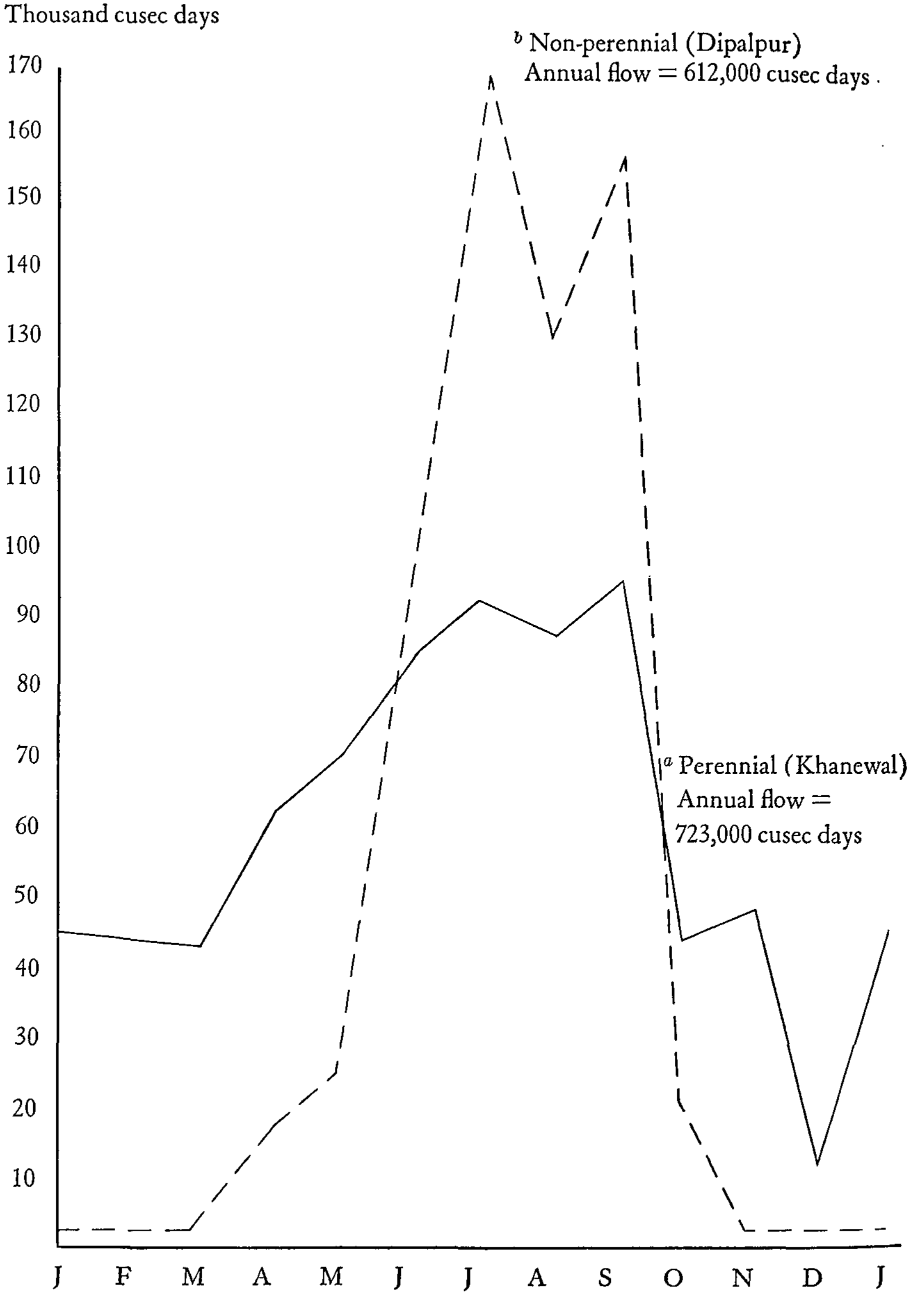
Chart 1.2 does not show the nature of the competition among crops for water.

---

[4] A discussion of the origin of the Punjab's irrigation system may be found in *11*. "Perennial" canals carry water throughout the year; "nonperennial" canals usually do not.

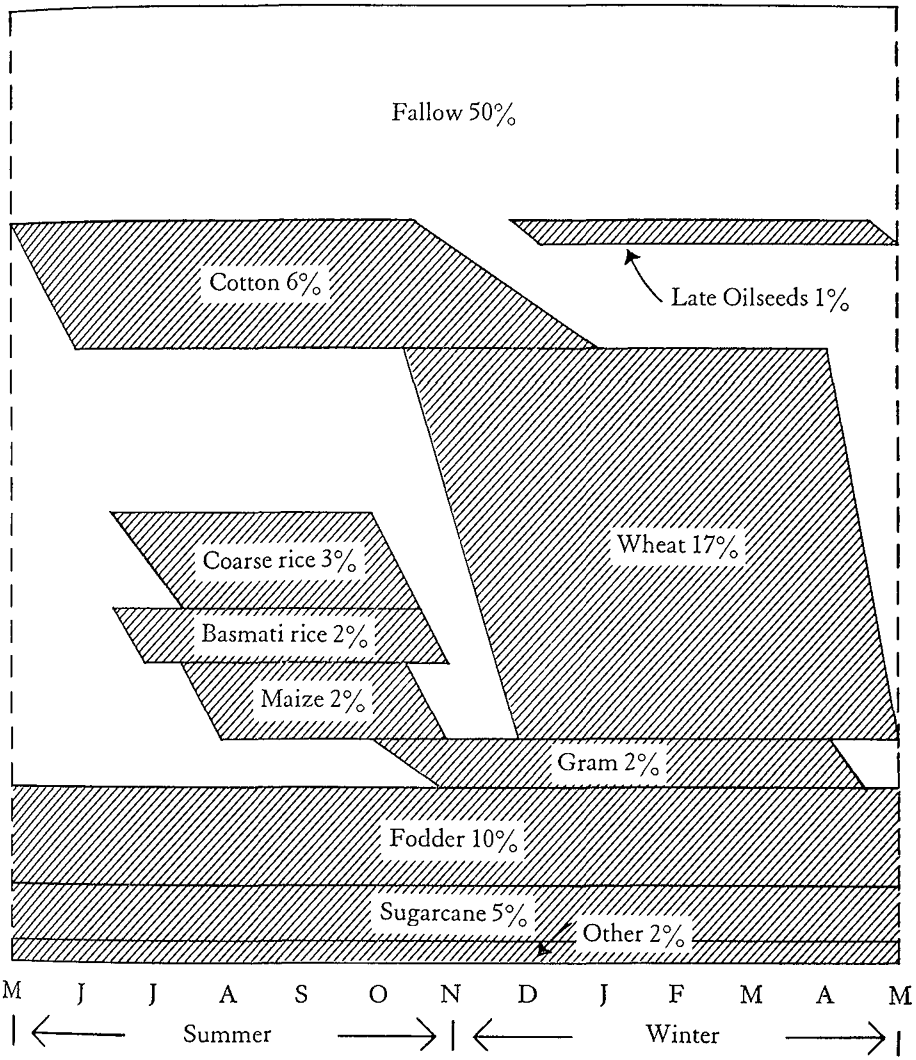
[5] Percent cropping intensity is defined as the cropped area over the cultivated area multiplied by 100. Double-cropping gives an intensity of 200 percent.

CHART 1.1.—DISCHARGE OF TYPICAL PERENNIAL AND NON-PERENNIAL CANALS IN LOWER BARI DOAB



[a] A perennial canal is one in which there is always some water available for irrigation.
[b] A non-perennial canal normally carries water for the summer season, i.e., for 6 to 8 months.

CHART 1.2.—ILLUSTRATIVE CROPPING CALENDAR AND CROPPING PATTERN FOR DISTRICTS IN THE CENTRAL PUNJAB, 1960
(Cropping intensity = 100 percent)



Examination of the crop calendar suggests, however, that the least land is lying fallow during October to December. Comparing this with the schedule of canal flows in Chart 1.2 shows that, in the absence of rain, the competition during this period between maturing summer crops and the seedbed preparation and sowing of winter crops is likely to be intense. The seasonality of the supply and demand for irrigation water is a critical determinant of the behavior of the linear programming models.

STRUCTURE OF THE MODEL

The linear programming model designed to capture some of the complexity of the environment at the farm level has the following structure.

Maximize:

$$R = \sum_{i=1}^{k} c_i X_i - \sum_{i=k+1}^{m} d_i X_i - \sum_{i=m+1}^{n} e_i X_i, \tag{1}$$

where c_i = the net revenue per acre obtained from the i^{th} crop activity (gross revenue minus variable costs)
d_i = the variable cost of the i^{th} water producing activity
e_i = the wages paid for the i^{th} labor-hiring activity.

Equation (1) is maximized subject to a series of constraints

$$\sum_{i=1}^{n} a_{ij} X_i \leq b_j \; j = 1, \ldots, z, \tag{2}$$

where a_{ij} = the input-output coefficient of the j^{th} resource used or contributed by the i^{th} activity, (e.g., the amount of water required in November to produce one acre of wheat)[6]
b_j = a vector of resource availability.

A schematic representation of the model is presented in Table 1.1. (Copies of the tableau are available from the Food Research Institute at cost.)

Water Constraints

The first group of restrictions describes the role of irrigation. Water use and water availability are divided into twelve time periods assumed to be one month in length. Such a breakdown of annual water use is important since the moisture needs of plants must be met throughout the growing season. The water a_{ij}'s are at the heart of the model and their estimation is discussed in some detail in the appendix.

Land Constraints

In addition to the water needs, land requirements are estimated for each crop. The resulting coefficients are simply a description of the periods during which a particular crop occupies the land. They are not strictly synonymous with the plant's growing season since some time must be allotted for seedbed preparation and the removal of crop residues. Total land availability is assumed to be 12.5 acres, a typical farm size for the area.

Bullock Constraints

A third group of constraints describes the animal power needed in the production of an acre of each crop, again by month. Bullock services are treated as a fixed resource because they represent a highly indivisible input for which virtually no rental market exists. As a consequence, nearly all farmers own at least one pair of bullocks regardless of the size of the farm. From several farm management studies it appears that the animals can be worked about six hours a day and 24 days a month. This gives a limit of 144 hours as the appropriate monthly animal-power constraint.

Human Labor Constraints

Human labor requirements are also calculated per acre by crop for each month of the growing season. The fixed nature of this resource stems from its interpre-

---

[6] All crop a_{ij}'s have been standardized to reflect the requirements of one acre of land.

TABLE 1.1.—SCHEMATIC REPRESENTATION OF THE MODEL*

	Activities			
Constraints	Crops (*35 alternatives*)	Water production (*Persian wheel*)	Labor-hiring	Resource availabilities
Water	Irrigation requirements (*acre-inches*)	Supplementary water (*acre-in./hr.*)		Canal water (*acre-inches*)
Land	Land requirements			Land (*acres*)
Animal power	Animal power requirements (*hr./acre*)	Animal power requirements		Animal power requirements
Labor	Labor requirements (*hr./acre*)		Supplementary labor	Family labor (*hours*)
Special crop constraints	Land use of specific crops			Historical levels (*acres*)
Objective function	Rupees per acre (*net revenue*)	Rupees per hour	Rupees per hour	

* Water, land, animal power, and labor and water production, as well as labor-hiring activities are for 12 months.

tation as the labor of the tenant or owner and his family. Again based on farm management data collected in the Punjab, it appears that a farm of 12.5 acres would have about one and one-half man years of adult male equivalent family labor associated with it. Assuming an eight-hour day and 25 work-days per month, a total of about 300 hours of family labor would normally be available each month.

Crop Constraints

Several bounds that directly affect the cropping pattern have been introduced into the constraint set. For example, after determining the fodder requirements of a pair of bullocks, minimum constraints on acreage under these crops have been introduced to insure that the necessary fodder will be forthcoming. For certain high-value crops that would otherwise dominate the model's cropping pattern—summer and winter vegetables, fruit and sugarcane—acreage maximums based on historical plantings have been imposed. All are subject to limited markets and high transportation costs, considerations that have not been included in the model's specification.

Resource-Augmenting Activities

In addition to processes that use resources, two types of resource-augmenting activities are included. The first represents the operation of Persian wheels in shallow wells that tap the underground water reservoir of the Indus Plain and add to the water available from canals. The second permits the hiring of additional labor beyond that supplied by the family.

Both activities, of course, have their costs. The Persian wheel entails direct out-of-pocket maintenance costs and the indirect (opportunity) costs of bullock

Table 1.2.—Optimal Cropping Patterns and Cropping Intensities: Central Punjab, Historical Canal Water Supplies*

	Model		District data[a]		Ghulam Mohammad survey[b]	
Crops	Acres	Percent	Acres	Percent	Acres	Percent
Winter crops						
Wheat	5.26	45.0	4.51	34.4	4.14	30.1
Barley			.13	1.0		
Oilseeds			.25	1.9	.17	1.2
Gram			.41	3.1	.31	2.3
Fodder	1.17	10.0	1.59	12.1	1.63	11.9
Sugarcane	1.00	8.5	.89	6.8	.58	4.2
Vegetables			.04	.3	.04	.3
Orchards			.08	.6	.14	1.0
Subtotal	7.43	63.5	7.90	60.1	7.01	51.1
Summer crops						
Rice	.72	6.2	1.76	13.4	2.26	16.5
Cotton	1.23	10.5	.98	7.5	1.89	13.8
Maize	.02	.2	.71	5.4	.35	2.5
Fodder	1.20	10.2	.79	6.0	1.44	10.5
Sugarcane	1.00	8.5	.89	6.8	.58	4.2
Vegetables	.10	.9	.03	.2	.06	.4
Orchards			.08	.6	.14	1.0
Subtotal	4.27	36.5	5.24	39.9	6.72	48.9
Total	11.70	100.0	13.14	100.0	13.73	100.0
Cropping intensity		94.0		105.0		110.0

* Based on a 12.5-acre farm.

[a] Crop acreage data for Lyallpur and Gujranwala Districts taken from West Pakistan, Bureau of Statistics, Planning and Development Department, *Agricultural Statistics of West Pakistan, 1962/63* (Lahore), mimeo. Data on cultivated area are from Pakistan, Ministry of Agriculture and Works, *Agricultural Census of Pakistan*, 1960 (Lahore).

[b] Figures are a composite of two surveys in the Central Punjab. Cropping intensities are slightly different than reported by Ghulam Mohammad (*4*) because the entire sugarcane acreage has been assumed to occupy the land for two full seasons.

power required to operate it. Outside labor must be paid wages. (Prices for the latter have been obtained from survey data and reflect the documented phenomena that they vary considerably by season.)

THE BASIC SOLUTION

Table 1.2 shows the optimal solution of the model when it is assumed that water availability is limited to historical supplies on a perennial canal in the central plains of the Punjab. Comparison with relevant district and survey data show both similarities and differences.

Cropping patterns are reproduced with reasonable accuracy. The split between the summer and winter seasons, for example, is almost identical. The percentage of cropped acreage devoted to major summer crops such as cotton and rice are also similar. In the winter, the model solution shows only wheat; other major winter crops like gram and oilseeds that compete directly for the same resources, are excluded entirely. (These crops appear in the historical cropping patterns both because they provide some additional hedge against uncertainty and because oilseeds are an early source of cash toward the end of the winter period.)

The model differs most from the historical data in the matter of cropping intensity. A plausible explanation of the difference is that it results from the assumption about the availability of supplementary irrigation water. As subsequent sections describing the simulation of the Persian wheel attest, even small amounts of supplementary water can produce significant improvements in the cropping intensity. Large numbers of such devices did exist in the Central Punjab at the turn of the decade and they undoubtedly affected the relationship between cropped and cultivated acreage.

Scarcity Values of Binding Constraints

Table 1.3 gives the values imputed to the various resources and special constraints in the production process. An examination of these scarcity values (shadow prices) gives further evidence that the basic model is consistent with impressions formed about the economics of agriculture gained from other published materials. Perhaps of greatest interest in this regard are the scarcity values for water. Their magnitude supports earlier comments concerning the importance of certain critical periods because of intraseasonal variations in availabilities and requirements. Water deliveries for specific months are binding for different reasons, for example:

June—large amounts of water needed to "puddle" rice,
September–October—competition of summer and winter crops,
December—low winter canal flows.

Also of interest is the fact that land is not constraining and that, in the absence of a Persian wheel, animal power also does not limit output. Family labor is

TABLE 1.3.—SCARCITY VALUES OF THE BINDING CONSTRAINTS IN THE BASIC SOLUTION

Constraint	Scarcity value per unit (*rupees*)
Water (*per acre-inch*)	
June	3.71
September	7.59
October	16.81
December	59.94
Labor (*per hour*)	
April	.30
May	.40
Crop constraints	
Minimum winter fodder required for bullocks (*per maund*)	.64
Minimum summer fodder required for bullocks (*per maund*)	.18
Maximum summer fodder that could be sold (*per maund*)	.66
Maximum sugarcane acreage (*per acre*)	53.21
Maximum summer vegetables acreage (*per acre*)	174.78

scarce in April although not enough to cause its scarcity value to exceed the wage rate. In May, however, the threshing period produces substantial labor demands and family resources are augmented by some 60 hours of hired labor.

SIMULATION OF A PERSIAN WHEEL

From the foregoing discussion, it is obvious that supplementary water would be extremely valuable in the area from which the model's parameters are drawn. Moreover, the marginal productivity of water differs significantly between months, suggesting that flexible increases in water supplies would minimize the diminishing returns that would otherwise accompany a larger total availability.

The traditional means of obtaining additional water in the Punjab has been the Persian wheel. This device utilizes the tractive power of animals walking in a circle to drive an endless chain of buckets that lift water from a shallow percolation well dug some 20 to 50 feet below the surface. The discharge is dependent, among other things, on the speed that can be coaxed out of the bullocks. It varies from 1/5 to 1/2 cubic feet per second or roughly 1/10 acre-inch per hour.

The Persian wheel simulation involves three kinds of entries in the tableau. First, there are the unit variable costs (standardized on one hour) that subtract from the value of the objective function. These consist of routine maintenance on the wheel and a small allowance for extra concentrates fed to the bullocks. Second, there are the negative entries (a_{ij}'s) in the monthly water availability rows indicating that the operation of the wheel delivers water to these rows; e.g., an hour of Persian wheel operation in November increases water availability in that month by 0.1 acre-inches. Lastly, the Persian wheel uses bullock power and hence a series of positive entries in the bullock availability rows is required.

Cropping Patterns and Cropping Intensities

Table 1.4 gives the cropping intensity and cropping pattern of the optimal solution after entries simulating a Persian wheel have been added to the model.

Perhaps the most significant difference that emerges from a comparison of the solutions with and without a wheel is the increase in cropping intensity from 94 percent to 116 percent. This increase is primarily responsible for the substantial (30 percent) increase in the net revenue when the Persian wheel is used.

An added source of revenue is the shift to higher-valued, water-intensive, crops. The amount of winter and summer fodder for sale has increased, and both winter and summer vegetables and orchards are included up to the maximum acreage.

Additional insights into the effect of adding the Persian wheel to the model can be gained by noting the changes produced in the scarcity values of the farm's fixed resources. Table 1.5 provides the details. First, breaking the serious December bottleneck with respect to water obviously produces a variety of changes in the monthly "shadow prices" of this consistently scarce resource. Second, the competition for land in the month of October has become an important determinant of the cropping pattern. Third, bullock power has become extremely valuable in the months of October and November as the need for water to mature the summer crops competes with the necessity to prepare the seedbed and plant the

TABLE 1.4.—OPTIMAL CROPPING PATTERNS WITH AND WITHOUT A PERSIAN WHEEL

	Without wheel		With wheel	
Crops	Acres	Percent	Acres	Percent
Winter crops				
Wheat	5.26	45.0	4.43	30.6
Barley				
Oilseeds			2.66	18.4
Gram				
Fodder	1.17	10.0	1.65	11.4
Sugarcane	1.00	8.5	1.00	6.9
Vegetables			.20	1.4
Orchards			.30	2.1
Subtotal	7.43	63.5	10.24	70.8
Summer crops				
Rice	.72	6.2	1.32	9.1
Cotton	1.23	10.5		
Maize	.02	.2	.20	1.4
Fodder	1.20	10.2	1.32	9.1
Sugarcane	1.00	8.5	1.00	6.9
Vegetables	.10	.9	.10	.7
Orchards			.30	2.1
Subtotal	4.27	36.5	4.24	29.2
Total	11.70	100.0	14.48	100.0
Cropping intensity		94		116
Net revenue (*rupees*)	1,937		2,575	

winter crops. The problem is very similar to that described in the report on a village study done in Multan District in 1938 (6, p. 85):

> One, and sometimes two, well waterings are given to the mature cotton, bajra and jowar sown late in Sawan. When the canals dry up, this assistance becomes indispensible. As this period coincides with the time when the fields for *rabi* (winter) are being prepared, the extent of this assistance depends on how the cultivator is prepared to restrict the cultivation of *rabi* crops on his well. Costly crops, such as cotton, fodder crops and jowar, are then selected for irrigation and the rest allowed to fail.

Rate of Return on Persian Wheel Investment

Net revenue increases from Rs. 1,937 to Rs. 2,575 when the water production activities are added to the programming matrix, a result that invites a calculation of the rate of return on the well. As indicated earlier, this type of device has been available for decades and if Schultz's hypothesis that agricultural growth has stagnated because of a lack of investment opportunities is correct, one would expect the rate of return to be rather low. Such a conclusion conflicts, however, with previous evidence which indicates that additional water supplies are extremely valuable and with the obvious difference in net revenue between the two solutions.

In 1959/60, the year on which all prices are standardized, the cost of a brick-

TABLE 1.5.—SCARCITY VALUES OF THE BINDING CONSTRAINTS WITH AND WITHOUT A PERSIAN WHEEL

Constraints	Scarcity value (*rupees*) Without wheel	 With wheel
Resource constraints		
Water (*per acre-inch*)		
April		.73
May		3.44
June	3.71	.73
July	7.59	.73
August	16.81	.73
September	59.94	.73
October		12.21
November		18.44
December		.73
February		1.13
Land (*per acre*)		
October		73.31
Bullock power (*per hour*)		
May		.42
October		1.26
November		1.95
Labor (*per hour*)		
April	.30	
May	.40	.40
Crop constraints		
Minimum winter fodder for bullocks (*per maund*)	.64	.62
Minimum summer fodder for bullocks (*per maund*)	.18	.24
Maximum winter fodder for sale (*per maund*)		.06
Maximum summer fodder for sale (*per maund*)	.66	.59
Maximum acreage under winter vegetables (*per acre*)		47.39
Maximum acreage under summer vegetables (*per acre*)	174.78	197.59
Maximum acreage under sugarcane (*per acre*)	53.21	129.70
Maximum acreage under orchards (*per acre*)		54.46

lined well was approximately Rs. 3,500. Another Rs. 1,500 was required for an iron Persian wheel capable of giving the discharge used in the programming activities. The total initial investment would, therefore, have been on the order of Rs. 5,000.

It is unlikely, however, that a farmer of 12.5 acres would own a wheel entirely by himself. Statistics on acreage irrigated by wells suggest that an average of 25 acres can be irrigated per well (*10*). Hence, in the calculations that follow, it is assumed that the individual farmer's investment involved a one-half share in the well or approximately Rs. 2,500.

A reasonable life expectancy for a well in the Punjab is 20 years; Persian wheels, however, can be expected to last only about 10 years. Hence, for the purpose of estimating the rate of return, it has been assumed that the initially installed wheel would be replaced by a similar wheel at the end of 10 years.

The future expenditure has been discounted at the rate of 10 percent. The expression for calculating the rate of return (r) then becomes

$$2{,}500 + \frac{750}{(1+.10)}10 = \sum_{t=1}^{20} \frac{638}{(1+r)^t}\,.$$

In this case, r equals approximately 20 percent. (If the farmer owns more than half the well, the rate of return would be somewhat lower.)

A 20 percent return on investment, when considered in an economy in which the opportunity cost of capital for other nonagricultural purposes may range from 10 percent to 30 percent, must be considered modest. However, judging from the fact that in 1960 nearly 200,000 such wells existed in the Punjab, it must be concluded that investment in water production was found by many farmers to be an attractive proposition. In fact, it raises the question of why the level of water development did not far exceed that observed. For the magnitude of the figure given does suggest that Schultz's hypothesis regarding the paucity of profitable investment possibilities is open to question.

Additional reflection, however, suggests that the high rate of return is a result of energy provided by bullocks whose opportunity cost on a 12.5 acre farm is virtually zero. As Table 1.6 indicates, the optimal solution to the basic model shows over 100 hours available to operate the wheel during the critical months of September, October, and December. The benefits derived from producing additional water with this underutilized resource have been credited entirely to the wheel.

Table 1.6 also shows, however, that the value of supplementary water is such that the possibility of producing water with animal power has positive scarcity values for bullock resources in a number of months. The question that the positive scarcity values raises is whether the rate of return on additional bullocks would be sufficient to justify further investments in animals.

Sensitivity Analysis of the Bullock Constraint

The effect of adding an additional pair of bullocks to the farm is relatively small because the returns from the increase in cropping intensity are offset by the cost of additional fodder. Net revenue rises from Rs. 2,575 to Rs. 2,764, an increase of Rs. 189. The rate of return on a pair of animals costing Rs. 1,400 and expected to have a lifetime of eight years, would be on the order of 2 percent.

A somewhat more favorable result is obtained under the assumption that a cultivator is joined by his neighbor in the purchase of a team to work on their common well. This would increase revenue by Rs. 162 and yield a rate of return of 15 percent.

It could be expected that at a 15 percent rate of return, some additional investment in animals beyond what was necessary for tillage purposes might have taken place. Unfortunately, available data on numbers of livestock are not sufficiently disaggregated to test the hypothesis, and no attempt was made during the field surveys to ask questions relevant to the issue. Under any circumstances, even if the investment in some additional animals was made, the increment to the water supply must have been small. The inefficiency of producing water with

TABLE 1.6.—SCARCITY VALUE OF WATER AND BULLOCK POWER BEFORE AND AFTER THE ADDITION OF A PERSIAN WHEEL

Month	Scarcity value of water (*Rs./acre-inch*)		Bullock hours devoted to Per. wheel		Bullock hours devoted to tillage		Unused bullock hours		Scarcity value of bullock hours (*Rs./hour*)	
	Before	After	Before	After	Before	After	Before	After	Before	After
April		.73	—	1.1	23.6	17.6	120.4	125.3	—	
May		3.44	—	67.3	100.0	76.7	44.0	—	—	.42
June	3.71	.73	—	62.6	19.7	23.5	124.3	57.9	—	
July		.73	—	33.1	31.3	53.0	112.7	57.9	—	
August		.73	—	55.8	59.4	68.5	85.6	19.7	—	
September	7.59	.73	—	55.9	35.7	58.2	108.3	29.9	—	
October	16.81	12.21	—	103.1	38.0	40.9	106.0	—	—	1.26
November		18.44	—	103.9	43.4	40.1	100.6	—	—	1.95
December	59.94	.73	—	119.7	13.5	13.5	130.5	10.8	—	
January		—	—	—	13.5	15.6	130.5	128.4	—	
February		—	—	—	22.5	36.9	121.5	107.1	—	
March		1.13	—	95.3	21.0	48.7	123.0	—	—	.40

animals and mechanical devices like Persian wheels simply precluded widespread groundwater development.

SHADOW PRICES AND AGRICULTURAL RESEARCH

The scarcity values of the resources shown in Table 1.5 offer important insights into those areas of traditional agriculture toward which technical change could most profitably be directed. Indeed, the systematic elimination of resource "bottlenecks" can become the basis of an approach to the whole problem of agricultural research and technology diffusion. For example, had the high value of seasonal flexibility in the water supply that is demonstrated by this model, been fully understood by agricultural planners in the early 1950s, the rapid increase in tubewell installation that ultimately occurred in the mid '60s might have been accelerated.

Table 1.5 suggests other ways in which the dual portion of the optimal solution might provide a basis for developing a research strategy. As a result of some additional water via the operation of the Persian wheel, certain land constraints have become more critical. This is the result of the overlap between summer and winter crops and the competition between crops for land instead of water. Traditionally, the ability to alter the harvesting and planting dates of major crops was not crucial since much of the land was devoted to fallow. But when the "bottleneck" with respect to water is solved, it is clear where the next series of bottlenecks will arise. In some cases this may mean that plant breeders will be called upon to select for varieties that can be planted later or harvested earlier so that an additional crop can be squeezed into the rotation. In other cases, it may be the work of the entomologist and plant pathologist that is crucial. For example, one finds upon inquiry that planting of much of the rice crop is delayed to avoid attacks by the stem borer. It was discovered long ago that without modern plant protection measures, the only effective means of holding down infestations by this extremely damaging pest was to deny it the residues of rice plants long enough to break its life cycle. The result was an ordinance forbidding the planting of rice before June 15. Given the maturation period of rice, such a late start makes it extremely difficult to prepare the seedbed for winter crops. Entomologists examining the rice pest problem have suggested that there are now economic plant protection measures, such as systemics, that can significantly dampen the effect of rice pests. Widespread adoption of these techniques would pave the way for a revision of traditional wisdom on planting dates and thereby permit land to be double-cropped.

Lastly, the figures in Table 1.6 point to another type of research question that has not yet been seriously addressed, namely, that of intermediate mechanization. For according to the model results, even without the Persian wheel a high portion of the available animal power is committed during the month of May. This is when threshing of wheat competes for bullocks with seedbed preparation and planting of summer cash crops like cotton. Were the assumed holding only slightly larger, power would become a binding constraint to further increases in output. The same would be true if the cropped acreage were increased significantly. In either case, the model suggests the need to examine carefully alternatives by which the power "bottleneck" in May could be alleviated.

SUMMARY AND CONCLUSIONS

Many problems in the efficient management of agricultural resources at the farm level are undoubtedly best undertaken with simple budgeting techniques. However, in a number of areas, primarily in the arid and semi-arid zones of the world where the availability of irrigation water is an important determinant of output, linear programming is an appropriate technique for investigating the economics of enterprise combination. The agro-climatic environment of the Pakistan Punjab appears to fit this category, an observation that is confirmed by the results of the programming exercise. In every solution, at least a half-dozen fixed resource constraints were binding. As additional water supplies produced greater flexibility, this number rose to more than a dozen and included every primary resource: water, land, bullock power, and human labor. Attempts to arrive at an optimal allocation of resources under such conditions using traditional budgeting methods would be extremely difficult if not impossible.

The behavior of the basic model in the absence of the Persian wheel is determined largely by the amount and timing of surface water supplies. June, September–October, and December are the crucial periods and they virtually determine the cropping pattern. Seasonal land constraints are not binding, which is consistent with historical cropping intensities of approximately 100 percent. On the 12.5-acre farm, bullock constraints are also not binding, although in May there is little excess animal power. The same congestion of harvesting and sowing activities produces a positive scarcity value for labor in May.

The addition of supplementary water-producing activities altered the results of the model significantly. Net revenues increased by 30 percent as a result of both increased cropping intensity and shifts in the cropping pattern toward high value crops. Land constraints became binding as the addition of the Persian wheel shifted enterprise competition from water to land. The shadow prices for bullocks increased substantially both because of the demand for animal power derived from the added water and because of the increased tillage requirements associated with the increase in cropped acreage.

Sensitivity analysis of the value of additional investment in bullocks for water production suggested, however, that the traditional cultivator's failure to expand the amount of supplementary water supplied was economically rational. The relatively high returns to the investment in a Persian wheel were in part the result of large amounts of excess bullock power that was available in months of low canal flow to operate the wheel. Further investment in animal power yields low rates of return when compared to the cost of capital.

The programming approach also served to pinpoint areas on which scientists might concentrate their efforts to increase agricultural output. For example, it is clear that with increased water supplies, double-cropping will be dependent upon the ability (1) to alter the planting and harvesting dates of certain key crops and (2) to introduce suitable modification in the availability of draught power to insure timely harvesting and planting operations.

CITATIONS

1 C. H. Gotsch, "Technological Change and Private Investment in Agriculture: A Case Study of the Pakistan Punjab" (unpub. Ph.D. diss., Harvard Univ., 1966).

2 Harza Engineering Company International, "A Sample Survey of Private Tubewells and Farms: Gujranwala Area" (Water and Power Dev. Authority [WAPDA], Lahore, 1967), mimeo.

3 International Agricultural Consultants Associated, *Program for the Development of Irrigation and Agriculture in West Pakistan: Comprehensive Report* (Intl. Bank for Reconstr. and Dev [IBRD], Washington, 1966).

4 Ghulam Mohammad, "Private Tubewells and Cropping Patterns in West Pakistan," *Pakistan Dev. Rev.* (Karachi), Spring 1965.

5 Pakistan, Ministry of Agriculture and Works, *Agricultural Census of Pakistan, 1960* (Lahore).

6 Punjab, Board of Economic Enquiry, *An Economic Survey of Dunana Langana: A Village in Multan District of the Punjab* (Lahore, 1938).

7 T. W. Schultz, *Transforming Traditional Agriculture* (New Haven, Conn., 1964).

8 Tipton and Kalmbach, *Salinity Control and Reclamation Program Project No. 4* (WAPDA, June 1965).

9 West Pakistan, Planning and Development Dept., Bureau of Statistics, "Agricultural Statistics of West Pakistan, 1962/63" (Lahore), mimeo.

10 ———, *Season and Crop Report of the Northern Zone* (Lahore, 1959/60).

11 White House, Dept. Interior Panel on Waterlogging and Salinity in West Pakistan, *Report on Land and Water Development in the Indus Plain* (Washington, 1964).

12 Dan Yaron, "Economic Criteria for Water Resource Development and Allocation, Supplement A" (Rehovat/Hebrew Univ., 1966), mimeo.

APPENDIX
DIMINISHING RETURNS TO WATER

Methods of estimating most of the parameters of the model may be found elsewhere (*1*, *3*). However, the central role of the water coefficients in the constraint matrix suggests that at least a brief description of their derivation be given in this paper.

Although the model described above is a straightforward application of the linear programming technique, an attempt was made in the case of water to permit some deviations from fixed input proportions. Such a modification was felt to be necessary in view of the widely demonstrated diminishing response of plant growth to increments in water availability. For example, a large number of field experiments have shown that the water response curve for wheat has the shape indicated in Chart A1.1.

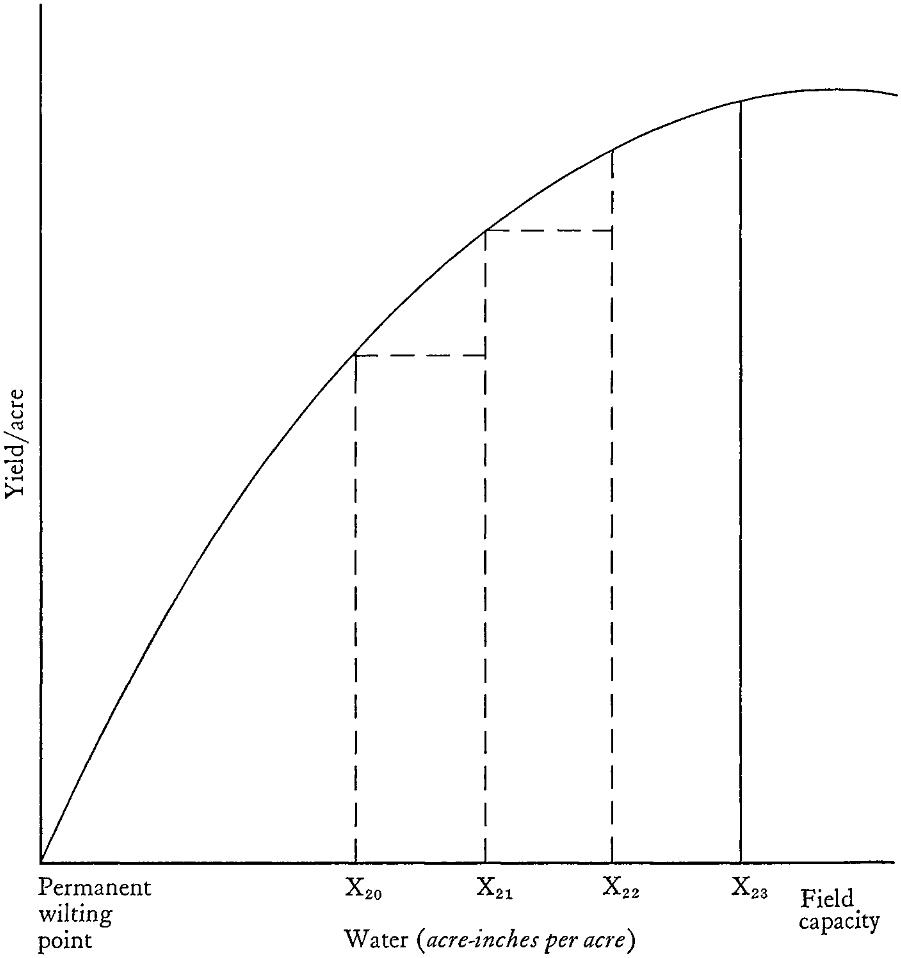
For inclusion in the model, the curve in Chart A1.1 was approximated by a step function.[7] The linear segments so derived became the basis for the wheat activities in the program. (For example, X_{20} through X_{23} all refer to wheat.) A similar procedure was applied to the remaining crops.

Since one of the primary objectives of the model was to take into account the importance of intraseasonal competition for resources in a climate where continuous cropping is possible, the second step in developing the water coefficients for wheat activities was to break down the total annual water application reported in the agronomic experiments into monthly coefficients. This was done by assuming that, for a given amount of water, the time distribution that would maximize the output of wheat was proportional to the monthly net consumptive

---

[7] For a discussion of the methodology involved in developing suitable curves from a large number of experiments, see *1*.

CHART A1.1.—APPROXIMATED WATER RESPONSE CURVE FOR WHEAT



use requirements.[8] That is, if the net consumptive use requirement of the month of October was 20 percent of the total requirement, water supplies which were less than the full requirements were also distributed so that 20 percent of the available water was used in October.

The approach outlined above for obtaining monthly water coefficients for the constraint matrix, A, is clearly crude and does not include the recognition that optimal irrigation practices are essentially a sequential decision-making problem. The use of evapotranspiration estimates at point X_{23} in Chart A1.1 can be justified unambiguously. By definition there is no appreciable water shortage in any period and hence the timing of water application is of marginal significance. But it is well known that when the quantity of water available is less than that

---

[8] Net consumptive use requirement refers to the total calculated water requirement of the plant minus the effective precipitation. Meeting consumptive use requirements insures that the plant is not hindered in its growth by moisture deficiencies.

required for maximum yield, its distribution over the growing period of the plant is a significant determinant of the effect of moisture shortages. Nevertheless, lacking more empirical material on the effects of drought at various points on the plant's growth stage curve, the approximation suggested above permitted the inclusion in the model of a good deal of information on the timing of water requirements and water availability.